



Volume (11)

Issue (1)

Part (1)

May 2026

Dhul-
Qi'dah 1447H

J
N
B
A
S

Journal of the North for Basic and Applied Sciences

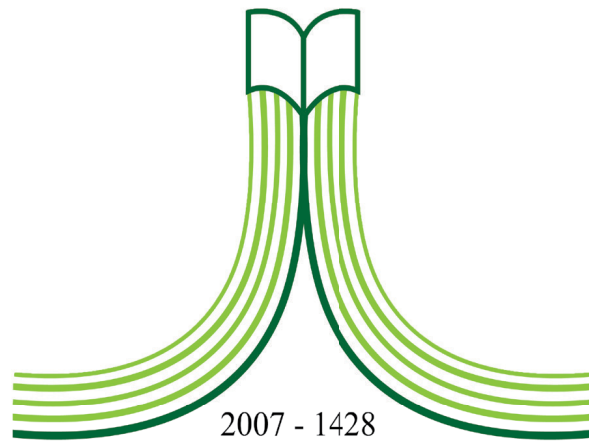
Peer-Reviewed Scientific Journal

Northern Border University
www.nbu.edu.sa

p- ISSN: 1658 - 7022
e- ISSN: 1658 - 7014



IN THE NAME OF ALLAH
THE MOST GRACIOUS, THE MOST MERCIFUL



2007 - 1428

جامعة الحدود الشمالية

NORTHERN BORDER UNIVERSITY

Kingdom of Saudi Arabia

Journal of the North for Basic and Applied Sciences (JNBAS)

Peer-Reviewed Scientific Journal

Published by

**Translation, Authorship, and Publishing Center
Northern Border University**

Volume (11) - Issue (1) - Part (1)

May 2026 - Dhul-Qi'dah 1447H

Website & Email

www.nbu.edu.sa

s.journal@nbu.edu.sa

p- ISSN: 1658 - 7022 e- ISSN: 1658 - 7014

Editor-in-Chief

Prof. Mohammed Abdulaziz Tashkandi
Professor, Mechanical Engineering

Editorial Board Members

Dr. Muflih Battah Alhazmi
Associate professor, Mathematics

Dr. Fahdah Ayed Alshammari
Associate professor, Biology

Dr. Munirah Mutlaq Aljuaid
Associate professor, Mathematics

Dr. Ali El-Said El-Rayyes
Associate professor, Chemistry

Dr. Tarek Ibrahim Alanazi
Assistant professor, Physics

Journal of the North for Basic and Applied Sciences (JNBAS)

About the Journal

The Journal of the North is concerned with the publication of original, genuine scholarly studies and researches in Basic and Applied Sciences in Arabic and English. It publishes original papers, review papers, book reviews and translations, abstracts of dissertations, reports of conferences and academic symposia. It is a biannual publication (May and November).

Vision

The journal seeks to achieve leadership in the publication of refereed scientific papers and rank among the world's most renowned scientific periodicals.

Mission

The mission of the journal is to publish refereed scientific researches in the field of Basic & Applied Sciences according to well-defined international standards.

Objectives

1. Serve as a scholarly academic reference for researchers in the field of Basic & Applied Sciences.
2. Meet the needs of researchers, publish their scientific contributions and highlight their efforts at the local, regional and international levels.
3. Participate in building a knowledge community through the publication of research that contributes to the development of society.
4. Cover the refereed works of scientific conferences.

Terms of Submission

1. Originality, innovation, and soundness of both research methodology and orientation.
2. Sticking to the established research approaches, tools and methodologies in the respective discipline.
3. Accurate documentation.
4. Language accuracy.
5. The contribution must be unpublished or not submitted for publication elsewhere.
6. The research extracted from a thesis/dissertation must be unpublished or not submitted for publishing elsewhere and the researcher must indicate that the research submitted for publishing in the journal is extracted from a thesis/dissertation.

Correspondence

Editor-in-Chief
Journal of the North for Basic and Applied Sciences (JNBAS),
Northern Border University, P.O.Box 1321, Arar 91431,
Kingdom of Saudi Arabia.
Tel: +966(014)6615499
Fax: +966(014)6614439
email: s.journal@nbu.edu.sa
Website: www.nbu.edu.sa

Subscription & Exchange

Translation, Authorship, and
Publishing Center,
Northern Border University,
P.O.Box. 1321, Arar 91431,
Kingdom of Saudi Arabia.



PUBLICATION INSTRUCTIONS FOR AUTHORS

Submission Guidelines

1. Manuscript must not exceed 35 pages of plain paper (A4).
2. Manuscript must have a title and an abstract in both Arabic and English on one page; the abstract should not be more than 250 words. The manuscript should include, in both languages, keywords that indicate the field of specialization. The keywords are written below each summary and should not be more than six.
3. The author(s) name(s), affiliation(s) and address(es) must be written immediately below the title of the article, in Arabic and English.
4. The Arabic manuscript is typed in Simplified Arabic, in 14-font size for the main text, and 12-font size for notes.
5. The English manuscript is typed in Times New Roman, in 12- font size for the main text, and 9-font size for notes.
6. The manuscript is typed only on one side of the sheet, and line spacing should be single. Margins should be 2.5 cm (or 1.00 inches) on all four sides of the page.
7. The manuscript must have the following organization:
 - Introduction:** It should indicate the topic and aims of the research paper, and be consistent with its ideas, information and the established facts. The research problem(s) and importance of the literature review should also be introduced.
 - Body:** The manuscript body includes all necessary and basic details of research approach, tools and methods. All stated information should be arranged according to priority.
 - Findings and Discussion:** Research findings should be clear and brief, and the significance of these findings should be elucidated without repetition.
 - Conclusion:** It is a brief summary of the research topic, findings, recommendations and suggestions.
8. Figures, diagrams and illustrations should be included in the main text and consecutively numbered and given titles, with explanatory notes beneath them.
9. Tables should also be included in the main text, consecutively numbered and given titles at the top, with explanatory notes below.
10. Footnotes should be added at the bottom of each page, when necessary. They are to be indicated by numbers or asterisks, in 12-font size for Arabic and 9-font size for English.
11. The Journal of the North does not publish research and measurement tools (instruments). However, they must be included in the submission(s).
12. Citations must follow the American Psychological Association (APA) reference style in which both the author's name and year of publishing are mentioned in the main text, i.e. (name, year). Numbering the references inside the main text and adding footnotes are not allowed.

Researchers' documentation must be as follows:

 - For single author, the author's family name, followed by a comma, and the publishing year, such as (Khayri, 1985).
Page numbers are indicated in the main text in case of quotations, such as (Khayri, 1985, p. 33).
 - If a manuscript has two authors, they must both be cited as shown previously, e.g. (AL-Qahtani & AL-Adnani, 1426 H).
 - If there are multiple (more than two) authors, their family names must be mentioned the first time only, e.g. (Zahran, Al-Shihri, & Al-Dusari, 1995); if the researcher is quoting the same work several times, the family name of the first author followed by "et al." [for papers in English] and by "وأخرون" [for papers in Arabic] must be used, e.g. (Zahran et al., 1995) / (زهران وأخرون، 1995). Full publishing data must be mentioned in the bibliography.
13. The bibliography, list of all the sources used in the process of researching, must be added in alphabetical order using the author's last name according to the APA reference style (6th edition) in 12-font size for Arabic and 9-font size for English.

The bibliography should be organized as follows:

Citation from books:

Citation from a one-authored book:

Shotton, M. A. (1989). Computer education? A study to computer dependency . London, England: Taylor & Francis.

Citation from a book of more than one author:

Timothy, N., Stepich, D., & James, R. (2014/1434 H) *Instructional technology for teaching and learning*. Riyadh, Kingdom of Saudi Arabia: University of King Saud Publications.

Citation from Periodicals:

Al Nafaa, A. H. (1427 H). Effect of driving off-road on wild vegetation parks: A study in environmental protection, in the center of the Kingdom of Saudi Arabia. *Saudi Journal of Life Sciences*, 14(1), 35-72.

Citation from M.A. or Ph.D. Thesis:

AlQadi, I. A. (1429 H). *Natural Plants in a Coastal Environment between Rassi Tanoura and Elmalouh in the Eastern Region: A Study in Botanical Geography and the Protection of Environment*. Unpublished Ph.D. Dissertation, College of Arts for Girls, Dammam, Kingdom of Saudi Arabia: King Faisal University.

Citation from Internet References:**Citing an online book:**

Almazroui, M .R. & Madani, M. F. (2010). *Evaluation of performance in Higher Education Institutions*. Digital Object Identifier (doi:10.xxxx/xxxx-xxxxxxx-x), or the Hypertext Transfer Protocol (http://www...), or the International Standard Book Number (ISBN: 000-0-00-000000-0) must be mentioned.

Citing an article in a periodical:

Almadani, M. F. (2014). The definition of debate in reaching consensus. *The British Journal of Educational Technology*, 11(6), 225-260. Digital Object Identifier (doi:10.xxxx/xxxx-xxxxxxx-x) or the Hypertext Transfer Protocol (http://onlinelibrary.wiley.com/journal/10.1111), or the International Standard Serial Number of the journal (ISSN: 1467- 8535) must be mentioned.

14. It is the researcher's responsibility to translate into English the Arabic bibliography.

Example:

الجبر، سليمان. (1991م). تقويم طرق تدريس الجغرافيا ومدى اختلافها باختلاف خبرات المدرسين وجنسياتهم وتخصصاتهم في المرحلة المتوسطة بالمملكة العربية السعودية. *مجلة جامعة الملك سعود- العلوم التربوية*، 3(1)، 143-170.

Al-Gabr, S. (1991). The evaluation of geography instruction and the variety of its teaching concerning the experience, nationality, and the field of study in intermediate schools in Kingdom of Saudi Arabia (*in Arabic*). *Journal of King Saud University- Educational Sciences*, 3(1), 143-170.

15. Numerals should be the original Arabic numbers (0, 1, 2, 3 ...) in the manuscript.

Required Documents

Researchers are required to submit the following:

1. An electronic copy of their submissions in two formats: Microsoft Word Document (WORD) and Portable Document Format (PDF), to be sent to the following email:

s.journal.nbu@gmail.com

&

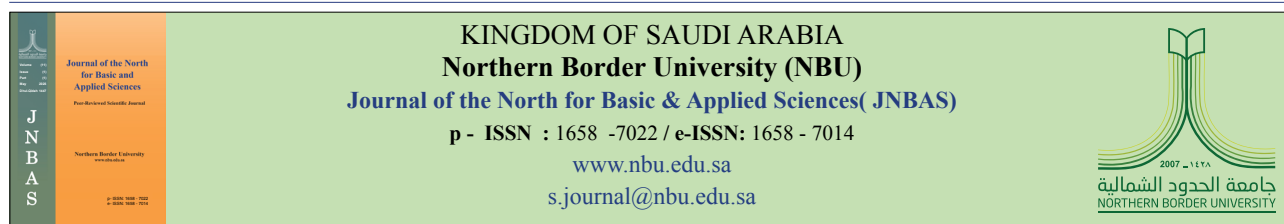
s.journal@nbu.edu.sa

2. The researcher's CV, including his/her full name in Arabic and English, current work address, email, and academic rank.
3. The researcher must fill out and submit the application for publishing in the Journal of the North, along with the Pledge Statement that his/her submission has not been published before or has not been submitted for publishing elsewhere.

NB

1. The submissions received by the Journal of the North will not be returned whether they are published or not.
2. The published papers reflect only the author's points of view.
3. All accepted manuscripts devolve their property to *the Journal of the North for Basic and Applied Sciences (JNBAS)*.

- **Impact of Nursing Education Program on Knowledge and Practice in Thermal Care Practices for Newborns in the NICU of Omdurman Teaching Hospital**
Maha Abdalla Abdelsadig Ali* 1
- **The Impact of Hourly Nursing Rounds on Patient Satisfaction and Safety Outcomes in Hospitalized Adult Patients: A Systematic Review**
Maha Abdalla Abdlsadig Ali - Mohammed Khalid Hussein Khalid - Omnia Abdalla Mohammed Higazy - Salwa Ali Mousa - Wafa Abdein Humza Bashir - Fatma Abdalla Mohamed Abdalla - Shahenda Ateyat allah Salih - Ghada AbdElsalam Ahmed Eldeeb - Hawa Ibrahim Abdalla Hamid 11
- **PHENOLICS AND FLAVONOIDS PROFILING IN *LEPIDIUM AFRICANUM* METHANOL EXTRACT AND EVALUATION OF ITS ANTIOXIDANT, ANTIDIABETIC, ANTI-INFLAMMATORY, AND ANTICANCER PROPERTIES**
Esam A. Alqurashi 21
- **Analysis of Critical Buckling Moments in Steel I-Girders with Initial Imperfections**
Amr B. Saddek | Brahim Bousalem | Saif Eldeen A.S. Yousef | Abbas M. A. Alshehari | Abdullah Albogami | Ahmed M. Farag El Sheikh 41
- **Variability of Four Home Blood Pressure Monitoring Devices: Insights from a 2024 Cross-Sectional Study**
Abdulrahman T. Abudawood - Hala A. Bagabir - Iman W. Salem - Shahad A. Alghanmi - Reham M. Alharbi - Shoug T. Alaslani - Shooq S. Samkari - Fatimah Y. Fallatah 52
- **GNN-AOI: A GRAPH NEURAL SCHEDULING FRAMEWORK FOR AGE-AWARE REAL-TIME STREAMING OVER MPTCP IN 5G EDGE NETWORKS**
Hamed D. Al-Sharari 60
- **Analytical Traveling-Wave Solutions of the Conformable Fractional (2+1)-Dimensional Zakharov–Kuznetsov Equation via the Unified Method**
Elzain A. E. Gumma 71
- **Blockchain-Driven Privacy Preservation for Robust IoT Security with an Attribute-Reduced Hybrid Deep Representation Learning Approach**
Sultan Alkhliwi 79
- **Nurses' Knowledge of Diabetic Ketoacidosis Management: A Cross-Sectional Study in Omdurman Teaching Hospital, Sudan**
Huda Hassabelrasool Abdelwahed Yousef 97
- **The Role of Virtual Simulation Environments (the Metaverse) in Improving Construction Methodologies and Processes**
Ahmed R. Attia 104
- **Effect of a combination of newly synthesized two thiazole derivatives with curcumin and quercetin on the regulation of mTOR, Bcl-2, IL6, and Caspase3 genes Expression in HepG2 Cells**
Rasha Alnefaie 124



Impact of Nursing Education Program on Knowledge and Practice in Thermal Care Practices for Newborns in the NICU of Omdurman Teaching Hospital

Maha Abdalla Abdelsadig Ali*

Department of Nursing, College of Nursing and Health Sciences, Jazan University, Saudi Arabia.

(Received: 16th November 2025; Accepted: 20th December 2025)

Abstract: Background: Hypothermia remains one of the most preventable complications among newborns, particularly in resource-limited neonatal intensive care units (NICUs) such as Omdurman Teaching Hospital.

Objective: To evaluate the effectiveness of a structured nursing education program in improving the knowledge and clinical practices related to thermal care among NICU nurses at Omdurman Teaching Hospital.

Methods: A quasi-experimental pre-test/post-test design was adopted. A total population sample of 86 registered NICU nurses participated. Data were collected using a 20-item multiple-choice knowledge questionnaire and a 15-item observational checklist assessing thermal care practices. The study was conducted from November 2024 to January 2025. Baseline and one-week post-intervention assessments were carried out. Data analysis was performed using SPSS version 25, and changes were examined using paired t-tests.

Results: The educational program produced significant improvements in both knowledge and practice. The mean knowledge score increased from 12.3 ± 3.5 to 19.7 ± 2.8 ($p < 0.001$), with notable gains in thermal physiology, heat-loss prevention, and incubator use. Practice scores improved significantly from 15.6 ± 4.1 to 23.4 ± 3.2 ($p < 0.001$), particularly in drying techniques and incubator handling. A strong positive correlation between post-test knowledge and practice was observed ($r = 0.78$, $p < 0.001$), indicating that higher knowledge levels were associated with better clinical performance.

Conclusion: The study demonstrates that evidence-based nursing education is highly effective in enhancing NICU nurses' knowledge and clinical practice in neonatal thermal care. Implementing such programs can improve newborn outcomes and support sustainable quality care in low-resource settings.

Keywords: NICU, neonatal thermal care, nursing education, Omdurman Teaching Hospital, hypothermia, knowledge and practice



(*) **Corresponding Author:**

Maha Abdalla Abdelsadig Ali*

Department of Nursing, College of Nursing and Health Sciences, Jazan University, Saudi Arabia.

E-mail: mahaaballa@gmail.com

1. Introduction

Thermal regulation in infancy is the natural ability of a newborn to maintain body temperature within the normal range (36.5–37.5°C, axillary) by balancing heat production and heat loss (Bach & Libert, 2021). A core temperature below 36.5°C is defined as neonatal hypothermia, which can lead to serious complications such as hypoglycemia, respiratory distress, metabolic acidosis, and increased risk of morbidity and mortality (Prajapati et al., 2025; Saha, 2023).

Neonatal hypothermia is a major global health concern, contributing significantly to neonatal deaths. Worldwide, approximately 2.8 million neonatal deaths occur during the first 28 days of life each year, with a substantial proportion related to preterm birth, neonatal infections, and complications of hypothermia (Bhutani et al., 2024; Ibrahim et al., 2021; Organization, 2022). The World Health Organization (WHO) specifically defines neonatal hypothermia as an axillary temperature below 36.5°C and highlights it as a risk factor for hypoglycemia, sepsis, intraventricular hemorrhage, and other morbidities (Organization, 2022).

Therefore, NICU nurses should play a crucial role in preventing heat loss by maintaining warm room temperatures, promoting direct skin-to-skin contact, transporting infants in thermally controlled environments, encouraging early breastfeeding, and educating parents about proper thermal care (da Silva Lima et al., 2020; Raber et al., 2024).

Nurses have a central role to play in providing thermal protection of newborns in NICU (Wang et al., 2025). Their responsibility lies in constant monitoring of temperatures, incidental control of ambient room temperatures, use of radiant warmers or incubators, and intervening when the temperature of a baby drops below 36.5°C (Kassaw, 2024). They also use the techniques of immediate drying, contact with the skin (kangaroo care), use of hats, and warm blankets to resist the heat losses through evaporation, convection, conduction or radiations (Anggeriyane et al., 2021). However, the lack of proper staff training in neonatal thermoregulation, inconsistent monitoring practices, excessively cold room environments, and equipment that requires complex maintenance and transition processes continue to contribute to the problem (Harwood, 2025; Struzik & Dow, 2020). These obstacles lead to alarming percentages of admission hypothermia in some units studies describe as high as 50-70 of the newborns being cold at the arrival at the NICU units (Ali et al., 2022). However, reduction in neonatal hypothermia and improvement in newborn survival rates can be achieved when nurses are well trained and supported, accompanied by decreased incidence of conditions such as hypoglycemia, cold stress-related respiratory distress, and sepsis (Dang et al.,

2024).

A gap in knowledge and practice related to incorporating thermal-care guidelines into NICU is evident at Omdurman Teaching Hospital (OTH), with the notable variations in applying the thermal-care protocols to newborns. The healthcare system in Omdurman, including the teaching hospital, is currently affected by war-related destruction, equipment loss, and supply chain disruptions (Badawi et al., 2022). Additionally, heavy workloads, staff shortages, and unreliable electricity and water supply increase the burden on nurses to maintain best practices and continuously monitor neonatal temperatures (Al-Kamali, 2023; Singh et al., 2024). Furthermore, there is limited auditing and inconsistent documentation of essential thermal care procedures such as skin-to-skin contact, immediate drying, and warm chain steps (Kyokan et al., 2023). These structural and infrastructural barriers contribute to gaps in nurses' knowledge and highlight the need for a dedicated educational program to improve protocol adherence and strengthen neonatal thermal care practices (Kolbugri et al., 2024). This study aims to address these challenges by providing targeted training to NICU nurses.

This study has novel applications in promoting clinical nursing education and better neonatal outcomes in resource limited environments. In such NICUs as Omdurman Teaching Hospital providing nurses with specific knowledge and practical skills on thermal care directly help decrease avoidable complications related to hypothermia. The study documents quantifiable changes in knowledge and clinical practice and thus illustrates viable information that utilized in nursing curricula and in-service education units. The purpose of the research was to evaluate how a structured nursing education program can enhance knowledge and practice in thermal care of newborns in nurses of the NICU of Omdurman Teaching Hospital. This study aimed to assess nurses' initial knowledge and thermal care practices, implement an educational intervention to address identified gaps, and evaluate improvements using pre- and post-tests.

2. Methodology

2.1 Study Design

The study adopted a quasi-experimental pre-test/post-test design to evaluate the efficacy of a structured educational program on nurses regarding their knowledge and practices with regards to newborn thermal care. The design is suitable in assessing the educational outcomes in a healthcare setting in which random assignment is inapplicable.

2.2 Study Setting

The study was done in Neonatal Intensive Care Unit (NICU) of Omdurman Teaching Hospital, which is among the largest tertiary hospitals of Sudan. The setting

was relevant and practical due to its high patient load and complicated neonatal cases to evaluate the impact of an educational program in the implementation of effective practices in thermal care.

2.3 Study Population and Sampling Technique

The target population included all nurses ($N \approx 100$) working in the NICU of Omdurman Teaching Hospital during the study period. A convenience sampling technique was used to recruit nurses who met the inclusion criteria. This non-selective method aimed to minimize selection bias and improve the generalizability of findings.

2.4 Inclusion and Exclusion Criteria

Inclusion criteria: Registered nurses working in the NICU with at least three months of experience and who provided written informed consent.

Exclusion criteria: Nurses with less than three months of experience, nurses on leave during the study period, and those who declined participation.

2.5 Sample size determination

The sample size was calculated using Cochran's formula for a single population proportion:

$$n = \frac{Z^2 \cdot p \cdot (1 - p)}{d^2}$$

n = required sample size

Z = standard normal deviation at 95% confidence level (1.96)

p = estimated proportion of nurses with adequate knowledge/practice (assumed 0.5 since no prior study was available)

d = margin of error (0.1 or 10%)

Substituting the values:

$$n = \frac{(1.96)^2 \cdot 0.5 \cdot (1 - 0.5)}{(0.1)^2} \approx 96.04$$

Considering an expected 10% non-response rate, the adjusted sample size was calculated as:

$$\text{Adj } n = 96.04 \times (1 - 0.1) = 86.4 \approx 86 \text{ nurses}$$

Thus, 86 nurses were recruited. The study assumed a power of 80% to detect significant differences in knowledge and practice scores at $p < 0.05$.

Data Collection Tools

Two structured instruments were used for data collection: a knowledge questionnaire and a practice observation checklist. Both tools were developed specifically for this study, drawing on previously

published research for conceptual guidance (e.g., (Abou El Fadl et al., 2023)). The tools were not adopted verbatim from any single study; therefore, formal permission from the original authors was not required.

1. Knowledge Questionnaire: This tool consisted of 20 multiple-choice questions covering three subdomains of neonatal thermal care: thermal physiology, heat-loss prevention, and equipment use. The maximum achievable score was 20.

2. Practice Observation Checklist: The checklist included 10 essential clinical practices related to thermal care, scored on a 3-point scale (0 = not performed, 1 = partially performed, 2 = correctly performed), with a total possible score of 20.

Validity and Reliability: Content validity was ensured through expert review by senior NICU nurses and academic specialists. Reliability testing yielded high internal consistency (Cronbach's $\alpha = 0.85$ for the knowledge questionnaire and 0.88 for the practice checklist).

Data collection: was carried out in three structured phases: pre-test assessment, implementation of the educational program, and post-test evaluation.

1. Pre-test Phase: Paper-based questionnaires were used to assess nurses' baseline knowledge, and a direct observational checklist was employed to evaluate routine clinical practice. All observations were conducted by two trained senior NICU supervisors who were not involved in delivering the educational program, to minimize observer bias.

2. Educational Program: A structured educational intervention on neonatal thermal care was designed based on WHO neonatal thermal protection guidelines, relevant literature, and previously validated training modules (e.g., Abou El Fadl et al., 2023; WHO, 2022). The program consisted of two sessions, each lasting 90 minutes, delivered over one week.

The main components of the educational program included:

- Thermal physiology in newborns
- Mechanisms of heat loss
- WHO warm chain steps (immediate drying, skin-to-skin care, delayed bathing, appropriate clothing, and thermal protection during transport)
- Correct incubator use and temperature control
- Recognition and management of neonatal hypothermia
- Hands-on skills training using real incubators and warming equipment

Mode of Delivery:

Training was delivered face-to-face through:

- Interactive lectures
- Demonstrations
- Short instructional videos
- Practical skills sessions

Educational materials were developed by the research team and reviewed by NICU consultants. All presentations, handouts, and videos were based on WHO recommendations, Sudan Ministry of Health neonatal guidelines, and peer-reviewed research.

Training Providers: The sessions were delivered by a neonatologist and a senior NICU nurse educator with more than 10 years of clinical teaching experience.

3. Post-test Evaluation: The post-test was conducted one week after completion of the educational program to allow time for nurses to apply skills in practice. The same knowledge questionnaire and practice checklist used in the pre-test were administered again. Observations were done by the same independent supervisors to ensure consistency.

3. Data Analysis

Data were analyzed using SPSS version 25. Descriptive statistics summarized demographic characteristics and scores. Paired t-tests compared pre- and post-test knowledge and practice scores. A p-value < 0.05 was considered statistically significant. Correlation analysis examined the relationship between post-test knowledge and practice scores.

Normality of continuous variables (knowledge and practice scores) was assessed using the Shapiro–Wilk test. Results showed $p > 0.05$ for all variables, indicating that the data followed a normal distribution. Therefore, parametric tests, including paired t-test and Pearson correlation, were applied.

4. Ethical Consideration

Ethical approval was obtained from the Research Ethics Committee, Ministry of Health, Omdurman Teaching Hospital (Approval No: OM-2024-115A, 3 November 2024). Participation was voluntary, with written informed consent obtained from all nurses. Confidentiality, anonymity, and the right to withdraw were strictly ensured, following the Declaration of Helsinki guidelines.

5. Result

Demographic Characteristics of Nurses

A total of 86 nurses working in the NICU participated in the study.

Table 1: Demographic Characteristics of Nurses (n = 86)

Characteristic	Frequency (n)	Percentage (%)
Gender		
Female	72	83.7
Male	14	16.3
Age (years)		
22–30	38	44.2
31–40	32	37.2
41–50	16	18.6
Years of Experience in NICU		
<5 years	45	52.3
≥5 years	41	47.7
Highest Educational Level		
Diploma	30	34.9
Bachelor	50	58.1
Master	6	7.0

Knowledge Scores Pre- and Post-Intervention

After the educational intervention, nurses' knowledge of neonatal thermal care improved significantly across all domains.

Table 2: Knowledge Scores Pre- and Post-Intervention

Knowledge Domain	Pre-Test Mean ± SD	Post-Test Mean ± SD	Mean Difference	t-value	p-value
Thermal physiology	2.8 ± 1.1	4.6 ± 0.7	1.8	10.2	<0.001
Heat loss prevention	3.1 ± 1.0	5.0 ± 0.6	1.9	12.1	<0.001
Incubator & equipment	2.5 ± 0.9	4.3 ± 0.8	1.8	11.4	<0.001
Total Knowledge	12.3 ± 3.5	19.7 ± 2.8	7.4	18.7	<0.001

Overall, Knowledge Scores

Before the intervention, most nurses demonstrated limited knowledge regarding neonatal thermal care, with a mean pre-test score of 9.8 ± 2.1 . Following the structured educational program, there was a marked improvement in knowledge, with the post-test mean rising to 17.4 ± 1.6 , indicating a statistically significant increase ($p < 0.001$).

Table 3: Distribution of Responses to Knowledge Questions (n = 86)

Q No.	Knowledge Question	Correct Responses Pre-test n (%)	Correct Responses Post-test n (%)
1	Definition of neonatal hypothermia	41 (47.7%)	83 (96.5%)
2	Normal neonatal temperature range	38 (44.2%)	81 (94.1%)
3	WHO thermal protection steps	36 (41.9%)	79 (91.8%)
4	Causes of neonatal heat loss	40 (46.5%)	84 (97.7%)
5	Effects of hypothermia	42 (48.8%)	82 (95.3%)
6	Signs of mild hypothermia	39 (45.3%)	80 (93.0%)
7	Signs of moderate hypothermia	35 (40.7%)	78 (90.7%)
8	Recommended clothing layers	44 (51.2%)	85 (98.8%)
9	Kangaroo Mother Care temperature effect	37 (43.0%)	79 (91.8%)
10	Temperature monitoring frequency	41 (47.7%)	82 (95.3%)
11	Immediate steps after birth	43 (50.0%)	83 (96.5%)
12	Safe rewarming methods	36 (41.9%)	78 (90.7%)
13	Risk factors for hypothermia	37 (43.0%)	80 (93.0%)
14	Complications of severe hypothermia	39 (45.3%)	81 (94.1%)
15	Use of skin-to-skin contact	41 (47.7%)	85 (98.8%)
16	Appropriate incubator settings	40 (46.5%)	84 (97.7%)
17	Use of heated mattresses	40 (46.5%)	84 (97.7%)
18	Infection risk related to hypothermia	42 (48.8%)	82 (95.3%)
19	Managing temperature instability	38 (44.2%)	80 (93.0%)
20	Documentation of temperature	40 (46.5%)	83 (96.5%)

There was a consistent improvement across all 20 knowledge items, with correct responses increasing from an average of 48% to more than 94% after the intervention.

Practice Scores Pre- and Post-Intervention

The findings also show that the thermal care practices of nurses have significantly improved following the educational intervention.

Table 4: Practice Scores Pre- and Post-Intervention

Practice Item	Pre-Test Mean $\pm$ SD	Post-Test Mean $\pm$ SD	Mean Difference	t-value	p-value
Drying newborn immediately	1.2 $\pm$ 0.5	1.8 $\pm$ 0.4	0.6	8.5	<0.001
Use of incubator	1.0 $\pm$ 0.6	1.9 $\pm$ 0.3	0.9	12.0	<0.001
Thermal wrapping	1.1 $\pm$ 0.5	1.9 $\pm$ 0.3	0.8	10.5	<0.001
Temperature monitoring	1.3 $\pm$ 0.6	1.8 $\pm$ 0.4	0.5	7.9	<0.001
Total Practice	15.6 $\pm$ 4.1	23.4 $\pm$ 3.2	7.8	16.3	<0.001

Practice Performance Results

Practice performance also improved substantially. The mean practice score increased from 7.6 $\pm$ 1.9 (pre-test) to 14.2 $\pm$ 1.5 (post-test), showing a statistically significant improvement ($p < 0.001$).

Table 5: Distribution of Responses to Practice Checklist Items (n = 86)

Q No.	Practice Item (Observed During Routine NICU Care)	Correct Practice Pre-test n (%)	Correct Practice Post-test n (%)
1	Checks incubator temperature before admission	39 (45.3%)	82 (95.3%)
2	Ensures newborn is dried immediately after birth	42 (48.8%)	84 (97.7%)
3	Performs skin-to-skin care when appropriate	38 (44.2%)	83 (96.5%)
4	Uses pre-warmed linens	41 (47.7%)	85 (98.8%)
5	Monitors neonatal temperature hourly	36 (41.9%)	79 (91.8%)
6	Identifies early signs of hypothermia	35 (40.7%)	81 (94.1%)
7	Safely rewarms neonates using WHO protocol	34 (39.5%)	78 (90.7%)
8	Maintains appropriate room temperature	40 (46.5%)	84 (97.7%)
9	Documents temperature correctly	43 (50.0%)	85 (98.8%)
10	Applies thermal protection during transport	37 (43.0%)	82 (95.3%)

Practice improvements were strong across all items, with mean performance rising from 44% pre-intervention to more than 95% post-intervention.

Correlation between Knowledge and Practice Scores

A significant positive correlation was observed between post-test knowledge and practice scores, indicating that higher knowledge was associated with better clinical performance.

Table 6: Correlation between Knowledge and Practice Scores (Post-Test)

Variable	Post-Test Knowledge	Post-Test Practice	R	p-value
Knowledge	19.7 ± 2.8	23.4 ± 3.2	0.78	<0.001

6. Discussion

The discussion evaluates the effectiveness of a systematic nursing education program in improving the knowledge and professional practices of nurses regarding neonatal thermal care in the NICU at Omdurman Teaching Hospital. The study population consisted mainly of young female nurses with varying educational backgrounds and NICU experience, which reflects a workforce capable of adapting to structured educational interventions. This demographic profile aligns with findings from Ayed et al. (2024), (Ayed et al., 2024), which indicated that female nurses are more likely to work in pediatric and neonatal care due to their nurturing capacity and effective communication skills. The high proportion of nurses aged 22–40 suggests a workforce in early to mid-career stages, an optimal period for acquiring advanced clinical competencies, consistent with observations by Ravi et al. (2025) in similar low-resource settings (Ravi et al., 2025).

The results show that academic qualifications positively correlate with clinical performance, as demonstrated by the majority of participants holding a bachelor's degree, supporting Abou El Fadl et al. (2023), who highlighted that higher education enhances decision-making and adherence to neonatal care protocols (Abou El Fadl et al., 2023). Consequently, planned educational interventions are crucial to maximize neonatal care outcomes among young, motivated, and academically competent nurses in the NICU.

The structured educational program significantly improved nurses' knowledge in thermal physiology, heat loss prevention, and proper equipment use. These findings are consistent with international studies emphasizing the importance of thermal regulation in early life (Bedwell & Holtzclaw, 2022) and the effectiveness of organized educational interventions in enhancing knowledge and skills in neonatal care (Abuhammad et al., 2024; Altirkawi, 2025; Stein et al., 2023).

Importantly, integrating regional studies strengthens the contextual relevance. For example, in Sudan, the study "Effect of the training program on nurses' practice regarding premature nursing care in Pediatric Teaching Hospital Wad Medani, Gezira State" demonstrated that

structured education improved both knowledge and practical skills in NICU nurses. Similarly, "The Effect of Neonatal Training Programs addressing Neonatal Hypothermia on NICU Nurses' Knowledge and Practice in the Military and Police Hospitals of Khartoum State" confirmed that targeted educational programs effectively enhanced neonatal thermal care practices. These regional findings align closely with our results, supporting the applicability and effectiveness of educational interventions in Sudanese NICUs.

The practical outcomes of the program showed a significant improvement in the proper drying of newborns, incubator usage, thermal wrapping, and temperature monitoring. These findings are supported by Ompusunggu et al. (2024) and Broom et al. (2025), highlighting that focused, hands-on training enhances adherence to evidence-based thermal care protocols (Broom et al., 2025; Ompusunggu et al., 2024). The study also confirms a strong positive correlation between knowledge and practical skills ($r = 0.78$, $p < 0.001$), consistent with Cassidy et al. (2021) and McNair et al. (2022), reinforcing that theoretical knowledge coupled with practical training optimizes clinical performance (Cassidy et al., 2021; McNair et al., 2022).

Limitations of the study include the quasi-experimental design without a control group, a short follow-up interval, potential observer bias during practice assessments, and a single-center setting. Despite these limitations, the findings provide strong evidence that structured educational interventions, both internationally and regionally, improve NICU nurses' knowledge and practice, with potential to enhance neonatal outcomes in Sudanese hospitals.

Clinical Implications

The present study identifies a number of practical clinical implications that can be used to inform the practices of neonatal care in Omdurman Teaching Hospital. Institutionalization of structured in-service education of NICU nurses should become a standard practice since the changes in knowledge and practice identified validate the presence of its definite effect on the quality of care. The incidence of neonatal hypothermia is also considerably

lower able via regular, competency-based thermal care procedure refresher training, that is, immediate drying, correct use of incubator, and continuous temperature monitoring, particularly in settings where resource is more susceptible, e.g., due to constrained resources. The educational interventions that can improve the translation of theoretical knowledge into trustworthy clinical practice include hands-on checklists, bedside simulation, and constant supervision. The effectiveness of such approaches has been proven by evidence available in related studies that have confirmed that these ways in reducing hypothermia-related admissions and improving survival outcomes. In addition, the health institutions are to promote policy changes that would require periodical review of the thermal care competencies in place, with accountability and consistency. All these steps support the systematic process of constant training of nurses is one of the cornerstones of the enhancement of neonatal care in such hospitals as Omdurman Teaching Hospital.

7. Conclusion

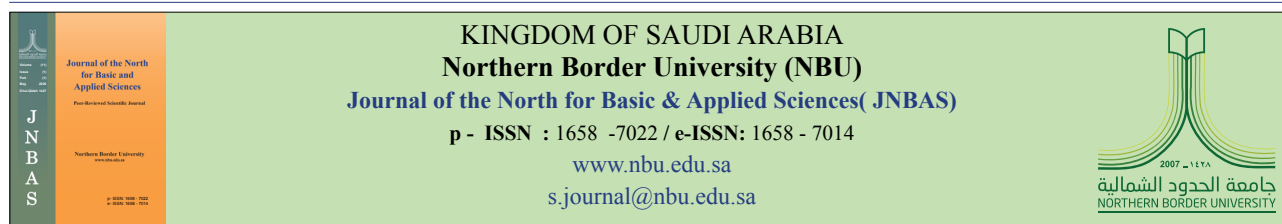
This research has provided clear evidence that a targeted nursing education program could play an important role in improving the level of knowledge and clinical practice of neonatal thermal treatment in NICU of the Omdurman Teaching Hospital. Nurses demonstrated significant positive changes in all spheres of thermal care, such as thermal physiology, heat loss prevention, and incubator usage that were reflected into the bedside. The positive relationship between knowledge and practice is also high and this emphasizes on the importance of integrating theoretical teaching with practical reinforcement. It implies that any existing gaps in practice can be addressed to close the existing drivers of disparity in clinical environment practice and enhance the quality of neonatal outcomes via continuous education and promotion of the specified practice. Although the research involved only one institution and did not have a long a follow-up, the study provides a sustainable design of capacity-building in comparable low-resource NICUs. Regular evidence-based training programs should be implemented to maintain enhanced neonatal care and decrease complications, which are preventable, such as hypothermia.

8. References

- Abou El Fadl, D. K., Aly, Y. A., Darweesh, E. A. G., Sabri, N. A., & Ahmed, M. A. (2023). *Assessment of neonatal intensive care unit nurses' compliance with standard precautions of infection control and identification of enabling factors. Future Journal of Pharmaceutical Sciences*, 9(1), 6. <https://doi.org/10.1186/s43094-022-00456-y>
- Abuhammad, S., Karimeh, R., & Mahadeen, A. (2024). *The impact of an educational intervention on neonatal intensive care unit nurses' knowledge, attitudes, and perceptions of parental participation in kangaroo mother care. Plos one*, 19(8), e0306888. <https://doi.org/10.1371/journal.pone.0306888>
- Al-Kamali, S. (2023). *Factors influencing access to and utilization of maternal health services in South Sudan. Master's thesis, KIT – Royal Tropical Institute & Vrije Universiteit Amsterdam, The Netherlands.*
- Ali, T. A. B., Osman, N. M., Ali, N. M. T., & Mustafa, A. E. M. (2022). *Pattern of Low Birth Weight and Early Outcome of Neonates Admitted at Neonatal Unit in Omdurman Maternity Hospital from December 2019 to May 2020. Bahrain Medical Bulletin*, 44(1). <https://doi.org/10.26715/bmb.2022.44.1.824>
- Altirkawi, K. (2025). *Therapeutic hypothermia in neonatal encephalopathy: current challenges and future prospects. Academia Medicine*, 2(3). <https://doi.org/10.20935/AcadMed7908>
- Anggeriyane, E., Noorhasanah, E., & Nurhayati, I. (2021). *The effectiveness of the kangaroo mother care for low birth weight baby in maintaining thermoregulation stabilization: A case study. Jurnal Pendidikan Keperawatan Indonesia*, 7(2), 151–158. <https://doi.org/10.17509/jpki.v7i2.39191>
- Ayed, A., Ejheisheh, M. A., Salameh, B., Batran, A., Obayat, A., Melhem, R., & Alkhatib, S. (2024). *Insights into the relationship between professional values and caring behavior among nurses in neonatal intensive care units. BMC nursing*, 23(1), 692. <https://doi.org/10.1186/s12912-024-02343-8>
- Bach, V., & Libert, J.-P. (2021). *Thermoregulation and metabolism. In D. Gozal & L. KheirandishGozal (Eds.), Pediatric Sleep Medicine: Mechanisms and Comprehensive Guide to Clinical Evaluation and Management (pp. 73–86). Springer.* https://doi.org/10.1007/978-3-030-65574-7_6

- Badawi, S. E. A., Khalifa, A. K., Abdallah, A. J., & Musa, I. A. (2022). Challenges facing medical waste management and disposal in Khartoum State hospitals: Focus on Omdurman Teaching Hospital. *The Ahfad Journal*, 39(2), 3-22.
- Bedwell, S., & Holtzclaw, B. J. (2022). Early interventions to achieve thermal balance in term neonates. *Nursing for Women's Health*, 26(5), 389-396. <https://doi.org/10.1016/j.nwh.2022.07.006>
- Bhutani, V. K., Vidavalur, R., & Wong, R. J. (2024). Advances to diminish global newborn kernicterus mortality. *Journal of Perinatology*, 44(4), 493-500. <https://doi.org/10.1038/s41372-023-01862-7>
- Broom, M., Briguglio, L., Lowe, P., Muirhead, R., Jyoti, J., Ng, L., Blay, N., Pathrose, S. P., Trajkovski, S., & Spence, K. (2025). Mapping neonatal nursing interventions that significantly impact on neonatal outcomes to neonatal practice standards. *Journal of Neonatal Nursing*, 31(1), 196-205. <https://doi.org/10.1016/j.jnn.2024.07.030>
- Cassidy, C. E., Harrison, M. B., Godfrey, C., Nincic, V., Khan, P. A., Oakley, P., Ross-White, A., Grantmyre, H., & Graham, I. D. (2021). Use and effects of implementation strategies for practice guidelines in nursing: a systematic review. *Implementation Science*, 16(1), 102. <https://doi.org/10.1186/s13012-021-01124-4>
- da Silva Lima, L., Reis, E. A. F., da Silva, E. M., & Gomes, J. P. (2020). Nursing care in the thermo-regulation of preterm newborns: An integrative review. *Cogitare enferm*, 25, e70889. <https://doi.org/10.5380/ce.v25i0.70889>
- Dang, R., Patel, A. I., Weng, Y., Schroeder, A. R., Aby, J., & Frymoyer, A. (2024). Management and Clinical Outcomes of Neonatal Hypothermia in the Newborn Nursery. *Hospital Pediatrics*, 14(9), 740-748. <https://doi.org/10.1542/hpeds.2023-009870>
- Harwood, E. (2025). Timing and Temperature of Newborn Baths: A Qualitative Improvement Initiative Through Nursing Staff Development. <https://doi.org/10.1016/j.jnn.2025.02.015>
- Ibrahim, A. M., Farah, A. M., Osman, M. O., & Hashi, A. (2021). The effect of admission hypothermia for neonatal death among neonates admitted to neonatal intensive care unit at Sheik Hassan Yabare Jigjiga University Referral Hospital in Jigjiga City, Somali Region, Eastern Ethiopia. *Research and Reports in Neonatology*, 43-55. <https://doi.org/10.2147/RRN.S297470>
- Kassaw, E. A. (2024). Design of costeffective Automatic Infant Radiant Warmer by using manually operated warmers (mini project). Preprint. <https://doi.org/10.21203/rs.3.rs-4539821/v1>
- Kolbugri, P., Boateng, B., Kansangabata, E., & Danso, K. O. (2024). Challenges and opportunities in implementing nationwide nursing education reforms: Lessons from Nigeria's experience. *Ghana Journal of Nursing and Midwifery*, 1(3), 26-52. <https://doi.org/10.69600/gjnmid.2024.v01.i03.26-52>
- Kyokan, M., Rosa-Mangeret, F., Gani, M., & Pfister, R. E. (2023). Neonatal warming devices: What can be recommended for low-resource settings when skin-to-skin care is not feasible? *Frontiers in Pediatrics*, 11, 1171258. <https://doi.org/10.3389/fped.2023.1171258>
- McNair, C., Chirinian, N., Uleryk, E., Stevens, B., McAllister, M., Franck, L. S., Taddio, A., & Shah, V. (2022). Effectiveness of parental education about pain in the neonatal period on knowledge, attitudes, and practices: A systematic review and meta-analysis. *Paediatrics & Child Health*, 27(8), 454-463. <https://doi.org/10.1093/pch/pxac045>
- Ompusunggu, F., Rustina, Y., & Efendi, D. (2024). The Effectiveness of Incubator Humidity Education on Nurse's Knowledge, Attitude, and Skills in Perinatology Room. *Jurnal Keperawatan Priority*, 7(2), 40-49. <https://doi.org/10.34012/jukep.v7i2.5027>
- Organization, W. H. (2022). WHO recommendations on maternal and newborn care for a positive postnatal experience. Geneva: World Health Organization.
- Prajapati, A. S., Patel, K., Chauhan, P. M., & Devi, S. (2025). Hypothermia and hypoglycemia. In T. Rana (Ed.), *Elements of Reproduction and Reproductive Diseases of Goats* (pp. 457-462). John Wiley & Sons.
- Raber, R., Waskosky, A., & Moore, S. (2024). An educational initiative in the neonatal intensive care unit for the novice nurse on thermoregulation. *Journal of Neonatal Nursing*, 30(6), 747-764. <https://doi.org/10.1016/j.jnn.2024.07.016>

- Ravi, R. K., Oommen, A., Jacob, J., Sarate, S., Pareek, B., Ahmed, M. F., Renitha, S., Muthugounder, K., Sanogo, I., & Baby, P. (2025). Migration intent, health, and higher education plans as determinants of professional identity and image of nursing among future nurses in resource-limited health systems: a cross-sectional study. *BMC nursing*, 24(1), 1297. <https://doi.org/10.1186/s12912-025-01397-8>
- Saha, U. (2023). General anatomical and physiological considerations in the newborn and neonates. In U. Saha (Ed.), *Clinical Anesthesia for the Newborn and the Neonate* (pp. 137–204). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-5458-0_10
- Singh, K., Alomari, A. M. A., Sayed, H. M. A., Mannethodi, K., Kunjavara, J., Joy, G. V., Hassan, N., Martinez, E., & AlLenjawwi, B. A. (2024). Barriers and solutions to the gap between theory and practice in nursing services: A systematic review of qualitative evidence. *Nursing Forum*, 2024, Article ID 7522900. <https://doi.org/10.1155/2024/7522900>
- Stein, M. L., O'Donnell, R. F., Kleinman, M., & Kovatsis, P. G. (2023). Anesthetic Complications in the Neonate: Incidence, Prevention, and Management. In *Neonatal Anesthesia* (pp. 553-579). Springer.
- Struzik, S., & Dow, A. (2020). A narrative review of thermoregulation techniques used by paediatric theatre staff during intra hospital transfer from paediatric theatres to the Neonatal Intensive Care Unit (NICU). *Journal of Neonatal Nursing*, 26(1), 25-29. <https://doi.org/10.1016/j.jnn.2019.11.002>
- Wang, L., Zheng, Y., Wang, X., Liu, A., Cui, N., & Zhang, W. (2025). Knowledge and practices of neonatal intensive care unit nurses concerning hypothermia in preterm infants: A descriptive cross-sectional study. *Journal of Advanced Nursing*, 81(4), 1845-1855. <https://doi.org/10.1111/jan.15946>



The Impact of Hourly Nursing Rounds on Patient Satisfaction and Safety Outcomes in Hospitalized Adult Patients: A Systematic Review

Maha Abdalla Abdlsadig Ali - Mohammed Khalid Hussein Khalid - Omnia Abdalla Mohammed Higazy - Salwa Ali Mousa - Wafa Abdein Humza Bashir - Fatma Abdalla Mohamed Abdalla - Shahenda Ateyat Allah Salih - Ghada AbdElsalam Ahmed Eldeeb - Hawa Ibrahim Abdalla Hamid

(Received: 9th November 2025; Accepted: 15th December 2025)

Abstract: Background: Nursing rounds are a structured approach in which nurses systematically visit patients to assess their condition, address their needs, and plan care effectively. This practice has become a cornerstone of quality nursing care in modern healthcare settings.

Objectives: To evaluate the impact of hourly nursing rounds on patient satisfaction and safety-related outcomes (falls, comfort, and communication) among hospitalized adult patients.

Methods: A systematic literature review was conducted in accordance with the PRISMA 2020 guidelines. Literature searches were conducted across CINAHL (Cumulative Index to Nursing and Allied Health Literature), Scopus, PubMed, Google Scholar, and other reputable healthcare and nursing journals. focused on measuring satisfaction with care, communication, and responsiveness, and the care provided to patients after the implementation of "rounding." The Prisma framework was used for article screening, and 12 studies were selected according to the inclusion criteria. These studies used diverse methods, including clinical trials, quasi-experimental studies, and cross-sectional studies.

Results: All studies found that incorporating hourly nursing rounds improved satisfaction scores, with patients reporting better comfort, improved communication, and a stronger sense of security. Specifically, the most beneficial were the structured rounds during which care was accompanied by assessment, clear communication, and prompt attention to requests. As the review discusses, challenges such as inadequate staff and inconsistent adherence to these practices hinder implementation.

Conclusion: The review concludes that patient satisfaction is positively influenced by nursing staff routinely checking on patients' well-being and suggests conducting further studies centered on the enduring impact of hourly rounds on patients and other clinical outcomes and safety measures.

Keywords: Hourly nursing rounding, Patient satisfaction, Patient safety, Nurse-patient communication, Nursing care, Hospital outcomes, Systematic review.

1658-7022© JNBAS. (1447 H/2026). Published by Northern Border University (NBU). All Rights Reserved.



DOI: 10.12816/0062495

(*) Corresponding Author:

Maha Abdalla Abdlsadig Ali¹, Mohammed Khalid Hussein Khalid², Omnia Abdalla Mohammed Higazy³, Salwa Ali Mousa⁴, Wafa Abdein Humza Bashir⁵, Fatma Abdalla Mohamed Abdalla⁶, Shahenda Ateyat Allah Salih⁷, Ghada AbdElsalam Ahmed Eldeeb⁸, Hawa Ibrahim Abdalla Hamid⁹

1. Assistant professor of Pediatric Nursing-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(ORCID 0009-0009-4574-1392)
2. Assistant professor of Medical Surgical Nursing-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(<https://orcid.org/0000-0001-8254-7234>)
3. Assistant professor of Medical Surgical Nursing-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(ORCID 0000-0002-6020-5126)
4. Assistant professor of Pediatric Nursing-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(ORCID 0000-0002-7848-512X)
5. Assistant professor in obstetrics and gynecological-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(ORCID 0000-0002-8822-2569)
6. Assistant professor of Pediatric Nursing-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(ORCID 0009-0000-8425-7150)
7. Assistant professor in obstetrics and gynecological-department of maternity and child health nursing- College of nursing -Jouf university-KSA-(ORCID 0000-0001-7612-3187)
8. Assistant professor of Nursing administration-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(ORCID 0009-0008-2878-7307)
9. Assistant professor of Medical Surgical Nursing-department of Nursing- College of nursing and health sciences-Jazan university-KSA-(ORCID 0000-0002-2567-7427)

E-mail: Mkhaliid@jazanu.edu.sa

1. Introduction

Healthcare organizations primarily depend on patient satisfaction since this produces high-quality care treatment, leading to better results. These organizations rely on patient satisfaction measurements to evaluate service value and advance medical practice through continuous improvement initiatives. The caregiving responsibilities of nurses in healthcare facilities directly influence how patients view their care journey and how satisfied they remain with their experiences. Hospital patient experience depends mainly on clinical staff interacting directly with patients by delivering responsive care, compassionate practices, and accessibility actions (Aiken et al., 2021). Hourly rounding has emerged as a fundamental element in nursing care while becoming integral to patient satisfaction strategies.

Nursing staff conduct hourly patient checks to evaluate required assistance, pain management, and necessary support following preset one-hour protocols (Anderson, 2010). Anderson (2010) explains how this patient monitoring approach helps providers build better anticipation to enhance clinical success rates and patient satisfaction (Anderson 2010). Several hospitals and healthcare facilities now use hourly rounding as a new approach to improve their overall nursing care quality. This research evaluates patient care satisfaction through routine nursing rounding by measuring how rounding impacts subjective care delivery perceptions and analyzing environmental stability in healthcare facilities.

Studies conducted by Allari & Hamdan (2023) and Wilson (2017) show that hourly rounding produces positive effects on various aspects of patient care (Allari & Hamdan, 2023; Wilson, 2017). Regular nurse rounds reduce patient complaints through specific research findings that show enhanced pain management, decreased fear, and increased assistance needs (Flowers et al., 2016). Through continuous observation by nurses, healthcare complications can be detected early, which leads to superior patient outcomes during recovery. The modern approach to patient-centric care emphasizes predictive treatment delivery methods that directly respond to individual patient needs before medical symptoms emerge (Baron, 2014).

The practice of hourly rounding derives its theoretical foundation from established principles in quality improvement combined with patient-centered care approaches. Healthcare quality improvement activities use systematic methods to develop evidence-based practices while performing continuous assessments to enhance the quality of patient care delivery (Endalamaw et al., 2024). Hourly rounding operates as a structured intervention in the framework to deliver efficient and effective care by reducing gaps in patient service (Masangkay, 2021).

Research findings indicate that consistent rounding protocols better satisfy patients, but conflicting data exist about the importance of such protocols on patient outcomes (Alshammari et al., 2024). The discrepancies among study results stem from differences between research methodologies and, variations in sample sizes and rounded care protocols. The results from hourly rounding initiatives depend on several factors, including healthcare environment characteristics, nursing staff participation rates, and complementary quality improvement approaches (Jenkins, 2024).

This systematic review examines existing research evidence to determine how scheduled nursing rounding sessions affect patient satisfaction. It analyzes existing research investigating the effects of hourly rounding practices on patient satisfaction metrics regarding communication, responsiveness, comfort, and general nursing care evaluations. The review examines patterns and inconsistencies within the literature to establish effective hourly rounding implementation practices that boost patient satisfaction and quality nursing care.

2. Literature Review

2.1 Nursing Hourly Rounding and Patient Satisfaction

The hourly nursing rounding method is a proactive approach that requires nurses to attend to patients every hour (Hookmani et al., 2021). It is gaining popularity in hospitals to improve patient satisfaction, mitigating falls, pressure ulcers, and delays in care. Rounding permits nurses to promptly manage and respond to patient requests, leading to a more sophisticated and caring environment. Al-Nusair et al. (2023) demonstrate the positive effect nursing rounding has on patient satisfaction through improved communication, timely pain, and fall management. Wiratikusuma et al. (2023) propose that patients perceive an improvement in quality of care when they have frequent contact with their nursing team and staff, thus increasing satisfaction.

The relation of hourly rounding to patient satisfaction has been studied, and many researchers have shown how it improves patient care. Most importantly, communication with the patients has considerably increased (Al-Nusair et al., 2023). Giving patients attention increases the chances that nurses will capture early and address their issues before they escalate, thus leading to a positive care experience. Rounding remotely elevates nurses' ability to offer individualized attention, building trust and good relationships with patients and the entire healthcare team. In a Saudi Arabian hospital, Pappiya et al.'s (2022) study found that hourly rounding improved patient satisfaction. Notably, the increase in satisfaction became evident by the fifth day of the intervention and was statistically significant ($p < 0.001$). Also, in a different study, Negarandeh et al. (2014) reported that regular

nursing rounds also improved satisfaction among patients in the intervention group ($p < 0.001$). These results imply that the routine nature of hourly rounding assists nurses in addressing and talking to patients promptly, enhancing their perception of the care they receive.

2.2 The Impacts of Nursing Hourly Rounding on Falls Prevention

Rounding can also play a significant role in mitigating falls among nursing patients. Healthcare falls are one of the major problems in the health sector, especially for elderly patients or post-operative patients. These days, several studies have shown that hourly rounding helps reduce falls (Hamdan et al., 2022). Nurses can be proactive in the way that they efficiently assist in mobilizing patients who have call bells within reach and who do not need assistance, thereby preventing falls. Tucker et al. (2012) studied the use of hourly rounding in fall prevention in orthopedic wards in the USA and noted the patient falls per 1000 hospital days, which was 4.5 and is now ≤ 1.6 . Based on the study, the rounded figure was quite effective. In the same manner, Gliner et al. (2022) noted that enhanced communication with nurses during hourly rounds was responsible for the 21% reduction in falls (IRR=0.79, $p < 0.01$). These articles evidence the significance of nurse rounding for patient safety and reduced falls, enabled by prompt support and monitoring.

2.3 Patient Comfort and Quality of Nursing Care Due to Hourly Nursing Rounding

Patients are more comfortable, and the quality of nursing care is improved relative to fall occurrences when hourly nursing rounding is implemented. One of the primary goals of nursing rounding is to ensure that patients feel comfortable and attended to for the duration of their stay in the hospital. (Fan et al., 2021). It has been reported that patients subjected to regular rounds are more comfortable than patients who are not because their needs are being taken care of immediately; this includes attending to patients' calls, repositioning patients' beds, providing analgesics, etc. Roustaei et al. (2023) Evaluated the comfort and satisfaction of patients subjected to hourly rounding at an Iranian hospital. The results indicated that, compared to the control group, patients in the intervention group reported significantly greater comfort ($p < 0.001$), increasing nurses' job satisfaction. The study also noted reduced violence among nurses, indicating improved patient conditions. These results indicate that the impacts of hourly rounding are more far-reaching than simply meeting patient satisfaction but also improve the overall quality of care regarding nurse-patient interactions.

2.4 Barriers and Challenges to the Nursing Hourly Rounding

Numerous challenges inhibit the implementation of hourly nurse rounding despite the reported advantages of

this practice. One key issue is the potential impact on nursing resources. Efficient and orderly rounding consumes time and energy, resulting in workload congestion for nurses in busy hospitals with high patient-to-nurse ratios. Some studies have pointed out the difficulties of consistently meeting the rounds, particularly during peak times or when nurses are overworked and understaffed. In the study by Hamdan et al. (2022), nurses in Jordan were worried about the time burden associated with hourly rounding, particularly given that they had to perform other critical work when unoccupied. While most nurses universally accepted the importance of fall prevention and care of pressure ulcers, 19.4% indicated that their participation in implementing patient care decisions was restricted. It is clear from the above discussion that the realization of benefits associated with hourly rounding depends on the support that hospitals offer nursing staff in terms of staffing, time, and training on managing their time best: Staff Training and the Effectiveness of Hourly Nursing Rounding (Gliner et al., 2022).

Training personnel dramatically impacts the effectiveness of hourly nursing rounding. Rounding requires a high level of skill; thus, nurses must be trained in handoff communication, patient evaluation, and time management. Hamdan et al. (2022) have indicated that trained nurses positively impact patient satisfaction and care outcomes, particularly when paired with hourly rounding. Nurses trained in time management develop an appreciation for meeting patients in a timely, warm manner, enabling nurses to address patient needs professionally and compassionately. Al-Nusair et al. (2023) illustrated the benefits of structured nursing programs through marked improvements in nursing care quality and patient satisfaction. The study demonstrated an increase in nursing quality scores by 0.85 points ($p = 0.041$) alongside an increase in patient satisfaction by 8.28 points ($p < 0.001$) with the adoption of an hourly rounding program. These findings further highlight that improvements in care delivery through nursing rounding are stifled without appropriate training. There is a strong reliance on the training that enables nurses to perform rounding proficiently. To reap the full benefits of hourly nursing rounding, education, and support must be continuously available to nurses to enhance patient outcomes (Wiratikusuma et al., 2023).

3. Methods

3.1 Study Design

The present systematic literature review seeks to evaluate the impact of hourly nursing rounds on patient satisfaction and safety-related outcomes (falls, comfort, and communication) among hospitalized adult patients by synthesizing existing research. The article screening was conducted using the PRISMA approach outlined by Sarkis-Onofre et al. in 2021. A total of twelve studies met

the selection criteria. The study sample included clinical trials alongside quasi-experimental and cross-sectional studies. These documents systematically deepen the nursing care processes that, in turn, improve patient satisfaction. Utilizing evidence-based medicine will add value to care.

3.2 Databases and Keyword Strategies

The requirement of conducting a systematic analysis underpinned the necessity of carrying out an exhaustive literature search in various academic databases. Such databases include but are not confined to, CINAHL (Cumulative Index to Nursing and Allied Health Literature), Scopus, PubMed, Google Scholar, and

other reputable healthcare and nursing-related journals. Specific searching strategies were designed by applying appropriate rules about the topic so that all relevant studies on hourly nursing rounds and patient satisfaction were captured. Using keywords in combination enabled the retrieval of relevant studies and the exclusion of unrelated studies. Search queries were further streamlined by employing Boolean modifiers, “AND,” “OR,” and “NOT,” to maximize the relevancy of search outcomes. This allowed not only peer-reviewed journal articles but also grey literature, such as government policy documents and hospital policy documents, to be included to form a comprehensive view of the issue being investigated. Table 1 shows databases and search strategies.

Table 1 Databases and search strategy

Database	Keywords
PubMed	“Hourly nursing rounding,” “Patient satisfaction,” “Nurse-patient communication”
CINAHL	“Hourly nursing rounds,” “Nursing care,” “Hospital outcomes”
Scopus	“Nursing interventions,” “Patient satisfaction,” “Nursing quality improvement”
Google Scholar	“Impact of nursing rounds,” “Patient outcomes,” “Nursing care satisfaction”

3.3 Inclusion and Exclusion Criteria

Table 2 shows the inclusion and exclusion criteria

Table 2 inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Studies published in English between 2000 and 2023	Studies published in languages other than English
Peer-reviewed articles and clinical trials	Non-peer-reviewed literature (e.g., opinion pieces, editorials)
Studies focusing on hourly nursing rounds and patient satisfaction	Studies that do not report patient outcomes or nursing interventions
Studies conducted in hospital settings	Studies conducted in non-hospital settings (e.g., outpatient clinics)
Studies with patient and/or nurse participants	Studies without clear patient or nurse involvement
Quantitative and qualitative studies	Studies that lack a clear methodology or valid data analysis

3.4 Data Analysis

The approach applied in the content analysis of the data for this systematic review was primarily analytic, which entails the classification and integration of findings from different studies into logical categories. Content analysis is a qualitative approach to studying data to identify recurring elements in multiple studies. In this case, studies were analyzed to obtain relevant information about the study’s goal and the design and outcomes of hourly nursing rounds on patient satisfaction. The analysis process involves a comprehensive scrutiny of each study’s methodology and a detailed explanation, comprising the design adopted, the sample size chosen, and the instruments used for data collection.

4. Results

4.1 Study Selection:

A total of 3,469 records were identified after screening and removing duplicate records (260) from the databases. 2,589 papers were excluded as irrelevant after screening 3,209 records. Of the remaining 620 reports asked for retrieval, 560 could not be retrieved. After excluding 40 reports for publication dates before 2010 and additional reports not published in English, 60 reports were assessed for eligibility. This systematic review finally included 12 studies that met the inclusion criteria and were included in the final synthesis. The selection process is illustrated in the PRISMA flow diagram (Figure 1)

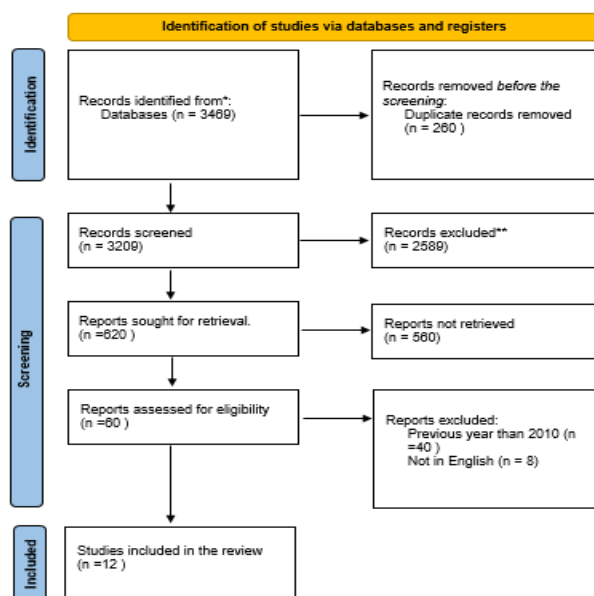


Figure 1: PRISMA Flow Diagram

Table 3 shows the Main findings of the studies.

Table 3 Main findings

No.	Author(s)	Title of the Study	Method	Population	Region	Sample Size	Analysis Technique	Results
1	Hamdan et al. (2022)	The Role of Nursing Rounds in Fall and Pressure Ulcer Prevention	Cross-sectional correlational design	Nurses	Jordan	1,378	Descriptive statistics, t-test, ANOVA, Kruskal–Wallis H test	87.9% of nurses agreed that nursing rounds improved fall prevention; 87.2% acknowledged their role in pressure ulcer prevention.
2	Ahmed (2023)	Evaluating Patient Satisfaction in Structured Nursing Rounds	Mixed-methods (Clinical trial + Interviews)	Patients	Saudi Arabia	68 (quantitative), 10 (qualitative)	Nonequivalent control group design, t-test	Structured nursing rounds significantly improved patient satisfaction, increasing the experimental group's mean score from 4.75 to 6.06.
3	Mulugeta et al. (2020)	Effectiveness of Nursing Rounds on Patient Satisfaction	Quasi-experimental, nonequivalent groups design	Hospitalized patients	Ethiopia	104 (52 control, 52 intervention)	Independent t-test	Nursing rounds significantly increased patient satisfaction scores from 71.02 ± 14.37 to 79.69 ± 12.21 ($p=0.001$).
4	Jennings & Mitchell (2017)	Quality Improvement in ICU Trauma Nursing through Structured Rounds	Quality improvement project	ICU trauma nurses	USA	132 trauma patients	Descriptive statistics	Implementing structured nursing rounds led to 452 patient care modifications, averaging three per patient.
5	Roustaei et al. (2023)	Impact of Nursing Rounds on Patient Comfort and Nurse Safety	Quasi-experimental	Patients and nurses	Iran	100 patients, 35 nurses	Chi-square, Fisher, independent t-test, paired t-test	Nursing rounds improved patient satisfaction ($p<0.001$) and comfort ($p<0.001$) and also reduced violence against nurses ($p=0.041$).

No.	Author(s)	Title of the Study	Method	Population	Region	Sample Size	Analysis Technique	Results
6	Tucker et al. (2012).	Nursing Rounds as a Strategy to Reduce Patient Falls	Repeated measures design	Orthopaedic inpatients	USA	Not specified	Descriptive statistics, focus groups	Nursing rounds helped reduce fall rates from 4.5 to 1.6 per 1,000 hospital days, though rates fluctuated post-intervention (3.2 per 1,000 days).
7	Pappiya et al. (2022)	Influence of Nursing Rounds on Patient Satisfaction Over Time	Clinical trial, nonequivalent control group	Hospitalized patients	Saudi Arabia	68 (34 control, 34 intervention)	Chi-square, independent t-test	Nursing rounds significantly increased patient satisfaction by the fifth day ($p<0.0001$), compared to no improvement on the first day ($p=0.288$).
8	Negarandeh et al. (2014)	Improving Nursing Care Quality Through Regular Rounds	Controlled clinical trial	Medical-surgical inpatients	Iran	100 (50 control, 50 intervention)	Patient Satisfaction with Nursing Care Quality Questionnaire	Structured nursing rounds led to a statistically significant increase in patient satisfaction ($p<0.001$) in the intervention group.
9	Al-Nusair et al. (2023)	Effect of Structured Nursing Rounds on Care Quality and Patient Experience	Nonequivalent control group pretest-posttest	Orthopaedic ward patients	Not specified	145 (70 experimental, 75 control)	Difference-in-difference analysis	Nursing rounds improved nursing care quality scores by 0.85 points ($p=0.041$) and patient satisfaction by 8.28 points ($p<0.001$).
10	Gliner et al. (2022)	Communication in Nursing Rounds and its Impact on Fall Prevention	Poisson regression	Military treatment facility patients	USA	31 facilities	Regression analysis	Improved nurse communication through structured rounds reduced fall rates by 21% ($IRR=0.79$, $p<0.01$), while poor nurse communication increased falls 8.6 times ($IRR=8.6$, $p<0.01$).
11	Wiratikusuma et al. (2023)	Enhancing Patient Empathy and Assurance Through Nursing Rounds	Pre-experiment design	Hospital patients	Indonesia	46	Chi-square, Mann-Whitney test	Nursing rounds enhanced patient empathy satisfaction ($p=0.007$) and assurance ($p=0.001$).
12	Ali et al. (2022)	Effect of Nursing Rounds on Patient Satisfaction Over Five Days	Clinical trial, nonequivalent control group	Medical-surgical inpatients	Saudi Arabia	68	Descriptive and inferential statistics	Nursing rounds significantly improved patient satisfaction from 6.06 (experimental) vs. 4.75 (control) on Day 1 to 8.21 (experimental) vs. 5.76 (control) on Day 5.

5. Study characteristics

5.1 Study Design and Analysis

The works in this analysis utilize various research methods such as clinical trials, repeated measures, controlled clinical trials, pre-experimental designs, and statistical regression modeling. These methods explain the implementation of fall preventative measures and patient satisfaction within the hospital environment. In the case of (Pappiya et al., 2022) and (Ali et al., 2022), both employed an interventional time-series design with nonequivalent control groups in their studies. They also measured the change in patient satisfaction from the baseline with descriptive statistics, t-tests, and chi-square tests. Similarly, (Negarandeh et al., 2014) conducted a controlled clinical trial using the Patient Satisfaction with Nursing Care Quality Questionnaire to assess the impact of clinical nursing educational interventions on patient satisfaction. Other studies, like (Tucker et al., 2012), employed a repeated measures design, which allowed them to assess the advanced change in the number of falls amongst orthopedic inpatients over time. (Gliner et al., 2022) used Poisson regression analysis for military treatment facilities and portrayed the consequences of inadequate nurse communication on patient falls.

Along with other studies, (Al-Nusair et al., 2023)) performed a difference-in-difference analysis, an approach that measures the effect of interventions using a pre-and post-approach, focusing on evaluating the change in patient satisfaction as well as nursing care quality scores before and after the intervention took place. Broadly speaking, as described above, some blend of experimental and quasi-experimental, alongside statistical modeling techniques, all at once served to reliably evaluate nursing interventions (Wiratikusuma et al., 2023). These methodologies made the accuracy of the results more reliable by adjusting for factors like initial patient demographics and the characteristic features of the hospital.

5.2 Type of Population and Sample Size

The population studied for this research was mostly composed of hospitalized patients from medical-surgical, orthopedic, and military treatment wards. There was some variation in the sample sizes across studies, which impacted the generalizability and the statistical power of the findings. (Pappiya et al., 2022) Moreover, (Ali et al., 2022) focused on studying hospitalized patients in Saudi Arabia, where they sampled 68 patients (34 in each interventional group). Likewise, (Negarandeh et al., 2014) focused on 100 medical-surgical inpatients in Iran (50 in each group). These sample sizes were adequate for determining statistical differences regarding patient satisfaction. Other studies, such as (Al-Nusair et al., 2023), observed 145 orthopedic ward patients, out of which 70 were assigned to the experimental group and 75 to the control group. (Tucker et al., 2012) did not mention exactly how many orthopedic inpatients they had.

However, we know from the analysis of fall rates that they did have a considerable number over several studied periods, suggesting a much larger sample. In contrast, (Wiratikusuma et al., 2023) studied 46 hospitalized patients in Indonesia, several subjects that pose limitations to generalizability. (Gliner et al., 2022) incorporated a large-scale dataset from 31 military treatment facilities in the US, which increased the external validity of the findings. Although most studies had sample sizes adequate to achieve statistical significance, differences in hospital settings and population types necessitate extreme caution when applying findings across diverse healthcare systems.

5.3 Main Outcomes

The literature under consideration has focused on investigating the effects of implementing a nursing round system on patient satisfaction, reducing fall rates, and the overall quality of nursing care provided to the patient. Findings consistently showed that patient satisfaction levels and the incidence of falls in the hospital's surgical units improved significantly when proactive, organized nursing rounds were performed. (Pappiya et al., 2022), (Ali et al., 2022) and many other authors provided evidence that nursing rounds greatly enhanced patient satisfaction, with the p values documented being less than 0.001 on the fifth day of the study. Study participants reported improved responsiveness, communication, and overall care as a result of active participation by nurses. Similarly, (Negarandeh et al., 2014) noted that the execution of hourly scheduled nursing rounds resulted in an increase in patient satisfaction scores ($p < 0.001$), which underscores the impact of consistent nurse availability and contact. Falls prevention studies emphasized the role of encompassing nursing rounds as part of the initiative. (Tucker et al., 2012) noted a decline in the rate of falls from 4.5 to 1.6 per 1,000 hospital days after the introduction of structured nursing rounds, which suggested that intent observation and early action positively impacted patient safety. (Gliner et al., 2022) showed that ineffective nurse communication was associated with an 8.6 increase in the IRR ($p < 0.01$) for falls while rounding led to a 21% decrease in falls ($IRR = 0.79$, $p < 0.01$). The above evidence strongly supports the claim that incorporating guided nursing rounds into the system positively impacted patient satisfaction and safety.

5.4 Efficacy

Nursing rounds were punctual and routinely completed. This led to profound advancements in comprehensive nursing care, patient satisfaction, and fall prevention. As noted from various studies, the quality of nursing care has improved remarkably. These included check-ins, proactive engagement, and optimized communication, which were effective in patient care. In regards to patient satisfaction, Pappiya et al. (2022) and Ali et al. (2022) noted that structured nursing rounds over five days significantly improved patient satisfaction

scores ($P < 0.001$). With timely rounds, patient needs could be addressed more easily, which enhances care and responsiveness perceptions. During the academic terms, nursing students reported high levels of satisfaction with clinical placements. According to FNegarandeh et al. (2014), consistent hourly nursing rounds improved patient satisfaction rates remarkably ($P < 0.001$), demonstrating the difference consistent nurse presence can make in attentive patient care experiences.

Regarding fall prevention, Tucker et al. (2012) demonstrated that falls per 1,000 hospital days dropped from 4.5 to 1.6 after implementing structured nursing rounds, and through the collaboration of patients, rounding with patients aided in fall prevention. Gliner et al. (2022) showed that poor nursing communication increased the odds of falls by 8.6 times ($IRR = 8.6$, $p < 0.01$). Moreover, the same research found that rounding interventions reduced the rate of falls by 21% ($IRR = 0.79$, $p < 0.01$).

6. Discussion

6.1 Improvement in Patient Satisfaction Through Nursing Rounds

The studies reviewed show that systematic nursing rounds enhance patients' satisfaction. (Pappiya et al., 2022) (Ali et al., 2022) cited that satisfaction scores shot up following the implementation of hourly nursing rounds. The studies included in this review granted that regular nurse contact improves patients' perceptions of nurse-mediated care. (Pappiya et al., 2022) Reported a statistically significant improvement in patients' satisfaction on day five of the intervention ($p < 0.0001$). This aligns with other studies that have demonstrated that patients' satisfaction depends on the number and quality of interactions they have with nurses during their admission. Previous studies, particularly the one conducted by (Negarandeh et al., 2014), have revealed that systematic nursing procedures like hourly rounds result in greater levels of satisfaction ($p < 0.001$). This improvement is due to the tailored care patients receive, the reassurance from regular check-ups, and the anxiety alleviation accompanying the uncertainty of care. Alongside the technical intricacies of the care provided, the satisfaction a patient receives also entails great attention to interrelations, thus forming a holistic experience throughout the service, as emphasized by (Mulugeta et al., 2020) and (Roustaei et al., 2023). These two studies further highlight the perception of care quality from a patient's viewpoint and emphasize that such perception is associated with the grade of attention and communication given to them by the health staff. The rationale for nursing care rounds influencing satisfaction levels is the proactive attention to patient needs. Nurses can respond to requests, alleviate discomfort, and provide reassurance, fostering patients' trust in the health care system. Hourly nurse-patient interaction, or the simple visibility of the nurse during the check, helps the patients

to feel that they are listened to, which alters their attitude toward satisfaction in a health institution.

6.2 Communication and Nurse-Patient Interaction

Effective communication with patients is essential to improving patient satisfaction, and the studies reviewed suggest that consistent nursing rounds improve communication between nurses and patients. As Gliner et al. (2022) explain, enhancing nurse-patient communication during rounds mitigates falls by improving the overall caregiving atmosphere, which shows that communication influences patient outcomes. This is based on findings from Tucker et al. (2012), who reported lower fall rates associated with structured nursing communication interventions. Similar results were reported by Wiratikusuma et al. (2023), where patients reported increased satisfaction with nurse empathy and assurance about hourly nursing rounds. Prior literature emphasizes that patient satisfaction is highly correlated with the quality of communication between nurses and patients. Gliner et al. (2022) study demonstrated that falls among patients were more likely in the case of poorly communicated by nurses, highlighting the need for safe communication practiced in nursing sufficiency. Regular nursing rounds allow effective communication between nurses and patients, explaining care procedures, addressing concerns, and providing emotional assistance. Such relationships help develop rapport, which is fundamental in improving a patient's satisfaction and perceptions about the care administered.

Furthermore, Roustaei et al. (2023) reported that hourly rounds not only enhance communication but also create a conducive atmosphere for patient support. This is where the nurses can empathize with the patients, listening and responding to their needs in good time. These communication components are of great importance in improving the patient experience and increasing satisfaction.

6.3 Patient Outcomes Beyond Satisfaction: Implications for Nursing Practice

Patient satisfaction is an important measure of quality care; however, other outcomes like fall prevention and reduced adverse events are also important in measuring the impact of nursing rounds. The review indicates that nursing rounds mitigate falls, which supports (Tucker et al., 2012) and (Gliner et al., 2022) conclusions. These two studies reported that structured initiatives enhanced communication between nurses and patients and prompted more proactive address of patients' needs, which significantly reduced fall risks—an important issue in patient safety. Reduction of falls during hourly nursing rounds has been reported in previous studies that highlight the significance of prompt nursing action in injury prevention. Gliner et al. (2022) reported that the combination of communication skills

with structured rounds led to a 21% reduction in falls (IRR=0.79, $p<0.01$), which supports the argument that nursing rounds aid in preventing avoidable incidents. Furthermore, Hamdan et al. (2022) and Al-Nusair et al. (2023) reported improvement in nursing care scores and patient satisfaction, highlighting the impact of nursing rounds on patient outcomes. Integrating hourly nursing rounds into standard practice enhances patient satisfaction and safety, improving healthcare outcomes. These rounds enable nurses to evaluate patients' psychosomatic requirements and risks and formulate the necessary modifications to care plans (Roustaei et al., 2023). The strategy allows nurses to recognize the signs of health deterioration and take immediate action, thus averting serious complications, including but not limited to falls, pressure sores, medication blunders, and medication errors. The effectiveness of hourly nursing rounding may vary across cultural contexts due to differences in patient expectations regarding nurse-patient interaction and communication styles.

Cultural norms dictate how patients expect to interact with their care providers, which directly impacts the effect of nursing rounds. A patient's cultural respect can influence their willingness to actively engage or voice concerns during nursing round. A culturally sensitive approach requires active listening and attention by the nurse to non-verbal cues.

In multicultural healthcare systems, language barrier may affect the patient- nurse communications. Relying on simple scripts, non-professional interpreters (like family members), or simply using non-verbal communication during nursing round can lead to misunderstandings about pain levels, medication instructions, and follow-up care, ultimately undermining patient safety and satisfaction.

7. Conclusion

The literature review on the effectiveness of nursing intervals posits that this intervention significantly enhances patient satisfaction, relationships with caregivers, and overall clinical metrics. These outcomes are consistent with the existing debate literature highlighting the constructive impact of nursing rounds on providing services in hospitals and healthcare facilities. The advantages of performing nursing rounds on an hourly basis extend well beyond clinometer satisfaction; there are also advancements in safety and reduced adverse outcomes such as falls. Incorporation of hourly nursing rounds into clinical practice is one of the simplest ways to enhance patient care and clinical outcomes. Developing and applying structured protocols for nursing rounds can effectively improve patient satisfaction metrics, patient safety measures, and overall satisfaction ratings for these healthcare facilities. More research is needed to understand the long-lasting impacts of nursing rounds on patients and how best to integrate such practices into nursing care.

7.1 Recommendation

From the findings of this systematic review, it is suggested that nursing rounds every hour be instituted at healthcare facilities to improve patient satisfaction and patient care. Facilities must educate and assist nursing personnel so that the rounds are systematic and address the physical and psychosocial needs of the patients. Hospital management also needs to provide the required resources, like additional nurses, to implement the nursing rounds properly. It is also essential that these healthcare institutions equip nurses with proper supervision and evaluation skills to realize these nursing rounds and rate these patient communication techniques. To optimize patient satisfaction, nurses should be trained to actively listen, show empathy, and deliver patient-centered care to ward patients. Nursing rounds should be assessed routinely for patient experience and safety ventilation. Nurse administrators need to collaborate with other healthcare professionals to deliver whole patient care during rounds.

7.2 Future Directions

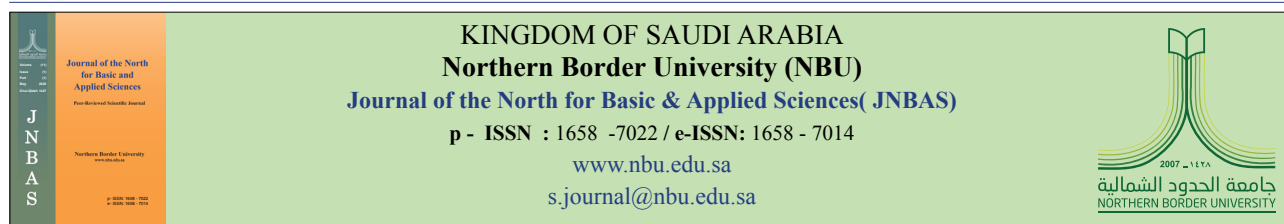
Further studies should assess the clinical outcomes, patient satisfaction metrics, rate of readmissions, and overall duration of hospitalization to better understand the longitudinal results of hourly nursing rounds. There remains a gap in the literature regarding randomized control trials (RCTs) that delve into the association between nursing rounds and achieving enhanced patient outcomes. Thus, more RCTs are warranted. Additionally, research should focus on the most effective methods of implementing hourly rounds in various healthcare settings and those that are under-resourced or experience high turnover. Understanding the perspectives of patients and nurses regarding the implementation of hourly rounds' strengths and weaknesses will be important to identify the gaps presented by this intervention. Moreover, additional research is needed to determine the impact of hourly nursing rounds for patients with chronic illnesses, elderly patients, and patients in critical care to better understand the differential advantages associated with these groups.

7.3 Study Limitations

Although this review followed PRISMA guidelines, several limitations should be acknowledged. The studies included demonstrated considerable heterogeneity in patient populations, rounding frequency, settings, and intervention duration. Most studies relied heavily on self-reported patient satisfaction measures, which may introduce response bias. Additionally, no quantitative meta-analysis was performed, limiting the statistical power and the estimation of pooled effects.

8. References

- Aiken, L. H., Sloane, D. M., Ball, J., Bruyneel, L., Rafferty, A. M., & Griffiths, P. (2021). Patient satisfaction with hospital care and nurses in England: an observational study. *BMJ open*, 8(1), e019189.
- Al-Nusair, H., Alnjadat, R., Mukona, D. M., Fonbuena, M., & Perinchery, S. (2023). The effect of intentional nurse rounding and nurse prompt response time to Call system on patient satisfaction, patient complaints, and patient clinical outcome: An Audit trial. *Nursing and Midwifery Studies*, 12(3), 142-150.
- Ali, A. K., Al Zamanan, A. M., Al-Rayshan, A. S., Al Zandan, S., Almuhamid, A. H., Sharyah, R. H. S., Ali, A. M., Moibed, A. M., Al Mutairi, S. O., & Noktan, A. B. (2022). Al GN Mofareh A, Alghamdi Z Ali, Almansour MF Hadi (2022). Optimizing Patient Satisfaction: The Impact of Nurse-Initiated Rounds with Collaborative Pharmacist Involvement. *Saudi J Med Pharm Sci*, 8(12), 813-820.
- Allari, R. S., & Hamdan, K. (2023). Caring Behavior and Hourly Rounding: Nurses' Perception. *The Open Nursing Journal*, 17(1).
- Alshammari, S. H. S., Alfowais, F. A., Al-Mutairi, M. G. A., Aldhfeeri, D. D., Alshmmri, F. A., & Khadhaier, A. M. (2024). The Effects of Hourly Rounding by Nursing Staff on Patient Safety and Satisfaction: Implications for Clinical Practice and Healthcare Administration. *Journal of Ecohumanism*, 3(8), 9406-9411-9406-9411.
- Anderson, D. A. (2010). Assessing the Impact of Hourly Rounding on Patient Satisfaction with Pain Management [Chatham University].
- Baron, S. (2014). Exploring the Patient Journey: a collaborative approach to patient-centred improvement in healthcare [Bournemouth University].
- Endalamaw, A., Khatri, R. B., Mengistu, T. S., Erku, D., Wolka, E., Zewdie, A., & Assefa, Y. (2024). A scoping review of continuous quality improvement in healthcare system: conceptualization, models and tools, barriers and facilitators, and impact. *BMC health services research*, 24(1), 487.
- Fan, Q. Q., Feng, X. Q., & Jin, J. F. (2021). Nursing rounds: a quality improvement project to improve outpatient satisfaction. *Journal of Nursing Management*, 29(2), 177-185.
- Flowers, K., Wright, K., Langdon, R., McIlwraith, M., Wainwright, C., & Johnson, M. (2016). Intentional rounding: facilitators, benefits and barriers. *Journal of Clinical Nursing*, 25(9-10), 1346-1355.
- Gliner, M., Dorris, J., Aiyelawo, K., Morris, E., Hurdle-Rabb, D., & Frazier, C. (2022). Patient falls, nurse communication, and nurse hourly rounding in acute care: Linking patient experience and outcomes—*Journal of Public Health Management and Practice*, 28(2), E467-E470.
- Hamdan, K., Zahran, Z., Allari, R. S., & Shaheen, A. (2022). Nurses' perceptions of hourly rounding in Jordanian hospitals: A national survey. *Journal of Nursing Management*, 30(7), 2945-2956.
- Hookmani, A. A., Lalani, N., Sultan, N., Zubairi, A., Hussain, A., Hasan, B. S., & Rasheed, M. A. (2021). Development of an on-the-job mentorship program to improve the nursing experience for enhanced patient experience of compassionate care. *BMC Nursing*, 20, 1-18.
- Jenkins, H. A. (2024). Nurses and the Importance of Consistent Hourly Rounding [National University].
- Masangkay, R. (2021). Purposeful Nurse Hourly Rounding: Plan to Decrease Patient Falls During a Pandemic.
- Mulugeta, H., Afenigus, A. D., Wagnaw, F., Haile, D., Tadesse, A., & Kibret, G. D. (2020). The effect of hourly nursing rounds on patient satisfaction at Debre Markos Referral Hospital, Northwest Ethiopia: A non-randomized controlled clinical trial—*International Journal of Africa Nursing Sciences*, 13, 100239.
- Negarandeh, R., Bahabadi, A. H., & Mamaghani, J. A. (2014). Impact of regular nursing rounds on patient satisfaction with nursing care. *Asian Nursing Research*, 8(4), 282-285.
- Pappiya, E. M., Al Baalharith, I. M., AlGrad, H. S., Alawad, A. B. S., Al Mohid, M. A., & Al Duways, S. M. (2022). Impact of nurse-initiated rounds on patient satisfaction at new Najran General Hospital in Saudi Arabia. *International Journal of Advance Research in Nursing*, 2 (5), 234-240.
- Roustaei, Z., Sadeghi, N., Azizi, A., Eghbalian, M., & Karsidani, S. D. (2023). The effect of regular nursing rounds on patients' comfort and satisfaction, and violence against nurses in surgical ward. *Heliyon*, 9(7).
- Sarkis-Onofre, R., Catalá-López, F., & Aromataris, E., & Lockwood, C. . (2021). How to properly use the PRISMA Statement. *Systematic Reviews*, 10, 1-3.
- Tucker, S. J., Bieber, P. L., Attlesey-Pries, J. M., Olson, M. E., & Dierkhising, R. A. (2012). Outcomes and challenges in implementing hourly rounds to reduce falls in orthopedic units. *Worldviews on Evidence-Based Nursing*, 9(1), 18-29.
- Wilson, L. W. (2017). Nursing Staff Responsiveness to Patients and Hourly Rounding.
- Wiratikusuma, Y., Acihayati, J. P., & Supardi, S. (2023). The Effect Of Nursing Round Training On Patient Satisfaction In Nursing Services At Rs X Jakarta. *Jurnal Mutiara Ners*, 6(1), 34-45.



PHENOLICS AND FLAVONOIDS PROFILING IN *LEPIDIUM AFRICANUM* METHANOL EXTRACT AND EVALUATION OF ITS ANTIOXIDANT, ANTIDIABETIC, ANTI-INFLAMMATORY, AND ANTICANCER PROPERTIES

Esam A. Alqurashi

Department of Chemistry, Faculty of Science, Al-Baha University, Al-Baha, Saudi

(Received: 11th November 2025; Accepted: 6th December 2025)

Abstract

Lepidium africanum, a member of the Brassicaceae family, is a medicinal plant known for its diverse bioactive compounds. This study investigates the phytochemical composition and evaluates the antioxidant, anti-diabetic, anti-inflammatory, and cytotoxic activities of the methanol extract of *L. africanum*. Phytochemical analysis using HPLC revealed high concentrations of phenolic and flavonoid compounds, with gallic acid (48.46%) and catechin (77.42%) being the predominant constituents. The extract exhibited moderate antioxidant activity through ABTS radical scavenging (IC_{50} : 58.72 $\mu\text{g/ml}$), suggesting its potential in mitigating oxidative stress-related conditions. Additionally, the extract demonstrated significant α -amylase inhibitory activity (IC_{50} : 57.46 $\mu\text{g/ml}$), indicating its possible role in managing postprandial hyperglycemia. The anti-inflammatory potential was confirmed *via* COX-1 enzyme inhibition (IC_{50} : 33.16 $\mu\text{g/ml}$), highlighting its ability to modulate inflammatory pathways. *In vitro* cytotoxicity assays on HepG-2, MCF-7, and CACO2 cell lines showed notable anticancer activity, with IC_{50} values ranging from 71.61 $\mu\text{g/ml}$ to 114.09 $\mu\text{g/ml}$, demonstrating selective cytotoxic effects across different cancer cell lines. These findings suggest that *L. africanum* methanol extract holds promise as a natural source of bioactive compounds with therapeutic applications in oxidative stress-related diseases, diabetes, inflammation, and cancer..

Keywords: *Lepidium africanum*, Bioactive compounds, Antioxidant activity, Anticancer properties, Antidiabetic.



(*) Corresponding Author:

Esam A. Alqurashi

Department of Chemistry, Faculty of Science, Al-Baha University, Al-Baha, Saudi

E-mail: ealqurashi@bu.edu.sa

1. INTRODUCTION

Medical plants are the main source of chemical compounds of treatment, and they have many pharmaceutical activities, while playing a decisive role in traditional medicine and contributing to the development and discovery of new drugs (Dar et al., 2017; Süntar, 2020). Several useful medications are found clinically to treat human diseases as a result of the search for natural resources, including plant excerpts, in the search for new active chemicals. In this context, the extraction, quantification, and identification of bioactive compounds from a wide variety of plants are carried out using diverse extraction and analytical techniques (Altemimi et al., 2017). Brassicaceae is a large and economically important family, and includes many types of cultivated food, oil production and other applications. It is characterized by its varied composition, which has been widely distributed through various climates, important environmental roles in many ecosystems (Long et al., 2011). *Lepidium* has received great attention in recent years due to its various biological activities and possible medical applications. *Lepidium*'s sex includes more than 200 species, many of which are traditionally used in folk medicine for its therapeutic properties (Shah et al., 2021). *Lepidium sativum*, in particular, was used in traditional african medicine to treat various diseases, including inflammation, diabetes, and microbes (Shah et al., 2021). *Lepidium africanum*, the subject of this study, is one such species predominantly found in Sub-Saharan Africa and South Africa, and is also native to the Al Baha region of Saudi Arabia (Tshikororo et al., 2023). While species like *Lepidium sativum* (garden cress) have been extensively researched for their rich profile of bioactive compounds such as glucosinolates, flavonoids, and phenolic acids, which contribute to noted anti-inflammatory, antidiabetic, and antioxidant activities (AL-SNAFI, 2019; Olotu et al., 2018; Shah et al., 2021; Vazifeh et al., 2022) scientific literature on *L. africanum* is remarkably scarce. No detailed phytochemical profiling or comprehensive evaluation of its biological potential has been reported to date. Vegetarian chemical studies have revealed that this plant is rich in biological active compounds such as glucose, Flavonoid, phenolic acids, and terpenoids (Olotu et al., 2018). These secondary interlocutors contribute greatly to the factory's biological activities, making them a promising candidate for the discovery of drugs and development. The ethnic importance of *Sativum* extends beyond its medical uses. The factory is also estimated for its nutritional content and cooking applications. Small leaves and buds are consumed as vegetables, as basic nutrients such as vitamins, minerals and dietary fiber provide (AL-SNAFI, 2019). Moreover, *Lepidium Sativum* seeds are used as a spice and flavor factor in different dishes, which adds a unique taste and smell to food preparations.

The phytochemical compositions of *Lepidium* species are diverse and complex, ranging from several classes of bioactive compounds. Among the constituents found in this plant, glucosinolates, a class of sulfur-containing compounds, are the most prominent. These compounds are known for their potent antioxidant and anticancer activity (Abu Ali et al., 2025). Another of the important classes of phytochemicals present in *Lepidium* species is flavonoids, which possess the activities of potent anti-inflammatory and antimicrobial agents (Ait-yahia et al., 2018; Amer et al., 2022; Ouattar et al., 2022; Vazifeh et al., 2022). The abundant phenolic acids are key contributors to the antioxidant ability of the plant (Ait-yahia et al., 2018; Amer et al., 2022; Vazifeh et al., 2022). *Lepidium* species have been the subject of extensive biological activity investigations and a therapeutic plant of multifaceted potential. One of its most noteworthy activities is anti-inflammatory. Inflammation is an elaborate physiological response that is central to the mechanism of several ailments, including arthritis, cardiovascular disorders, and cancers (Dzoyem et al., 2017). The anti-inflammatory activity of *Lepidium* species can be attributed to the flavonoids and phenolic acids readily present inside the plants while inhibiting the production of pro-inflammatory mediators, such as prostaglandins and cytokines (Elgorashi & McGaw, 2019). Another significant biological activity of *Lepidium sativum* is its antidiabetic effect. Diabetes mellitus is Chronic metabolic disorder characterized by hyperglycemia and severe complications in the absence of treatment (Olotu et al., 2018). It has been proven that extracts of *Lepidium sativum* reduce blood glucose levels and increase insulin sensitivity in diabetic animals. Hypoglycemic activity is attributed to increased glucose uptake in peripheral tissues and decreased intestinal absorption of glucose (Mu et al., 2023). Moreover, the antioxidant properties of *Lepidium sativum* are essential in protecting cells from oxidative stress and hence preventing the onset of numerous diseases (Al-Sheddi et al., 2016). The plant's antioxidant ability, being flavonoid and phenolic acid-rich, works through the scavenging of free radicals and inhibition of lipid peroxidation (Mu et al., 2023). This antioxidant capacity of *Lepidium sativum* makes it a potent candidate for the prophylaxis and management of disorders associated with oxidative stress, such as neurodegenerative disorders and cardiovascular diseases. The best possible understanding of the modes of action responsible for the biological activities of *Lepidium* species will lead to the use of this plant for therapeutic purposes. The anti-inflammatory actions of this plant are hypothesized to occur through several pathways. It is possible that flavonoids and phenolic acids found in *Lepidium* may exert their effect by depressing the activation of nuclear factor-kappa B (NF- κ B), a transcription factor known for regulating inflammatory genes (Oguntibeju, 2018). These compounds also inhibit

the production of pro-inflammatory cytokines such as tumor necrosis factor- α (TNF- α) or interleukin-6 (IL-6) by modifying the activity of mitogen-activated protein kinases (MAPKs) (Kulkarni-Almeida et al., 2016). The action of *Lepidium sativum* as an antidiabetic is mediated through several mechanisms. The extracts of *Lepidium sativum* can enhance glucose uptake in peripheral tissues via the activation of glucose transporters such as GLUT4 (Sobhi et al., 2023). Other mechanisms include the inhibition of enzyme activity in carbohydrate metabolism, such as α -amylase and α -glucosidase, leading to the reduction of glucose absorption in the intestines (Naquvi et al., 2011). In addition, *Lepidium sativum* increases insulin sensitivity by stimulating insulin receptor translocation to the cell surface (S. S. et al., 2017). The antioxidant mechanism of *Lepidium sativum* acts through the scavenging of reactive oxygen species (ROS) and inhibition of lipid peroxidation. Flavonoids and phenolic acids present in the plant act as potent free radical scavengers, neutralizing ROS and preventing cellular damage (Selek et al., 2018). These compounds also upregulate the expression of antioxidant enzymes such as superoxide dismutase (SOD) and catalase, further enhancing the plant's antioxidant capacity.

Building on previous research, we were motivated to explore *Lepidium africanum*. It is crucial to reiterate that these potential biological activities are based on inferences from related species. Direct experimental validation is absolutely necessary to confirm these hypotheses and to fully characterize the biological activities of *L. africanum*. Therefore, drawing on the ethnobotanical and pharmacological evidence from its relatives, this study aims to address the critical knowledge gap surrounding *L. africanum*. We present the first comprehensive investigation into the phytochemical composition of its methanol extract, with a specific focus on phenolics and flavonoids profiling using HPLC. Furthermore, we systematically evaluate its antioxidant, antidiabetic, anti-inflammatory, and anticancer properties in vitro, thereby providing foundational data on the therapeutic potential of this underutilized plant.

2. EXPERIMENTAL

2.1 Extraction

The aerial parts of *Lepidium africanum* were collected from the Albaha region, KSA, and taxonomically authenticated. The extraction protocol was designed to comprehensively isolate a broad spectrum of medium- and high-polarity bioactive compounds, with a specific focus on phenolic and flavonoid compounds. Methanol was selected as the solvent due to its well-established efficacy in extracting such polar metabolites. A sequential extraction strategy was employed, an initial maceration step was used to gently extract heat-labile compounds at room temperature, followed by a Soxhlet extraction to

ensure exhaustive recovery of intracellular metabolites using continuous solvent washing. A total of 500 g of the dried aerial plant material was soaked in 2,000 mL of methanol for 72 h to facilitate the extraction of methanol-soluble constituents. After soaking, the plant material was subjected to Soxhlet extraction using methanol as the extraction solvent. The combined methanolic extracts obtained from the soaking and Soxhlet processes were filtered and concentrated under reduced pressure using a rotary evaporator, and the resulting methanol extract was thoroughly dried under vacuum and preserved under refrigeration at 4 °C for further usage. The final dried extract weighed 3.37 g. Subsequently, the extract was subjected to phytochemical screening, evaluations of its antioxidant, antidiabetic, anti-inflammatory, and anticancer properties, and HPLC analysis.

2.2 Phytochemical analysis

2.2.1 Total Phenolic Content (TPC)

The TPC was determined using the Folin-Ciocalteu method (Sembiring et al., 2017). Briefly, 1 mg/mL of the extract solution was prepared. A 500 μ L aliquot of this solution was mixed with 2.5 mL of Folin-Ciocalteu reagent (diluted 1:10 with distilled water) and allowed to stand for 5 minutes. Then, 2.5 mL of sodium carbonate solution (75 g/L) was added. The mixture was vortexed and incubated in the dark for 2 hours at room temperature. The absorbance of the resulting blue complex was measured at 765 nm using a UV-Vis spectrophotometer (Shimadzu, Japan). A standard curve was prepared using gallic acid (0-100 μ g/mL), and the TPC was expressed as mg of Gallic Acid Equivalents (GAE) per gram of dry extract.

2.2.2 Total Flavonoid Content (TFC)

The TFC was determined using an aluminum chloride colorimetric method (Sembiring et al., 2017). Briefly, 200 μ L of the extract solution (1 mg/mL) was mixed with 75 μ L of a 5% sodium nitrite (NaNO_2) solution. After 5 minutes, 1.25 mL of a 7% aluminum chloride (AlCl_3) solution was added. After another 5 minutes, 0.5 mL of 1 M sodium hydroxide (NaOH) was added, and the total volume was made up to 2.5 mL with distilled water. The mixture was vortexed, and the absorbance was immediately measured at 510 nm. A standard curve was prepared using quercetin (0-100 μ g/mL), and the TFC was expressed as μ g of Quercetin Equivalents (QE) per gram of dry extract.

2.3 HPLC Analysis of Phenolics and Flavonoids

The phenolic and flavonoid profile of the extract was analyzed using an Agilent 1260 series HPLC system (Agilent Technologies, USA) equipped with a quaternary pump, an autosampler, and a diode array detector (DAD). Separation was achieved on a Zorbax Eclipse Plus C8 column (4.6 $\times$ 250 mm, 5 μ m). The mobile phase consisted of water with 0.1% formic acid

(A) and acetonitrile with 0.1% formic acid (B). A linear gradient elution program was used as follows: 0–5 min, 10% B; 5–25 min, 10–55% B; 25–30 min, 55–100% B; 30–35 min, 100% B; 35–36 min, 100–10% B; and 36–40 min, 10% B for column re-equilibration. The flow rate was 1.0 mL/min, the injection volume was 10 µL, and the column temperature was maintained at 30°C. Detection was carried out at 280 nm and 330 nm. Compounds were identified by comparing their retention times and UV spectra with those of authentic standards (Ahmed et al., 2024). Quantification was performed based on the peak areas of the external standards.

2.4 Antioxidant activity

The antioxidant activity of the extract was determined using the (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) ABTS and Ferric reducing antioxidant power (FRAP) free radical scavenging assay in triplicate. Average values were considered (Ling et al., 2009; Samaniego Sánchez et al., 2007).

2.4.1 ABTS Radical Scavenging Assay

The antioxidant activity of the extract was determined using the (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) ABTS radical scavenging assay in triplicate, according to the method of (Ling et al., 2009). The ABTS radical cation (ABTS•⁺) was produced by reacting 7 mM ABTS solution with 2.45 mM potassium persulfate and allowing the mixture to stand in the dark at room temperature for 12-16 hours before use. The ABTS•⁺ solution was then diluted with methanol to an absorbance of 0.70 ± 0.02 at 734 nm. For the assay, 1 mL of the diluted ABTS•⁺ solution was mixed with 10 µL of different concentrations of the extract or standard (Ascorbic acid). The reaction mixture was vortexed and incubated for 6 minutes in the dark, after which the absorbance was measured at 734 nm. The percentage inhibition was calculated using the formula:

% Inhibition = $[(A_{\text{control}} - A_{\text{sample}}) / A_{\text{control}}] \times 100$, where A_{control} is the absorbance of the ABTS solution with methanol, and A_{sample} is the absorbance of the ABTS solution with the extract/standard. The IC_{50} value was determined from the dose-response curve.

2.4.2 Ferric Reducing Antioxidant Power (FRAP) Assay

The FRAP assay was performed as described by (Samaniego Sánchez et al., 2007). The FRAP reagent was prepared by mixing 300 mM acetate buffer (pH 3.6), 10 mM TPTZ (2,4,6-tripyridyl-s-triazine) solution in 40 mM HCl, and 20 mM FeCl₃ solution in a 10:1:1 ratio. The reagent was warmed to 37°C before use. An aliquot of 10 µL of the extract or standard (Ascorbic acid) was mixed with 1 mL of the FRAP reagent and incubated at 37°C for 4 minutes. The absorbance of the colored product (ferrous tripyridyltriazine complex) was measured at

593 nm. A standard curve was prepared using ferrous sulfate (FeSO₄·7H₂O), and the results were expressed as µM Fe(II) equivalents per gram of extract. The IC_{50} value was determined from the dose-response curve of the percentage activity.

2.5 Antidiabetic activity based in α-amylase inhibition assay

The assay performed for the inhibition of α-amylase followed the DNSA method (Miller, 1959). The extract was dissolved in 10% DMSO and diluted subsequently in phosphate buffer (0.02 M Na₂HPO₄/NaH₂PO₄, 0.006 M NaCl, pH 6.9) to prepare a set of concentrations that ranged from 10 to 1000 µg/mL. A 200 µL aliquot of the α-amylase solution (2 U/mL) was mixed with 200 µL of extract and incubated for 10 minutes at 30°C. After incubation, 200 µL of a 1% starch solution was added and further incubated for 3 minutes. The reaction was stopped by adding 200 µL of DNSA reagent followed by heating at 85–90°C for 10 minutes. Then, the mixture was cooled, diluted to 5 mL with distilled water, and absorbance was recorded at 540 nm. Acarbose was used as a positive control, and appropriate blanks were prepared. The percentage of α-amylase inhibition was calculated, and IC_{50} values were determined from the inhibition curve.

2.6 Anti-inflammatory activity based on Cyclooxygenase (COX-1) Inhibition Assay

The assay for inhibition of COX-1 was carried out according to an established method (Abdel-Aziz et al., 2016). The test sample concentrations were subjected to a pre-incubation with the COX-1 enzyme at (25 °C) for 5 minutes in the presence of hematin for test samples ranging from 7.8 to 1000 µg/mL. After this step, the premixed phenol (500 µM), 1-leuco-dichlorofluorescein (20 µM), arachidonic acid (50 µM) and hematin (1 µM) in 1 mL of 0.1 M Tris-buffer (pH 8) was added to the enzyme in order to start the reaction. For the first 15 seconds after the start of the reaction, the absorbance was measured at 502 nm using UV-visible spectrophotometry. A blank control was prepared without enzyme for recording non-enzymatic activity. It was used a standard inhibitor for celecoxib. The IC_{50} was determined from the concentration-response curve, defined as the concentration of inhibitor required to inhibit 50% of COX-1 activity (units: µg/mL).

2.7 Anticancer activity

The aforementioned extract was evaluated for cytotoxicity using the MTT assay (Nazreen et al., 2022) against the cell lines MCF-7, Caco-2, and HepG2. These were previously described and were acquired from the American Type Culture Collection (ATCC) situated in Rockville, Maryland. The human cancer cell lines HepG-2 (hepatocellular carcinoma), MCF-7 (breast adenocarcinoma), and Caco-2 (colorectal adenocarcinoma) were selected for this study. This selection was based on the high global prevalence and

clinical significance of liver, breast, and colon cancers. Using these three distinct cell lines allows for an initial assessment of the extract's potential broad-spectrum cytotoxic activity against cancers of different tissue origins. Cisplatin was used as the positive control in this assay. It was selected as a reference standard because it is a well-established, potent, and broad-spectrum chemotherapeutic agent. Its use provides a robust benchmark for maximal cytotoxicity, allowing for a clear and standardized comparison of the relative potency of the plant extract, which is a common practice in preliminary phytochemical cytotoxicity screening. Cells were cultured in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum (FBS) and 1% penicillin-streptomycin at 37°C in a humidified atmosphere of 5% CO₂. For the assay, cells were seeded in 96-well plates at a density of 1x10⁴ cells/well and allowed to adhere for 24 hours. The cells were then treated with various concentrations of the extract (ranging from 3.9 to 1000 µg/mL) or the positive control, cisplatin, for 72 hours. The final concentration of DMSO in the culture medium was kept below 0.5% to avoid solvent toxicity. After the treatment period, 20 µL of MTT solution (5 mg/mL in PBS) was added to each well and incubated for 4 hours at 37°C. The resulting formazan crystals were dissolved in 100 µL of DMSO, and the absorbance was measured at 570 nm using a microplate reader (BioTek, USA). Cell viability was

calculated as a percentage relative to the untreated control cells, and the IC₅₀ values were determined from the dose-response curves. The percentage of cell viability was calculated using the following formula: Cell Viability (%) = [(Absorbance of Treated Well - Absorbance of Blank) / (Absorbance of Untreated Control - Absorbance of Blank)] × 100, the half-maximal inhibitory concentration (IC₅₀ value), defined as the concentration of the extract that caused a 50% reduction in cell viability, was determined from the dose-response curves using non-linear regression analysis.

3. RESULTS AND DISCUSSION

3.1 Phytochemical Analysis of *Lepidium africanum* Methanol Extract—Composition

L. africanum, a member of the Brassicaceae family, contains important classes of compounds like phenolics and flavonoids, as exhibited by the phytochemical analysis of its methanol extract. The phytochemical composition of its methanol extract has garnered significant interest due to the potential health benefits of its bioactive compounds, particularly phenolic and flavonoid derivatives, which are known for their antioxidant and pharmacological properties (Sembiring et al., 2017). This study provides a detailed analysis of the phytochemical composition of the methanol extract of *L. africanum*, integrating data from Table-1.

Table-1: Percentage Composition of Phenolic and Flavonoid Compounds in *Lepidium africanum* Methanol Extract

Compound	Retention Time (min)	Concentration (µg/mg)	Composition (%)
Phenolic Compounds			
Gallic acid	3.50	1.64	48.46
Chlorogenic acid	4.20	0.88	26.00
Methyl gallate	5.39	0.078	2.30
Syringic acid	6.31	0.398	11.76
Ellagic acid	7.21	0.0048	0.14
p-Coumaric acid	8.53	0.075	2.22
Vanillin	8.89	0.0137	0.41
Ferulic acid	9.58	0.0795	2.35
Rosmarinic acid	11.72	0.194	5.73
Total Phenolics		3.382	
Flavonoid Compounds			
Catechin	4.41	2.65	77.42
Naringenin	10.33	0.026	0.76
Daidzein	15.86	0.071	2.07
Quercetin	17.21	0.676	19.75
Total Flavonoids		3.423	

These compounds, identified through HPLC as shown in Figure-1, are critical secondary metabolites with established roles in antioxidant defense, enzyme inhibition, and disease prevention(Chatzitzika et al., 2020). The concentrations are converted into percentage compositions (w/w) to facilitate a comprehensive understanding and visual representation, correlating with the chromatographic peaks. The total concentration of phenolic compounds is 3.3821 $\mu\text{g}/\text{mg}$, with gallic acid emerging as the predominant component, accounting for nearly half of the phenolic content with 1.64 $\mu\text{g}/\text{mg}$ (48.46% of total phenolics). This dominance is reflected in the HPLC chromatogram (as shown in Figure S-1) by the prominent peak at ~3.50 minutes, indicating high abundance and purity. The retention times align with standard phenolic profiles, as gallic acid typically elutes early due to its polarity, followed by less polar compounds like rosmarinic acid. Methyl gallate (2.30%), syringic acid (11.76%), ellagic acid(0.14%), p-coumaric acid(2.22%), vanillin(0.44%), ferulic acid(2.53%), and rosmarinic acid are also present, albeit in lower concentrations. Notably, rosmarinic acid, with a concentration of 0.194 $\mu\text{g}/\text{mg}$, is recognized for its anti-inflammatory and neuroprotective effects.

The predominance of gallic acid and catechin in the methanol extract of *Lepidium africanum* further supports its potential as a rich source of antioxidants. Gallic acid, a polyphenol, exhibits strong radical-scavenging activity, chelating metal ions, and inhibiting lipid peroxidation, as supported by studies on Brassicaceae plants(Singh et al., 2019). Its high concentration (48.52%) and prominent HPLC peak (~3.50 min) suggest a robust capacity to mitigate oxidative stress, a key factor in chronic diseases such as cancer, cardiovascular diseases, and neurodegenerative disorders. Other phenolic compounds, such as chlorogenic acid (26.00%, ~4.20 min) and rosmarinic acid (5.73%, ~11.70 min), may contribute additional antioxidant and anti-inflammatory activities(Sforcin & Bankova, 2011). Chlorogenic acid, is known to inhibit glucose absorption and exhibit antimicrobial properties, while rosmarinic acid has been associated with anti-allergic and antiviral effects in plants like *Lepidium* species(Jaiswal & Kumar, 2022). Minor components e.g., ellagic acid(0.14%, ~7.20 min) may play synergistic roles, enhancing the overall bioactivity of the extract, as observed in recent phytochemical studies of methanol extracts from related medicinal plants(Pacifico et al., 2021).

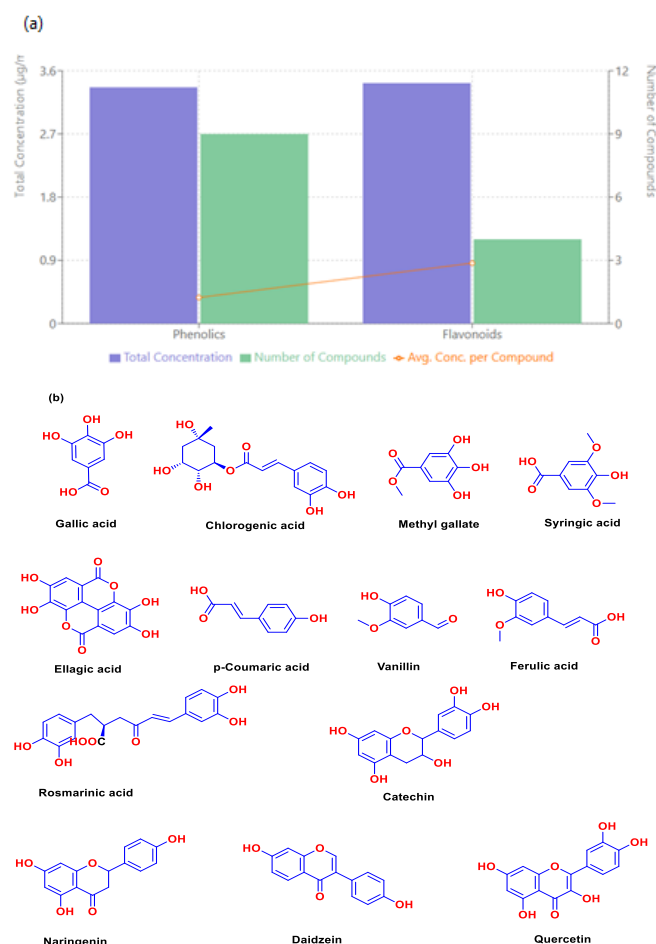


Figure-1: (a) A composite chart comparing the total concentration, number of compounds, and average concentration per compound between the two groups. (b) Chemical structure for all compounds.

The flavonoid compounds identified, along with their concentrations, retention times (as shown in Table-1), and percentage contributions, are as follows: Catechin: 2.65 $\mu\text{g}/\text{mg}$ (77.42% of total flavonoids, retention time ~ 4.41 min), Naringenin: 0.026 $\mu\text{g}/\text{mg}$ (0.76%, ~ 10.33 min), Daidzein: 0.071 $\mu\text{g}/\text{mg}$ (2.07%, ~ 15.85 min), Quercetin: 0.676 $\mu\text{g}/\text{mg}$ (19.75%, ~ 17.21 min). The total concentration of flavonoid compounds is 3.423 $\mu\text{g}/\text{mg}$, with catechin constituting the majority of the flavonoid fraction. The HPLC chromatogram (as shown in Figure S-1) shows a dominant peak at ~ 4.41 minutes for catechin, consistent with its high polarity and early elution, followed by less polar flavonoids like quercetin at ~ 17.21 minutes (Nwozo et al., 2023). Catechin, is a potent flavonoid with well-documented antioxidant, anti-inflammatory, and anticancer properties. Its hydroxyl-rich structure enables effective neutralisation of reactive oxygen species (ROS), as demonstrated in studies on related Brassicaceae plants, such as *L. sativum*, where flavonoids contribute to therapeutic efficacy (Raza et al., 2020). The presence of quercetin is another potent flavonoid, further enhances the extract's antioxidant profile, as quercetin is known for its ability to inhibit lipid peroxidation and modulate cellular signalling pathways involved in inflammation and cancer prevention (Nwozo et al., 2023). The phytochemical profile of *L. africanum* methanol extract, aligns with recent findings on Brassicaceae plants, which are rich in glucosinolates, phenolics, and flavonoids, contributing to their medicinal properties (Singh et al., 2019). Studies on *L. sativum* and *L. meyenii* have demonstrated that methanol extracts, due to their polarity, effectively extract polar compounds like phenolics and flavonoids, which are critical for antioxidant activity. For instance, study on

L. meyenii roots and leaves has identified high levels of saponins, phenols, and flavonoids, correlating with strong antioxidant capabilities, as measured by DPPH and FRAP assays (Raza et al., 2020). Similarly, the high phenolic and flavonoid content in *Lepidium africanum* suggests potential applications in antioxidant therapy, disease prevention, and pharmaceutical development. Generally (as shown in Figure-1), The dominance of gallic acid and catechin may also indicate anti-cancer and anti-inflammatory potential, as these compounds have been shown to modulate key signalling pathways (e.g., NF- κ B, MAPK) in cellular models (Nwozo et al., 2023). The presence of chlorogenic acid and quercetin could potentially contribute to antidiabetic and cardioprotective effects, as evidenced by studies on related Brassicaceae species (Jaiswal & Kumar, 2022). However, the low concentrations of minor compounds (e.g., ellagic acid, naringenin) suggest that their contributions may be supplementary, requiring further investigation to elucidate synergistic or additive effects.

3.2 Biological study:

3.2.1 Antioxidant activity of *L. africanum* methanol extract using ABTS scavenging capacity method

The methanol extract of *L. africanum* has garnered significant interest due to its potential antioxidant capacity, attributed to its rich phytochemical profile, particularly phenolic and flavonoid compounds. This analysis evaluates the antioxidant activity of the methanol extract using the ABTS radical scavenging assay, (Table S-1).

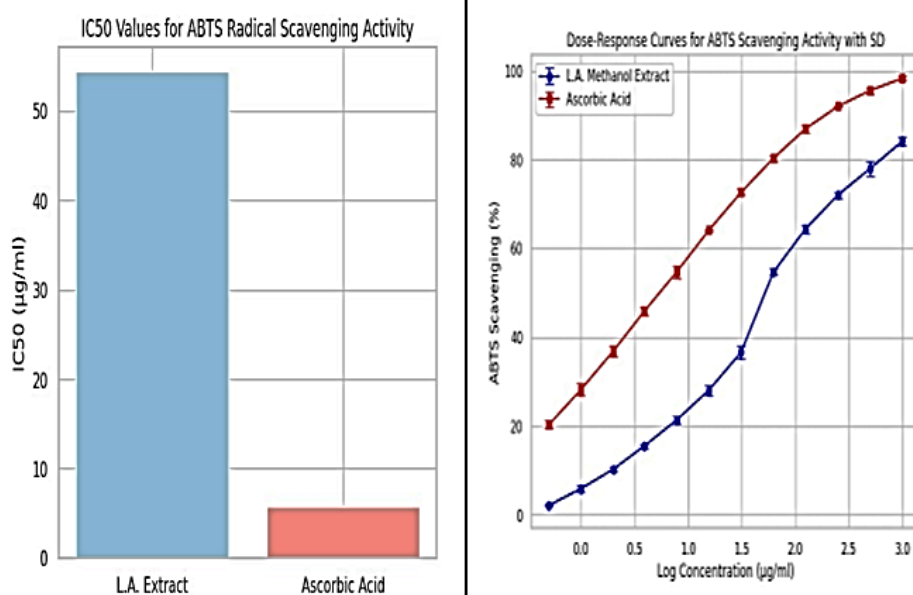


Figure-2. ABTS scavenging activity (from left to right pannel)for *L. africanum* and Ascorbic Acid, Bar chart comparing the IC50 values ($\mu\text{g}/\text{ml}$), Dose-Response Curves, ABTS Scavenging Percentage at Different Concentrations.

A potent polyphenol (Gallic acid ; 48.46% of phenolics) with strong radical-scavenging activity, capable of donating hydrogen atoms to neutralize ABTS radicals(Singh et al., 2019). Its high concentration (1.64 µg/mg) likely contributes significantly to the extract's antioxidant capacity (as shown in Figure-2). While Catechin (77.42%) with multiple hydroxyl groups, enabling effective electron donation to stabilize ABTS radicals. Its dominance (2.65 µg/mg) could be a major driver of the extract's antioxidant potential(Raza et al., 2020). Chlorogenic acid (26.00% of phenolics) and Quercetin (19.75% of flavonoids), these compounds further enhance antioxidant activity through their ability to scavenge free radicals and chelate metal ions(Jaiswal & Kumar, 2022). The synergistic interaction of these compounds, particularly gallic acid and catechin, likely amplifies the extract's ABTS scavenging capacity, as phenolic and flavonoid mixtures are known to exhibit additive or cooperative antioxidant effects(Pacifico et al., 2021). In conclusion, the methanol extract of *L. africanum* demonstrated moderate antioxidant activity in the ABTS assay, with an IC_{50} value of 58.72 µg/ml (as shown in Figure-2). As expected, the standard antioxidant ascorbic acid was significantly more potent (IC_{50} : 6.45 µg/ml). The observed activity is may be attributed to the extract's rich phenolic and flavonoid content (Table-1), particularly the high concentrations of gallic acid and catechin, which are established potent radical scavengers(Chatzitzika et al., 2020; Nwozo et al., 2023). The dose-response curve shows a clear concentration-dependent increase in

activity, reaching >84% scavenging at the highest tested concentration (1000 µg/ml), confirming its potential to mitigate oxidative stress.

3.2.2 Evaluation of Antioxidant Activity using Ferric Reducing Antioxidant Power (FRAP) Assay

The reducing power of a compound is a key indicator of its potential antioxidant activity. The FRAP assay was employed to evaluate the ability of the *L. africanum* methanol extract to reduce ferric ions (Fe^{3+}) to ferrous ions (Fe^{2+}). As illustrated in Figure-3, both the extract and the ascorbic acid standard demonstrated a concentration-dependent increase in ferric reducing power. The extract exhibited considerable reducing activity, reaching a maximum of $89.54 \pm 0.98\%$ at the highest concentration tested (1000 µg/mL). However, as quantified by the IC_{50} value (Table S-2), the reducing potency of the extract ($IC_{50} = 71.73 \pm 9.62$ µg/mL) was significantly lower than that of the potent standard antioxidant, ascorbic acid ($IC_{50} = 12.72 \pm 0.36$ µg/mL).

This result is consistent with the findings from the ABTS and FRAP assays, confirming the antioxidant capacity of the *L. africanum* extract. The observed activity can be attributed to its high content of phenolic compounds (like gallic acid) and flavonoids (like catechin), which are known to act as electron donors, effectively reducing oxidized intermediates and thereby terminating radical chain reactions (Chatzitzika et al., 2020; Nwozo et al., 2023).

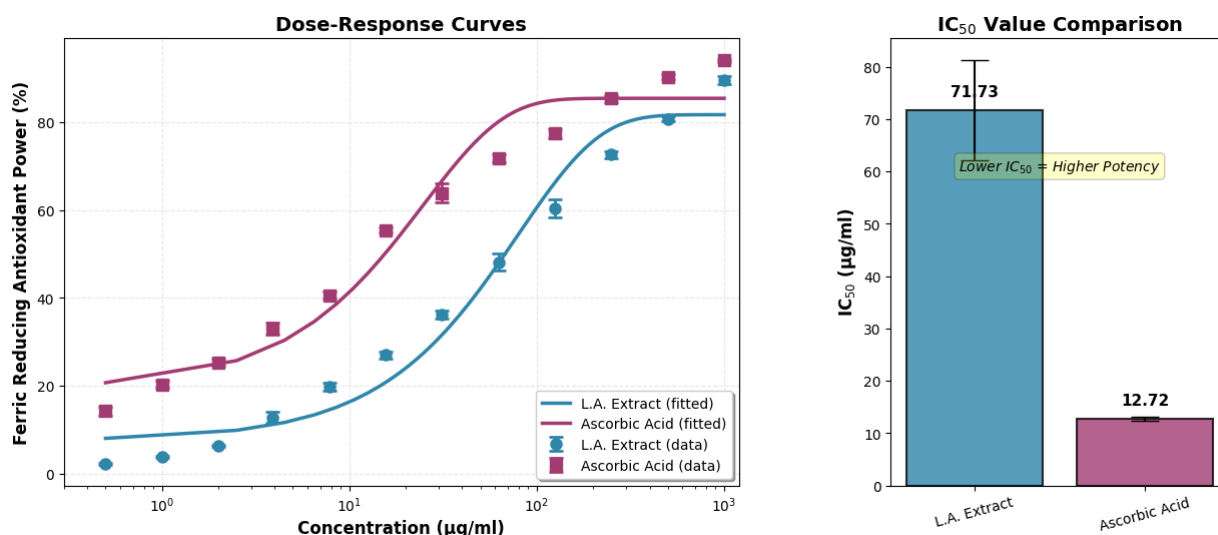


Figure-3. Evaluation of Antioxidant Activity using FRAP Assay for L.A

3.2.3 Anti-diabetic activity of *L. africanum* methanol extract using α -amylase enzyme inhibition

Diabetes mellitus, particularly type 2 diabetes, is characterized by chronic hyperglycemia resulting from impaired insulin action or secretion. One therapeutic strategy to manage postprandial hyperglycemia is to inhibit α -amylase, a key enzyme in the digestion of dietary starch. By reducing starch digestion, α -amylase inhibitors can lower the glucose absorption rate and thereby help manage blood glucose levels (Alasmari et al., 2025). The α -amylase enzyme inhibition assay is a

valuable method to assess the potential of plant extracts and compounds as anti-diabetic agents. To evaluate and compare the potency, we analyze the IC₅₀ values and dose-response relationships (Table S-3). The IC₅₀ for *L. africanum* methanol extract is 57.46 μ g/ml, while positive control acarbose is lower IC₅₀ of 4.65 μ g/ml.

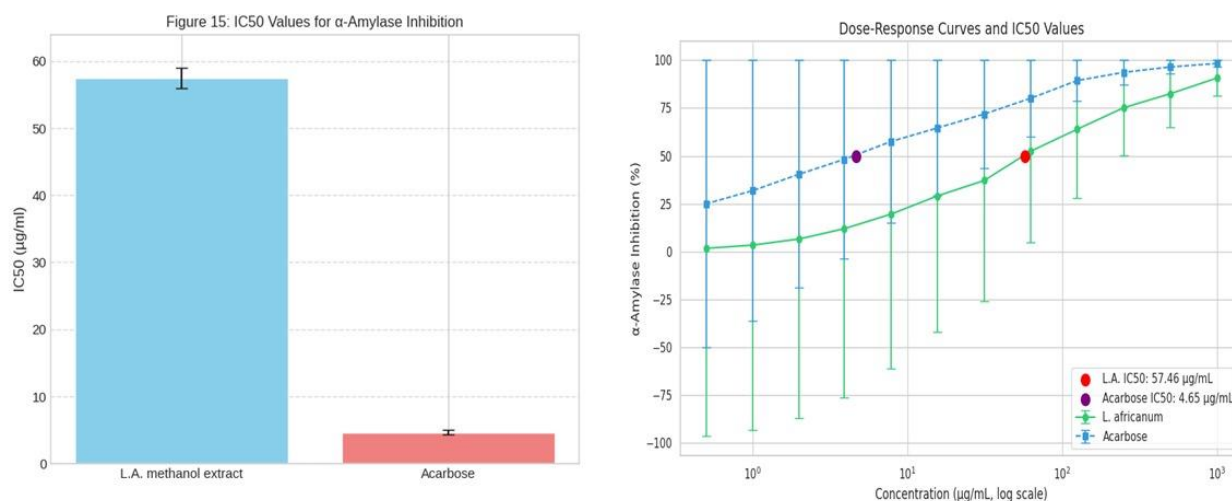


Figure-4. illustrates the dose-response curves for α -amylase enzyme inhibition for both *Lepidium africanum* methanol extract and acarbose. a dose-response curve graph showing % α -amylase inhibition vs. concentration for both extract and acarbose. Include error bars for SD, using data from Table S-3)

While acarbose, is more potent, the extract's inhibitory capacity is still noteworthy. At higher concentrations (e.g., 1000 μ g/ml), the extract achieves a substantial enzyme inhibition of approximately 91%, demonstrating its effectiveness at relevant concentrations (Figure-4). The observed α -amylase inhibitory activity of *L. africanum* methanol extract can be plausibly attributed to its complex phytochemical profile, especially flavonoids and phenolic acids, are well-documented for their ability to inhibit carbohydrate-hydrolyzing enzymes like α -amylase and α -glucosidase (Zainab et al., 2025). Chlorogenic acid, present in the *L. africanum* extract, is a known inhibitor of α -amylase and has been shown to reduce postprandial blood glucose levels in animal studies (Yan et al., 2022). Its mechanism involves competitive inhibition of the enzyme, thereby slowing down glucose release from starch digestion (Zheng et al., 2020). Catechin, the most abundant flavonoid in the extract, has also demonstrated α -amylase inhibitory effects (Xu et al., 2013). Catechins, and flavonoids in general, can interact with enzymes through hydrogen bonding and hydrophobic interactions, leading to conformational changes that reduce enzyme activity (Telagari & Hullatti, 2015). Quercetin is another flavonoid in the extract known for its anti-diabetic

properties, including α -amylase inhibition. Quercetin's inhibitory action may also involve similar enzyme-substrate interaction mechanisms, along with potential antioxidant protection of pancreatic β -cells (COSKUN et al., 2005). Other phenolic acids like gallic acid, syringic acid, and ferulic acid, also found in *L. africanum* extract, have been reported to exhibit α -amylase and α -glucosidase inhibitory activities, albeit to varying extents (Tan et al., 2017). The synergistic action of these and potentially other unidentified compounds in the extract may contribute to the overall anti-diabetic effect.

in conclusion, The *L. africanum* extract exhibited significant α -amylase inhibitory activity with an IC₅₀ value of 57.46 μ g/ml, suggesting its potential for managing postprandial hyperglycemia (as shown in Figure-4). Although the standard drug acarbose was more potent (IC₅₀: 4.65 μ g/ml), the extract's inhibitory capacity is notable, achieving ~91% inhibition at 1000 μ g/ml. This bioactivity can be plausibly linked to its flavonoid and phenolic acid content. Compounds like chlorogenic acid and catechin are well-documented for their ability to inhibit carbohydrate-hydrolyzing enzymes through interactions with the enzyme's active site (Telagari &

Hullatti, 2015; Xu et al., 2013; Zainab et al., 2025).

3.2.4 Anti-inflammatory activity of *L. africanum* methanol extract based on Cox-1 enzyme inhibition

Inflammation is a complex biological response to tissue injury, infection, or irritation. While acute inflammation is a protective mechanism, chronic inflammation underlies numerous diseases, including arthritis, cardiovascular diseases, and neurodegenerative disorders (Medzhitov, 2008). Cyclooxygenase-1 (COX-1) is a key enzyme involved in the biosynthesis of prostaglandins, which are crucial mediators of inflammation and pain (Simmons et al., 2004). Inhibition of COX-1 is a well-established therapeutic strategy for reducing inflammation, with non-steroidal anti-inflammatory drugs (NSAIDs) being primary examples (Vane & Botting, 1998). However, synthetic NSAIDs are often associated with adverse effects, prompting the search for safer, naturally derived

anti-inflammatory agents, particularly from plant sources (Bajpai et al., 2013). This analysis examines the anti-inflammatory potential of *L. africanum* methanol extract by evaluating its inhibitory activity against COX-1 enzyme and comparing it to celecoxib acid, a known COX inhibitor. The inhibitory potency of *L. africanum* methanol extract against COX-1 enzyme was evaluated using the COX-1 inhibition assay. Table S-4 presents the percentage inhibition of COX-1 enzyme activity at various concentrations of the extract and celecoxib acid. The IC₅₀ value, a key parameter for quantifying and comparing inhibitory potency. The IC₅₀ value for *L. africanum* methanol extract is 14.47 ± 0.30 $\mu\text{g/ml}$. Celecoxib acid, exhibited a significantly lower IC₅₀ of $7.19 \mu\text{g/ml} \pm 0.35 \mu\text{g/ml}$, indicating its greater potency as a COX-1 inhibitor in this assay. Figure 4 illustrates the dose-response curves for COX-1 enzyme inhibition by *Lepidium africanum* methanol extract and celecoxib acid.

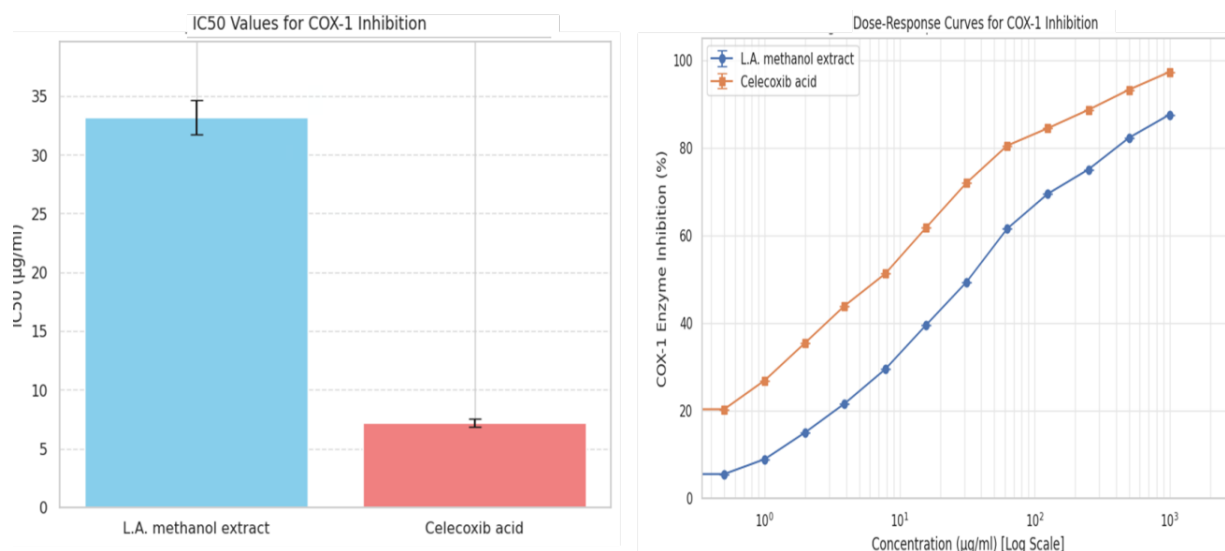


Figure-5: Dose-Response Curves for COX-1 Enzyme Inhibition for both extract and celecoxib acid. Include error bars for SD using data from Table S-4)

The dose-response curves in Figure 5 indicates that as the concentration of either the extract or celecoxib acid increases, the percentage of COX-1 enzyme inhibited also increases. While both exhibit this trend, celecoxib acid consistently shows a higher degree of inhibition at each concentration point compared to the *L. africanum* extract, which is consistent with its lower IC₅₀ value and greater inhibitory potency. At the highest concentration tested (1000 $\mu\text{g/ml}$), *L. africanum* methanol extract achieves approximately 87.5% COX-1 inhibition, demonstrating substantial, albeit not complete, enzyme inhibitory capacity. To visually compare the inhibitory strengths, Figure 5 presents a bar chart comparing the IC₅₀ values of *L. africanum* methanol extract and celecoxib acid for COX-1 inhibition. The observed COX-1 inhibitory activity

of *L. africanum* methanol extract indicates its potential to modulate inflammatory processes. While celecoxib acid, a selective COX-2 inhibitor with some COX-1 activity, is more potent, the extract's IC₅₀ of 33.16 $\mu\text{g/ml}$ suggests a significant level of COX-1 inhibition that could contribute to anti-inflammatory effects. This activity can be attributed to the phytochemical constituents present in the extract, particularly the phenolic and flavonoid compounds identified in previous analyses (Table-1).

Compounds like gallic acid, chlorogenic acid, syringic acid, catechin, and quercetin, all identified in *L. africanum* methanol extract, have been reported to possess COX-1 inhibitory properties. Their mechanisms of action may involve direct binding to the enzyme

active site, competitive or non-competitive inhibition, or modulation of enzyme expression. The most abundant phenolic compound (Gallic acid) in the extract (1.64 $\mu\text{g}/\text{mg}$), has demonstrated COX-inhibitory and anti-inflammatory effects in several studies (Kaur et al., 2009). Similarly, chlorogenic acid (0.88 $\mu\text{g}/\text{mg}$) and quercetin (0.676 $\mu\text{g}/\text{mg}$) have shown inhibitory effects on COX enzymes and prostaglandin production, contributing to their anti-inflammatory properties (Bajpai et al., 2013). Catechin (2.65 $\mu\text{g}/\text{mg}$) and syringic acid (0.398 $\mu\text{g}/\text{mg}$) also contribute to the overall COX-1 inhibitory profile of the extract. The presence of these and other bioactive phytochemicals in *Lepidium africanum* methanol extract likely contributes synergistically to its observed COX-1 inhibitory activity and, consequently, its potential anti-inflammatory effects.

3.2.5 In Vitro Cytotoxicity Evaluation of *L. africanum* Against HepG-2, MCF-7, and CACO2 Cell Lines.

Table S-5, S-6 and S-7 present the cell viability percentages for HepG-2, MCF-7, and CACO2 cell lines treated with varying concentrations of *L. africanum* methanol extract and cisplatin, respectively. As evident from IC₅₀ values, cisplatin demonstrates significantly higher cytotoxicity across all three cell lines, with IC₅₀ values substantially lower than those of *L. africanum* methanol extract. However, the *Lepidium africanum* extract also exhibits notable cytotoxicity, with IC₅₀ values in the range of 71.61 $\mu\text{g}/\text{ml}$ to 114.09 $\mu\text{g}/\text{ml}$, depending on the cell line. HepG-2 cells appear to be the most sensitive to the extract, followed by CACO2 and then MCF-7 cells, based on their respective IC₅₀ values. To visually represent the cytotoxic effects and compare the dose-response relationships, Figure 6 presents dose-response curves for *L. africanum* methanol extract and cisplatin against HepG-2, MCF-7, and CACO2 cell lines.

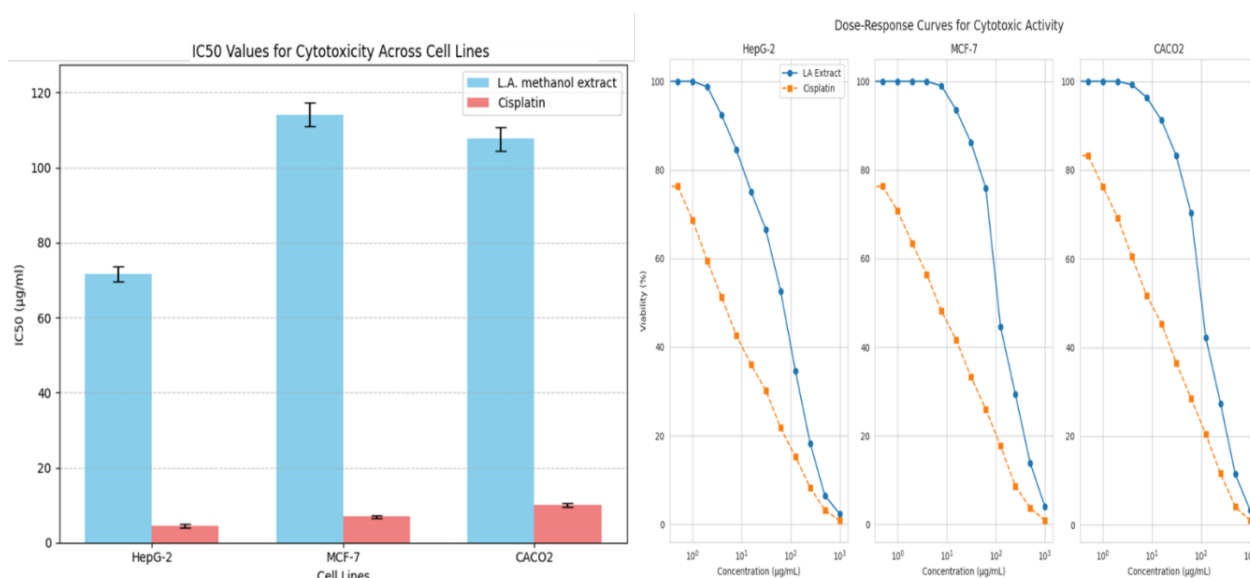


Figure-6: Dose-response curves and bar chart for *L. africanum* extract and Cisplatin against HepG-2, MCF-7, and CACO2 cell lines.

The MTT assay results demonstrate that *L. africanum* methanol extract exhibits promising anticancer activity against HepG-2, MCF-7, and CACO2 cell lines, with IC₅₀ values of $71.61 \pm 1.96 \mu\text{g}/\text{ml}$, $114.09 \pm 3.13 \mu\text{g}/\text{ml}$, and $107.63 \pm 3.25 \mu\text{g}/\text{ml}$, respectively, though significantly less potent than cisplatin ($4.49 \pm 0.44 \mu\text{g}/\text{ml}$ for HepG-2, $6.94 \pm 0.40 \mu\text{g}/\text{ml}$ for MCF-7, $9.95 \pm 0.53 \mu\text{g}/\text{ml}$ for CACO2). However, the IC₅₀ values of *L. africanum* suggest moderate cytotoxic potential, comparable to other plant extracts rich in phenolics and flavonoids, such as those from *Lepidium meyenii*, reported to exhibit IC₅₀ values of 70–120 $\mu\text{g}/\text{ml}$ in MTT assays against similar cell lines (Raza et al., 2020). The extract's activity

is likely driven by gallic acid, catechin, chlorogenic acid, and quercetin, which induce apoptosis and may be inhibit cell proliferation through ROS generation and signaling pathway modulation. The dose-response curves (as shown in Figure-6) illustrate sigmoid relationships, with *L. africanum* showing more gradual increases in cytotoxicity, indicating a broader concentration range for effective cell inhibition compared to cisplatin's steeper curves. This suggests that the extract's complex phytochemical matrix may involve synergistic or competitive interactions, potentially reducing its potency relative to the pure cisplatin standard (Pacífico et al., 2021).

in conclusion, The MTT assay revealed that *L. africanum* extract possesses promising, dose-dependent anticancer activity against all three tested cell lines (Figure 6). The extract was most potent against the HepG-2 hepatocellular carcinoma cell line (IC₅₀: 71.61 µg/ml), followed by CACO2 colorectal cancer cells (IC₅₀: 107.63 µg/ml) and MCF-7 breast cancer cells (IC₅₀: 114.09 µg/ml). As anticipated, the chemotherapeutic drug cisplatin was markedly more cytotoxic (IC₅₀: 4.49 - 9.95 µg/ml). The selective cytotoxicity of the extract may be likely mediated by its prominent bioactive compounds, such as gallic acid and quercetin, which are known to induce apoptosis and inhibit proliferation in cancer cells through mechanisms involving ROS generation and modulation of key signaling pathways (Jaiswal & Kumar, 2022).

3.3 Overall Implications and Future Perspectives

The collective findings from this study firmly establish *L. africanum* as a promising medicinal plant with multifaceted biological activities. The strong correlations between its rich phytochemical profile and the observed bioactivities provide a scientific basis for its ethnobotanical use. However, this study has some limitations. The crude extract was used, and the contributions of individual compounds or potential synergistic effects remain to be determined. Future work should therefore focus on the bioassay-guided fractionation of the extract to isolate and identify the specific compounds responsible for each activity. Furthermore, the underlying mechanisms, such as apoptosis induction or NF-κB pathway modulation, should be investigated using molecular techniques. It is also noteworthy that Soxhlet extraction was used in this study; future work could employ greener and more efficient techniques like ultrasound-assisted extraction to minimize potential thermal degradation and compare the yield and bioactivity of the resulting extracts. Finally, in vivo studies are essential to confirm these promising in vitro results and assess the safety and efficacy of the extract.

4. Conclusion

The present study comprehensively investigates the phytochemical composition and biological activities of *Lepidium africanum*, a plant predominantly found in Sub-Saharan Africa and Saudi Arabia. Our analysis reveals that *L. africanum* is a rich source of bioactive compounds, particularly phenolic acids and flavonoids, with significant antioxidant, antidiabetic, anti-inflammatory, and anticancer potentials. The HPLC analysis identified various phenolic and flavonoid compounds in the methanol extract of *L. africanum*, with gallic acid and catechin being the predominant components. The extract demonstrated significant multifunctional bioactivity, exhibiting antioxidant (ABTS IC₅₀: 58.72 µg/ml), antidiabetic (α-amylase IC₅₀: 57.46 µg/ml), anti-inflammatory (COX-1 IC₅₀: 14.47 µg/ml), and anticancer

effects (IC₅₀: 71.61-114.09 µg/ml across HepG-2, MCF-7, and Caco-2 cell lines). These findings validate the plant's traditional use and highlight its potential as a source of therapeutic agents. Future work should focus on compound isolation, mechanism elucidation, and exploring alternative extraction methods like ultrasound-assisted extraction.

5. REFERENCES

- Abdel-Aziz, A. A.-M., El-Azab, A. S., Abou-Zeid, L. A., ElTahir, K. E. H., Abdel-Aziz, N. I., Ayyad, R. R., & Al-Obaid, A. M. (2016). Synthesis, anti-inflammatory, analgesic and COX-1/2 inhibition activities of anilides based on 5,5-diphenylimidazolidine-2,4-dione scaffold: Molecular docking studies. *European Journal of Medicinal Chemistry*, 115, 121–131. <https://doi.org/10.1016/j.ejmech.2016.03.011>
- Abu Ali, O. A., Ali, A. A., Saleh, N. M., Elsayy, M. M., El-Henawy, A. A., & Abd El-Wahab, H. (2025). Innovative Synthesis and Application of Bridged Nitrogen Heterocycles: From Diazotized Sulfur Dyes to Enhanced Polyester Fabrics. *Chemistry Africa*. <https://doi.org/10.1007/s42250-024-01176-x>
- Ahmed, O. M., Mosa, N. M., & Abou-Seif, H. S. (2024). Antihyperlipidemic and cardiopreventive properties of Arabic gum in nicotinamide/streptozotocin-induced diabetic rats. *Journal of The Arab Society for Medical Research*, 19(1), 90–99. https://doi.org/10.4103/jasmr.jasmr_2_24
- Ait-yahia, O., Perreau, F., Bouzroua, S.-A., Benmalek, Y., Dob, T., & Belkebir, A. (2018). Chemical composition and biological activities of *n*-butanol extract of *Lepidium sativum* L. (Brassicaceae) seed. *Tropical Journal of Pharmaceutical Research*, 17(5), 891. <https://doi.org/10.4314/tjpr.v17i5.20>
- Al-Sheddi, E. S., Farshori, N. N., Al-Oqail, M. M., Musarrat, J., Al-Khedhairi, A. A., & Siddiqui, M. A. (2016). Protective effect of *Lepidium sativum* seed extract against hydrogen peroxide-induced cytotoxicity and oxidative stress in human liver cells (HepG2). *Pharmaceutical Biology*, 54(2), 314–321. <https://doi.org/10.3109/13880209.2015.1035795>
- AL-SNAFI, A. E. (2019). CHEMICAL CONSTITUENTS AND PHARMACOLOGICAL EFFECTS OF *LEPIDIUM SATIVUM*-A REVIEW. *International Journal of Current Pharmaceutical Research*, 1–10. <https://doi.org/10.22159/ijcpr.2019v11i6.36338>
- Alasmari, S. M. N., Alam, A., Fayaz Ur Rahman, Elhenawy, A. A., Ali, A., Ahmad, M., & Khan,

- M. (2025). Exploring the Versatility of Azine Derivatives: A Comprehensive Review on Synthesis and Biological Applications. *Mini-Reviews in Medicinal Chemistry*, 25(6), 425–439. <https://doi.org/10.2174/0113895575363243241129100845>
- Altemimi, A., Lakhssassi, N., Baharlouei, A., Watson, D., & Lightfoot, D. (2017). Phytochemicals: Extraction, Isolation, and Identification of Bioactive Compounds from Plant Extracts. *Plants*, 6(4), 42. <https://doi.org/10.3390/plants6040042>
- Amer, A. A., Mohammed, R. S., Hussein, Y., Ali, A. S. M., & Khalil, A. A. (2022). Development of *Lepidium sativum* Extracts/PVA Electrospun Nanofibers as Wound Healing Dressing. *ACS Omega*, 7(24), 20683–20695. <https://doi.org/10.1021/acsomega.2c00912>
- Bajpai, R., Sharma, N. K., & Rai, A. K. (2013). Physiological evidence indicates microcystin-LR to be a part of quantitative chemical defense system. *Journal of Applied Phycology*, 25(5), 1575–1585. <https://doi.org/10.1007/s10811-013-9981-y>
- Chatzitzika, C., Gatt, R., Valdramidis, V., & Mizzi, L. (2020). HPLC Analysis of Phenolic Compounds and Flavonoids with Overlapping Peaks. *Food Technology and Biotechnology*, 58(1), 12–19. <https://doi.org/10.17113/fib.58.01.20.6395>
- COSKUN, O., KANTER, M., KORKMAZ, A., & OTER, S. (2005). Quercetin, a flavonoid antioxidant, prevents and protects streptozotocin-induced oxidative stress and β -cell damage in rat pancreas. *Pharmacological Research*, 51(2), 117–123. <https://doi.org/10.1016/j.phrs.2004.06.002>
- Dar, R. A., Shah Nawaz, M., Qazi, P. H., & Qazi, H. (2017). General overview of medicinal plants: A review. In *The Journal of Phytopharmacology* (Vol. 6, Issue 6). www.phytopharmajournal.com
- Dzoyem, J. P., McGaw, L. J., Kuete, V., & Bakowsky, U. (2017). Anti-inflammatory and Anti-nociceptive Activities of African Medicinal Spices and Vegetables. In *Medicinal Spices and Vegetables from Africa* (pp. 239–270). Elsevier. <https://doi.org/10.1016/B978-0-12-809286-6.00009-1>
- Elgorashi, E. E., & McGaw, L. J. (2019). African plants with in vitro anti-inflammatory activities: A review. *South African Journal of Botany*, 126, 142–169. <https://doi.org/10.1016/j.sajb.2019.06.034>
- Jaiswal, N., & Kumar, A. (2022). HPLC in the discovery of plant phenolics as antifungal molecules against *Candida* infection related biofilms. *Microchemical Journal*, 179, 107572. <https://doi.org/10.1016/j.microc.2022.107572>
- Kaur, K., Jain, M., Kaur, T., & Jain, R. (2009). Antimalarials from nature. *Bioorganic & Medicinal Chemistry*, 17(9), 3229–3256. <https://doi.org/10.1016/j.bmc.2009.02.050>
- Kulkarni-Almeida, A., Shah, M., Jadhav, M., Hegde, B., Trivedi, J., Mishra, P. D., Mahajan, G. B., Dadarkar, S., Gupte, R., & Dagia, N. (2016). A semi-synthetic natural product blocks collagen induced arthritis by preferentially suppressing the production of IL-6. *International Immunopharmacology*, 33, 63–69. <https://doi.org/10.1016/j.intimp.2016.01.001>
- Ling, L. T., Yap, S.-A., Radhakrishnan, A. K., Subramaniam, T., Cheng, H. M., & Palanisamy, U. D. (2009). Standardised *Mangifera indica* extract is an ideal antioxidant. *Food Chemistry*, 113(4), 1154–1159. <https://doi.org/10.1016/j.foodchem.2008.09.004>
- Long, R. L., Stevens, J. C., Griffiths, E. M., Adamek, M., Gorecki, M. J., Powles, S. B., & Merritt, D. J. (2011). Seeds of Brassicaceae weeds have an inherent or inducible response to the germination stimulant karrikinolide. *Annals of Botany*, 108(5), 933–944. <https://doi.org/10.1093/aob/mcr198>
- Medzhitov, R. (2008). Origin and physiological roles of inflammation. *Nature*, 454(7203), 428–435. <https://doi.org/10.1038/nature07201>
- Miller, G. L. (1959). Use of Dinitrosalicylic Acid Reagent for Determination of Reducing Sugar. *Analytical Chemistry*, 31(3), 426–428. <https://doi.org/10.1021/ac60147a030>
- Mu, K., Yao, Y., Wang, D., & Kitts, D. D. (2023). Prooxidant capacity of phenolic acids defines antioxidant potential. *Biochimica et Biophysica Acta (BBA) - General Subjects*, 1867(7), 130371. <https://doi.org/10.1016/j.bbagen.2023.130371>
- Naquvi, K. J., Ahamad, J., Mir, S. R., Ali, M., & Shuaib, M. (2011). REVIEW ON ROLE OF NATURAL ALPHA-GLUCOSIDASE INHIBITORS FOR MANAGEMENT OF DIABETES MELLITUS. *International Journal of Biomedical Research*, 2(6). <https://doi.org/10.7439/ijbr.v2i6.121>
- Nazreen, S., Almalki, A. S. A., Elbehairi, S. E. I., Shati, A. A., Alfaifi, M. Y., Elhenawy, A. A., Alsenani, N. I., Alfarsi, A., Alhadhrani, A., Alqurashi, E. A., & Alam, M. M. (2022). Cell Cycle Arrest and Apoptosis-Inducing Ability of Benzimidazole Derivatives: Design, Synthesis, Docking, and Biological Evaluation. *Molecules*, 27(20), 6899. <https://doi.org/10.3390/molecules27206899>

- Nwozo, O. S., Effiong, E. M., Aja, P. M., & Awuchi, C. G. (2023). Antioxidant, phytochemical, and therapeutic properties of medicinal plants: a review. *International Journal of Food Properties*, 26(1), 359–388. <https://doi.org/10.1080/10942912.2022.2157425>
- Oguntibeju, O. (2018). Medicinal plants with anti-inflammatory activities from selected countries and regions of Africa. *Journal of Inflammation Research*, Volume 11, 307–317. <https://doi.org/10.2147/JIR.S167789>
- Olotu, I. A., Luka, C. D., & Olotu, P. N. (2018). Evaluation of the Effects of Aqueous Whole Plant Extract of *Lepidium sativum* L. (Brassicaceae) on some Biochemical and Hematological Parameters in Streptozotocin-Induced Diabetic Rats. In *J. Nat. Prod. Plant Resour* (Vol. 8, Issue 1). www.scholarsresearchlibrary.com
- Ouattar, H., Zouirech, O., Kara, M., Assouguem, A., Almutairi, S. M., Al-Hemaid, F. M., Rasheed, R. A., Ullah, R., Abbasi, A. M., Aouane, M., & Mikou, K. (2022). In Vitro Study of the Phytochemical Composition and Antioxidant, Immunostimulant, and Hemolytic Activities of *Nigella sativa* (Ranunculaceae) and *Lepidium sativum* Seeds. *Molecules*, 27(18), 5946. <https://doi.org/10.3390/molecules27185946>
- Pacifico, D., Lanzanova, C., Pagnotta, E., Bassolino, L., Mastrangelo, A. M., Marone, D., Matteo, R., Lo Scalzo, R., & Balconi, C. (2021). Sustainable Use of Bioactive Compounds from *Solanum Tuberosum* and Brassicaceae Wastes and by-Products for Crop Protection—A Review. *Molecules*, 26(8), 2174. <https://doi.org/10.3390/molecules26082174>
- Raza, A., Hafeez, M. B., Zahra, N., Shaukat, K., Umbreen, S., Tabassum, J., Charagh, S., Khan, R. S. A., & Hasanuzzaman, M. (2020). The Plant Family Brassicaceae: Introduction, Biology, And Importance. In *The Plant Family Brassicaceae* (pp. 1–43). Springer Singapore. https://doi.org/10.1007/978-981-15-6345-4_1
- S. S., D., V., W. M., & N. H., S. (2017). Cytoprotective Effects of *Lepidium sativum* Seed Extract on Liver and Pancreas of HFD/STZ Induced Type 2 Diabetic Mice. *International Journal of Pharmacognosy and Phytochemical Research*, 9(4). <https://doi.org/10.25258/phyto.v9i4.8121>
- Samaniego Sánchez, C., Troncoso González, A. M., García-Parrilla, M. C., Quesada Granados, J. J., López García de la Serrana, H., & López Martínez, M. C. (2007). Different radical scavenging tests in virgin olive oil and their relation to the total phenol content. *Analytica Chimica Acta*, 593(1), 103–107. <https://doi.org/10.1016/j.aca.2007.04.037>
- Selek, S., Koyuncu, I., Caglar, H. G., Bektas, I., Yilmaz, M. A., Gonel, A., & Akyuz, E. (2018). The evaluation of antioxidant and anticancer effects of *Lepidium Sativum* Subsp *Spinescens* L. methanol extract on cancer cells. *Cellular and Molecular Biology*, 64(3), 72–80. <https://doi.org/10.14715/cmb/2018.64.3.12>
- Sembiring, E. N., Elya, B., & Sauriasari, R. (2017). Phytochemical Screening, Total Flavonoid and Total Phenolic Content and Antioxidant Activity of Different Parts of *Caesalpinia bonduc* (L.) Roxb. *Pharmacognosy Journal*, 10(1), 123–127. <https://doi.org/10.5530/pj.2018.1.22>
- Sforcin, J. M., & Bankova, V. (2011). Propolis: Is there a potential for the development of new drugs? *Journal of Ethnopharmacology*, 133(2), 253–260. <https://doi.org/10.1016/j.jep.2010.10.032>
- Shah, M. B., Dudhat, V. A., & Gadhvi, K. V. (2021). *Lepidium sativum*: A potential functional food. *Journal of Ayurvedic and Herbal Medicine*, 7(2), 140–149. <https://doi.org/10.31254/jahm.2021.7213>
- Simmons, D. L., Botting, R. M., & Hla, T. (2004). Cyclooxygenase Isozymes: The Biology of Prostaglandin Synthesis and Inhibition. *Pharmacological Reviews*, 56(3), 387–437. <https://doi.org/10.1124/pr.56.3.3>
- Singh, B., Singh, S., Singh, B., Kitchlu, S., & Babu, V. (2019). Assessing Ethnic Traditional Knowledge, Biology and Chemistry of *Lepidium didymum* L., Lesser-Known Wild Plants of Western Himalaya. *Proceedings of the National Academy of Sciences, India Section B: Biological Sciences*, 89(3), 1087–1094. <https://doi.org/10.1007/s40011-018-1027-4>
- Sobhi, W., Derguine, R., Khenchouche, A., Rezgui, A., Tachour, R. A., Gaci, K., Cherif, D., Benguerba, Y., Rahmoune, H., Amrane, M., Abdelmelek, D. E., & Boutrid, N. (2023). Antidiabetic Effects of *Lepidium Sativum* Seeds. *Metabolism*, 142, 155475. <https://doi.org/10.1016/j.metabol.2023.155475>
- Süntar, I. (2020). Importance of ethnopharmacological studies in drug discovery: role of medicinal plants. *Phytochemistry Reviews*, 19(5), 1199–1209. <https://doi.org/10.1007/s11101-019-09629-9>
- Tan, Y., Chang, S. K. C., & Zhang, Y. (2017). Comparison of α -amylase, α -glucosidase and lipase inhibitory activity of the phenolic substances in two black legumes of different

- genera. *Food Chemistry*, 214, 259–268. <https://doi.org/10.1016/j.foodchem.2016.06.100>
- Telagari, M., & Hullatti, K. (2015). In-vitro α -amylase and α -glucosidase inhibitory activity of *Adiantum caudatum* Linn. and *Celosia argentea* Linn. extracts and fractions. *Indian Journal of Pharmacology*, 47(4), 425. <https://doi.org/10.4103/0253-7613.161270>
- Tshikororo, R. R., Ajao, A. A., & Moteetee, A. N. (2023). Exploring the Use of Indigenous Wild Vegetables by the Basotho People of Southern Africa: A Comprehensive Review of the Literature and Nutritional Analysis of Selected Species. *Foods*, 12(14), 2763. <https://doi.org/10.3390/foods12142763>
- Vane, J. R., & Botting, R. M. (1998). Anti-inflammatory drugs and their mechanism of action. *Inflammation Research*, 47(0), 78–87. <https://doi.org/10.1007/s000110050284>
- Vazifeh, S., Kananpour, P., Khalilpour, M., Eisalou, S. V., & Hamblin, M. R. (2022). Anti-inflammatory and Immunomodulatory Properties of *Lepidium sativum*. *BioMed Research International*, 2022(1). <https://doi.org/10.1155/2022/3645038>
- Xu, Y., Zhang, Z., Li, L., Joshi, M. K., Huang, N., Niu, J., & Lu, Y. (2013). Catechins play key role in green tea extract-induced postprandial hypoglycemic potential in vitro. *European Food Research and Technology*, 237(2), 89–99. <https://doi.org/10.1007/s00217-013-1945-6>
- Yan, Y., Li, Q., Shen, L., Guo, K., & Zhou, X. (2022). Chlorogenic acid improves glucose tolerance, lipid metabolism, inflammation and microbiota composition in diabetic db/db mice. *Frontiers in Endocrinology*, 13. <https://doi.org/10.3389/fendo.2022.1042044>
- Zainab, Khan, F., Alam, A., Rehman, N. U., Ullah, S., Elhenawy, A. A., Ali, M., Islam, W. U., Khan, A., Al-Harrasi, A., Ahmad, M., & Haitao, Y. (2025). Synthesis, anticancer, α -glucosidase inhibition, molecular docking and dynamics studies of hydrazone-Schiff bases bearing polyhydroquinoline scaffold: In vitro and in silico approaches. *Journal of Molecular Structure*, 1321, 139699. <https://doi.org/10.1016/j.molstruc.2024.139699>
- Zheng, Y., Yang, W., Sun, W., Chen, S., Liu, D., Kong, X., Tian, J., & Ye, X. (2020). Inhibition of porcine pancreatic α -amylase activity by chlorogenic acid. *Journal of Functional Foods*, 64, 103587. <https://doi.org/10.1016/j.jff.2019.103587>

Data File C:\CHEM32\1\DATA\POLYPHENOLS 14-1-2025 2024-12-11 21-14-48\013-1401.D
Sample Name: Dr.Esam LA.Me

```
=====
Acq. Operator   : SYSTEM                      Seq. Line   : 14
Acq. Instrument : hplc -2                     Location    : Vial 13
Injection Date  : 12/12/2024 3:13:52 AM      Inj         : 1
                                           Inj Volume  : 5.000 µl
Acq. Method     : C:\CHEM32\1\DATA\POLYPHENOLS 14-1-2025 2024-12-11 21-14-48\POLYPHENOL 2023.
M
Last changed    : 12/11/2024 9:14:52 PM by SYSTEM
Analysis Method : C:\CHEM32\1\DATA\POLYPHENOLS 14-1-2025 2024-12-11 21-14-48\POLYPHENOL 2023.
M (Sequence Method)
Last changed    : 2/5/2025 12:15:21 AM by SYSTEM
                (modified after loading)
Additional Info : Peak(s) manually integrated
```

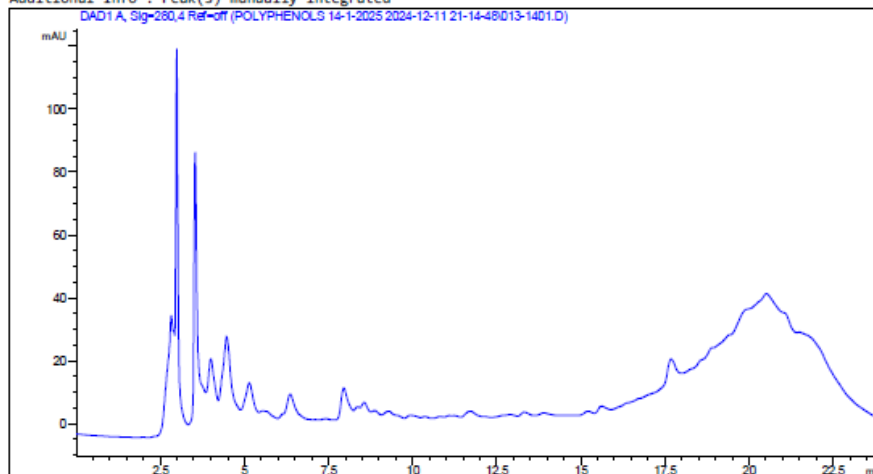


Figure S-1: HPLC Chromatogram of *L. africanum* methanol extract, showing the total phenolic and flavonoid content (µg/mg).

Data File C:\CHEM32\1\DATA\PP 8-10-2024 2024-10-08 16-07-33\001-0101.D
Sample Name: Polyphenols STD (1)

```
=====
Acq. Operator   : SYSTEM                      Seq. Line   : 1
Acq. Instrument : hplc -2                     Location    : Vial 1
Injection Date   : 10/8/2024 4:09:17 PM      Inj         : 1
                                           Inj Volume  : 5.000 µl
Acq. Method     : C:\CHEM32\1\DATA\PP 8-10-2024 2024-10-08 16-07-33\POLYPHENOL 2023.M
Last changed    : 10/8/2024 4:07:36 PM by SYSTEM
Analysis Method : C:\CHEM32\1\DATA\PP 8-10-2024 2024-10-08 16-07-33\POLYPHENOL 2023.M (
Sequence Method)
Last changed    : 10/9/2024 10:20:58 AM by SYSTEM
                (modified after loading)
Additional Info : Peak(s) manually integrated
```

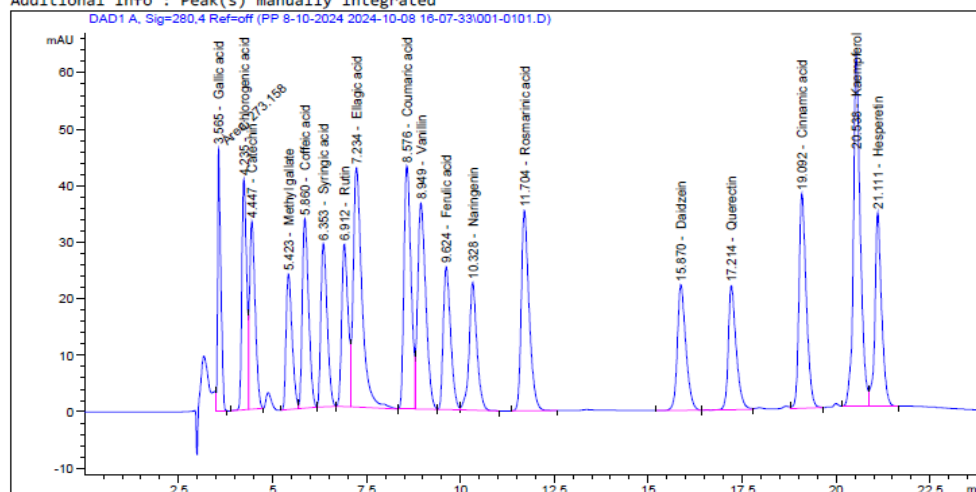


Figure S-2: HPLC Chromatogram of the polyphenols standards .

Table S-1: Evaluation of antioxidant of L.A. activity using ABTS. radical scavenging

Sample conc. (µg/ml)	ABTS scavenging %					ABTS scavenging %				
	3 Readings			Mean	S.D. (±)	3 Readings			Mean	S.D. (±)
	<i>L.A. methanol extract</i>					<i>Ascorbic acid</i>				
1000	83.16	85.09	84.26	84.17	0.97	98.13	98.78	98.06	98.32	0.40
500	76.34	79.53	78.14	78.00	1.60	95.02	95.42	96.31	95.58	0.66
250	71.96	72.88	71.32	72.05	0.78	91.86	91.97	92.15	91.99	0.15
125	63.8	65.49	64.07	64.45	0.91	86.31	86.74	87.89	86.98	0.82
62.5	54.91	55.23	53.85	54.66	0.72	80.42	79.53	80.94	80.30	0.71
31.25	36.78	38.02	35.14	36.65	1.44	72.96	71.85	73.12	72.64	0.69
15.6	27.19	29.41	27.68	28.09	1.17	63.88	64.19	64.19	64.09	0.18
7.8	21.37	22.13	20.64	21.38	0.75	54.09	53.67	56.28	54.68	1.40
3.9	15.28	16.04	15.28	15.53	0.44	46.21	44.82	46.57	45.87	0.92
2	10.45	10.67	9.85	10.32	0.42	37.07	35.49	38.12	36.89	1.32
1	6.71	5.94	5.23	5.96	0.74	28.42	26.84	29.47	28.24	1.32
0.5	1.89	2.16	2.43	2.16	0.27	19.86	19.65	21.38	20.30	0.94
0	0	0	0	0	0	0	0	0	0	0
	IC50					IC50				
	54.04	53.00	56.07	54.37	1.56	5.78	6.18	5.28	5.75	0.45

Table S-2: Evaluation of antioxidant of L.A. activity using FRAP.

Sample conc. (µg/ml)	ABTS scavenging %					ABTS scavenging %				
	3 Readings			Mean	S.D. (±)	3 Readings			Mean	S.D. (±)
	<i>L.A. methanol extract</i>					<i>Ascorbic acid</i>				
1000	89.43	90.57	88.62	89.54	0.98	93.47	94.05	94.31	93.94	0.43
500	80.57	81.32	80.19	80.69	0.58	89.62	90.53	90.53	90.23	0.53
250	72.38	73.45	71.86	72.56	0.81	84.59	85.23	86.14	85.32	0.78
125	60.51	62.38	58.27	60.39	2.06	76.14	77.89	78.06	77.36	1.06
62.5	49.69	48.73	46.08	48.17	1.87	70.87	71.94	72.51	71.77	0.83
31.25	37.08	36.41	35.29	36.26	0.90	61.34	65.29	64.85	63.83	2.16
15.6	26.45	27.98	26.74	27.06	0.81	54.93	56.04	55.42	55.46	0.56
7.8	20.78	19.83	19.05	19.89	0.87	39.75	41.53	40.68	40.65	0.89
3.9	13.92	13.25	11.43	12.87	1.29	31.42	34.21	33.56	33.06	1.46
2	6.71	6.48	6.25	6.48	0.23	24.59	26.08	25.37	25.35	0.75
1	4.08	3.92	3.64	3.88	0.22	19.56	20.91	20.68	20.38	0.72
0.5	2.45	2.31	1.96	2.24	0.25	13.48	15.32	14.05	14.28	0.94
0	0	0	0	0	0	0	0	0	0	0
	IC50					IC50				
	64.29	68.32	82.60	71.73	9.62	13.07	12.35	12.73	12.72	0.36

Table S-3: Evaluation of Antidiabetic of L.A. activity using α - Amylase Enzyme Inhibition (%)

Sample conc. ($\mu\text{g/ml}$)	α - Amylase Enzyme Inhibition (%)					α - Amylase Enzyme Inhibition (%)				
	(3 Replicates)			Mean	S.D. ($\pm$)	(3 Replicates)			Mean	S.D. ($\pm$)
	<i>L.A. methanol extract</i>					<i>Acarbose acid</i>				
	1 st	2 nd	3 rd			1 st	2 nd	3 rd		
1000	91.54	90.73	89.86	90.71	9.29	98.27	98.64	98.01	98.31	1.69
500	82.76	83.24	81.63	82.54	17.46	96.58	97.06	95.89	96.51	3.49
250	75.82	74.91	74.91	75.21	24.79	93.12	94.28	93.67	93.69	6.31
125	63.59	63.24	65.06	63.96	36.04	88.21	90.63	89.42	89.42	10.58
62.5	52.34	51.86	53.18	52.46	47.54	80.68	79.41	80.23	80.11	19.89
31.25	37.16	36.03	38.2	37.13	62.87	72.94	71.28	71.39	71.87	28.13
15.6	29.08	28.46	29.72	29.09	70.91	65.36	64.59	63.84	64.60	35.40
7.8	18.73	19.51	20.35	19.53	80.47	58.13	57.42	56.92	57.49	42.51
3.9	11.45	11.27	13.14	11.95	88.05	49.05	48.36	47.18	48.20	51.80
2	6.29	5.98	7.52	6.60	93.40	40.62	41.29	39.57	40.49	59.51
1	3.41	3.06	3.69	3.39	96.61	32.51	30.65	32.43	31.86	68.14
0.5	1.76	1.54	1.82	1.71	98.29	24.97	23.19	26.82	24.99	75.01
0	0	0	0	0		0	0	0	0	
	IC50					IC50				
	57.68	58.83	55.87	57.46	1.49	4.31	4.61	5.03	4.65	0.36

Table S-4: Evaluation of Anti-inflammatory of L.A. activity using Cox-1 enzyme inhibition (%)

Sample conc. ($\mu\text{g/ml}$)	COX-1 Enzyme Inhibition (%)					COX-1 Enzyme Inhibition (%)				
	(3 Replicates)			Mean	S.D. ($\pm$)	(3 Replicates)			Mean	S.D. ($\pm$)
	<i>L.A. methanol extract</i>					<i>Celecoxib drug</i>				
	1 st	2 nd	3 rd			1 st	2 nd	3 rd		
1000	92.03	92.46	91.89	92.13	7.87	97.64	97.23	96.87	97.25	2.75
500	87.64	88.31	86.47	87.47	12.53	93.56	93.14	92.85	93.18	6.82
250	82.75	84.69	81.23	82.89	17.11	89.12	88.71	87.92	88.58	11.42
125	75.86	77.28	74.19	75.78	24.22	85.03	84.95	83.16	84.38	15.62
62.5	69.42	70.54	67.85	69.27	30.73	81.36	80.92	78.93	80.40	19.60
31.25	60.54	63.18	59.43	61.05	38.95	73.59	71.87	70.26	71.91	28.09
15.6	51.98	52.37	51.54	51.96	48.04	61.34	62.16	61.34	61.61	38.39
7.8	38.17	39.42	37.18	38.26	61.74	50.63	51.95	50.87	51.15	48.85
3.9	29.46	31.63	28.88	29.99	70.01	43.28	44.39	43.85	43.84	56.16
2	21.08	22.19	20.67	21.31	78.69	35.16	36.24	34.92	35.44	64.56
1	14.92	15.87	14.53	15.11	84.89	26.93	27.8	25.74	26.82	73.18
0.5	8.75	9.58	8.49	8.94	91.06	19.42	21.83	19.42	20.22	79.78
0	0	0	0	0		0	0	0	0	
	IC50					IC50				
	14.48	14.17	14.76	14.47	0.30	7.47	6.79	7.32	7.19	0.35

Table S-5: Cytotoxicity Evaluation of L.A Against HepG-2

Sample conc. (µg/ml)	Viability (%)						Viability (%)					
	(3 Replicates)			Mean	Inhibitory %	S.D. (±)	(3 Replicates)			Mean	Inhibitory %	S.D. (±)
	<i>L.A. methanol extract</i>						Cisplatin Standard					
	1 st	2 nd	3 rd				1 st	2 nd	3 rd			
1000	2.64	1.87	2.39	2.30	97.70	0.39	0.81	0.94	0.87	0.87	99.13	0.07
500	6.93	5.64	6.85	6.47	93.53	0.72	3.17	3.42	2.96	3.18	96.82	0.23
250	18.76	17.59	18.47	18.27	81.73	0.61	8.29	8.57	7.83	8.23	91.77	0.37
125	34.68	35.72	33.51	34.64	65.36	1.11	15.32	16.08	14.27	15.22	84.78	0.91
62.5	51.97	53.06	52.84	52.62	47.38	0.58	21.79	22.93	20.54	21.75	78.25	1.20
31.25	65.42	66.89	67.13	66.48	33.52	0.93	30.45	31.79	28.32	30.19	69.81	1.75
15.6	73.81	75.43	76.09	75.11	24.89	1.17	37.18	36.26	34.59	36.01	63.99	1.31
7.8	84.19	84.19	85.32	84.57	15.43	0.65	43.21	44.05	40.71	42.66	57.34	1.74
3.9	91.73	92.36	93.17	92.42	7.58	0.72	52.37	51.13	50.34	51.28	48.72	1.02
2	98.67	98.59	99.06	98.77	1.23	0.25	60.78	59.32	58.29	59.46	40.54	1.25
1							69.83	68.14	68.14	68.70	31.30	0.98
0.5							76.13	75.06	74.98	75.39	24.61	0.64
0	100	100	100	100	0		100	100	100	100	0	
	IC50						IC50					
	69.62	73.53	71.68	71.61		1.96	4.91	4.52	4.04	4.49		0.44

Table S-6: Cytotoxicity Evaluation of L.A Against MCF-7

Sample conc. (µg/ml)	Viability (%)						Viability (%)					
	(3 Replicates)			Mean	Inhibitory %	S.D. (±)	(3 Replicates)			Mean	Inhibitory %	S.D. (±)
	<i>L.A. methanol extract</i>						Cisplatin Standard					
	1 st	2 nd	3 rd				1 st	2 nd	3 rd			
1000	4.07	3.85	4.21	4.04	95.96	0.18	0.83	0.96	0.88	0.89	99.11	0.07
500	13.74	13.12	14.68	13.85	86.15	0.79	3.46	3.71	3.92	3.70	96.30	0.23
250	29.03	28.46	30.71	29.40	70.60	1.17	8.03	8.69	9.14	8.62	91.38	0.56
125	44.96	42.78	45.83	44.52	55.48	1.57	16.37	18.24	18.53	17.71	82.29	1.17
62.5	76.02	74.23	77.49	75.91	24.09	1.63	24.52	26.03	27.31	25.95	74.05	1.40
31.25	85.94	84.71	87.85	86.17	13.83	1.58	32.19	33.46	34.06	33.24	66.76	0.95
15.6	93.28	92.83	94.39	93.50	6.50	0.80	40.56	41.82	42.39	41.59	58.41	0.94
7.8	99.15	98.76	99.02	98.98	1.02	0.20	47.08	48.23	49.12	48.14	51.86	1.02
3.9	100	100	100	100.00	0	0	56.27	55.92	57.03	56.41	43.59	0.57
2	100	100	100	100.00	0	0	61.88	63.15	65.03	63.35	36.65	1.58
1							69.84	70.49	71.81	70.71	29.29	0.99
0.5							77.16	75.82	77.16	76.71	23.29	0.77
0	100	100	100	100	0		100	100	100	100	0	
	IC50						IC50					
	114.86	110.65	116.77	114.09		3.13	6.56	6.90	7.37	6.94		0.40

Table S-7: Cytotoxicity Evaluation of L.A Against CACO2

Sample conc. (µg/ml)	Viability (%)						Viability (%)					
	(3 Replicates)			Mean	Inhibitory %	S.D. (±)	(3 Replicates)			Mean	Inhibitory %	S.D. (±)
	<i>L.A. methanol extract</i>						Cisplatin Standard					
	1 st	2 nd	3 rd				1 st	2 nd	3 rd			
1000	3.92	3.05	2.98	3.32	96.68	0.52	1.03	0.98	1.07	1.03	98.97	0.05
500	11.89	11.64	10.67	11.40	88.60	0.64	4.18	3.75	4.29	4.07	95.93	0.29
250	27.35	27.96	26.83	27.38	72.62	0.57	11.43	10.68	12.57	11.56	88.44	0.95
125	42.79	43.18	40.65	42.21	57.79	1.36	21.37	19.52	20.43	20.44	79.56	0.93
62.5	70.63	71.84	68.42	70.30	29.70	1.73	29.56	28.17	27.91	28.55	71.45	0.89
31.25	82.79	85.06	81.91	83.25	16.75	1.63	36.45	37.01	36.24	36.57	63.43	0.40
15.6	91.48	91.76	90.58	91.27	8.73	0.62	45.26	46.12	44.83	45.40	54.6	0.66
7.8	97.23	95.49	96.42	96.38	3.62	0.87	51.24	52.03	51.96	51.74	48.26	0.44
3.9	99.85	99.12	98.79	99.25	0.75	0.54	60.37	61.56	59.42	60.45	39.55	1.07
2	100	100	100	100.00	0	0	69.51	70.28	67.86	69.22	30.78	1.24
1							76.24	77.46	75.13	76.28	23.72	1.17
0.5							83.92	85.05	82.19	83.72	16.28	1.44
0	100	100	100	100	0		100	100	100	100	0	
	IC50						IC50					
	108.81	110.13	103.96	107.63		3.25	9.42	10.48	9.94	9.95		0.53



Analysis of Critical Buckling Moments in Steel I-Girders with Initial Imperfections

Amr B. Saddek | Brahim Bousalem | Saif Eldeen A.S. Yousef | Abbas M. A. Alshehari |
Abdullah Albogami | Ahmed M. Farag El Sheikh

Department of Civil Engineering, Faculty of Engineering, Al-Baha University, Al-Baha 65779, Saudi Arabia

(Received: 19th October 2025; Accepted: 3rd December 2025)

Abstract

The critical buckling moment is a fundamental parameter for the analysis of steel I-girders, particularly when accounting for initial imperfections that can significantly influence structural performance. This study presents a novel approach to accurately compute the critical buckling moments of steel I-girders by integrating the Spencer technique with finite element analysis (FEA) using ANSYS 20. This combined methodology leverages detailed deflection-load data from the FE model to apply the Spencer technique, which is traditionally used for plates, to the more complex I-girder geometry. A comprehensive parametric study was conducted to examine the influence of web slenderness (ranging from $h_w/t_w = 142$ to 200) and flange compactness (covering both compact and non-compact scenarios) at the critical moment. The results demonstrate that the proposed integrated approach provides a robust and precise estimation of the critical buckling moment, showing good agreement with established theoretical and numerical methods, thereby validating its application. Crucially, the findings provide specific insights into the required safety margins for I-girders with initial imperfections, offering engineers a practical tool for complying with design codes such as SBC 306 and ECP 205.

Keywords: Bending Stresses; Buckling Behavior; Theoretical Analysis; Steel I-girders; Plate Girders.



DOI:

(*) Corresponding Author:

Amr B. Saddek^{1,a}, Brahim Bousalem², Saif Eldeen A.S. Yousef^{3,b}, Abbas M. A. Alshehari^{4,c}, Abdullah Albogami^{5,*}, Ahmed M. Farag El Sheikh^{6,d}

^{1,2,3,4,5,6} Department of Civil Engineering, Faculty of Engineering, Al-Baha University, Al-Baha 65779, Saudi Arabia

* Corresponding author: albogami.a@bu.edu.sa (Abdullah Albogami) ORCID: 0009-0005-8540-7815

^a On Leave from the Department of Civil Engineering, Faculty of Engineering, Beni-Suef University, Egypt

^b On leave from the Civil Engineering Department, Faculty of Engineering, Aswan University, Egypt

^c On Leave from Department of Civil Engineering, Faculty of Engineering, Sana'a University, Yemen

^d On Leave from Department of Engineering Mathematics and Physics, Faculty of Engineering, Alexandria University, Alexandria, Egypt

Nomenclature

b_f	Flange width
c	The half-width of the flange
t_f	Flange thickness
d	Overall depth of girder
h_w	Web height
t_w	Web thickness of plate girder
w_o	Initial imperfection functions.
w	Deflections functions of plate.
H1	The first transformed variable, representing the deflection ratio
H2	The second transformed variable, representing the load-deflection ratio.
F1	A correction factor related to the total deflection
F2	A correction factor related to the initial imperfection

1. Introduction

Steel I-girders are fundamental components in structural engineering, valued for their high strength-to-weight ratio and efficiency in resisting bending moment and shear forces. However, their stability under load is a critical design consideration. Buckling, characterized by sudden lateral deflection or twisting, represents a significant failure mode, particularly under bending moments. The accurate determination of the critical buckling moment is therefore essential for ensuring the structural integrity and safety of these elements.

1.1 Initial Geometric Imperfections of Steel Plate Girders

The manufacturing and fabrication processes inherently introduce initial geometric imperfections in steel plate girders. These imperfections can significantly reduce the buckling capacity by leading to localized stress concentrations and premature failure [1]. Consequently, the accurate modeling and consideration of these initial defects are paramount in modern structural analysis.

Over the years, numerous studies have focused on quantifying and incorporating these imperfections into both experimental and numerical investigations. The rise of sophisticated finite element analysis (FEA) programs, such as ANSYS, has transformed the process of imperfections into a complex, strategic task [2-3]. However, current design guidelines, such as EN 1993-1-5 [2-4], recommend that the chosen imperfection should correspond to the mode of least resistance,

often employing buckling mode-affine or hand-defined sinusoidal geometric flaws [5-7]. Research has explored the use of various half-wavelengths to define local geometric imperfection shapes [8]. For instance, Boissonnade and Somja [9] showed that for a variety of cross-sections, setting the maximum imperfection amplitude to 0.1 times the plate thickness or the plate width divided by 200 resulted in negligible differences in local ultimate capacities. Eurocode 3 Part 1-5, which addresses plated structures [10], advises using an eigenmode shape obtained from an initial linear buckling analysis, scaled by a factor that correlates with the lowest ultimate strength [11-12].

More recent research continues to explore the complex interaction between imperfections and buckling behavior. Studies have investigated the influence of initial imperfections and residual stress on the lateral-torsional buckling of steel I-beams [13], while others have focused on the buckling strength of I-beams under extreme conditions, such as elevated temperatures [14]. Furthermore, the effect of initial geometric imperfections on the ultimate and post-buckling shear strengths of I-girders with web discontinuities has also been a subject of recent investigation [15]. The experimental and numerical analysis of high-strength stainless steel I-girders further highlights the ongoing need for accurate imperfection modeling in advanced materials [16].

The analysis of critical buckling moments in steel I-girders with initial defects is the primary goal of this study. The study examines how the size, shape, and distribution of imperfections affect critical buckling performance using both analytical techniques and numerical simulations.

1.2 Using the Southwell and Spencer Techniques to Calculate the Buckling Load.

The Southwell method [17] was developed to predict the buckling load of initially flawed columns without requiring failure testing. It relies on a specific linear relationship between the deflection-to-load ratio and the deflection itself, derived from the load-deflection data [18-20]. However, experiments have shown that the Southwell approach can occasionally produce non-linearities, particularly at low and high load categories [21].

To address these limitations, Spencer and Walker [21] proposed an alternative technique, known as the Spencer technique, which uses "pivot points" to linearize the data and provide a more robust estimation of the critical load for plates with minor flaws. This technique has proven to be a valuable tool for extracting the elastic critical load from experimental or numerical load-deflection data, especially in the presence of imperfections.

The current study aims to compute the critical buckling moments for steel I-girders by integrating the Spencer technique with deflection-load data obtained from finite element program analysis (ANSYS). This combined approach allows for a precise estimation of the elastic buckling load for plate girders under pure moment, considering the effect of initial imperfections and boundary conditions. A comprehensive parametric analysis is conducted, considering both material properties and geometric characteristics of the girders. Finally, the precision of applying these techniques is verified by judgment with several methods. The novelty of this work lies in the systematic application of the Spencer technique to a wide range of FE models of I-girders with varying geometric imperfections, providing a refined methodology for stability analysis relevant to modern design codes like the Saudi Building Code (SBC 306 CR) [22] and the Egyptian Code (ECP 205) [23].

While previous studies have focused on either finite element modeling of I-girder buckling or the theoretical application of techniques such as Southwell's to simple plates, a significant gap remains in the integrated, practical application of advanced theoretical methods to complex FEA results for I-girders with imperfections. Specifically, the Spencer technique, which offers a robust method for estimating critical loads from load-deflection data, has not been systematically applied to the numerical output of full-scale I-girder models. The primary novelty of this research is the pioneering integration of the Spencer technique with finite element simulation (ANSYS 20) to accurately determine the critical buckling moments of steel I-girders with initial imperfections. This combined approach not only enhances the precision of critical moment prediction but also provides a novel, validated methodology that can be adopted by researchers and practitioners to bridge the gap between theoretical stability analysis and complex numerical modeling in structural engineering.

2. Research Strategy and Methodology

The finite element analysis was performed using ANSYS Mechanical APDL Academic Research Version 20.0, for non-commercial academic research purposes. This combined approach significantly improves prediction accuracy while offering valuable insights into the stability and performance of structural components under diverse loading conditions. The detailed deflection analysis provided by ANSYS 20 highlights key patterns essential for understanding material buckling behavior, and the refinement offered by the Spencer technique ensures that the results are both precise and applicable in practical engineering scenarios.

2.1 Finite Element Modeling

ANSYS 20 was used to create precise finite element models that included all relevant characteristics, including

nodes, elements, material properties, dimensions, and boundary conditions, to theoretically analyze how thin plate girders would behave under bending force.

To ensure accuracy in replicating the actual structural dimensions, the modeling procedure began by defining the plate girder's geometric parameters, such as flange width, web height, web thickness, and overall girder length. Young's modulus, Poisson's ratio, and yield strength were among the material attributes carefully selected to represent the steel's physical characteristics.

Boundary conditions were applied to simulate realistic support and loading scenarios, including lateral support and simply supported ends. The meshing of the model was carried out at a high density to ensure precise node and element distributions, capturing intricate stress and deflection patterns. This systematic approach ensures that the ANSYS models accurately replicate the physical behavior of slender plate girders under bending, providing a robust foundation for analyzing their critical buckling behavior.

2.1.1 Building models and analysis

For the 3D modeling of the I-girder, the SOLID185 Structural Solid element was utilized. This element, illustrated in Figure (1), is an eight-node element with three degrees of freedom per node, capable of handling complex behaviors such as plasticity, large deflection, and large strain analysis, which are essential for accurately simulating the buckling phenomenon.

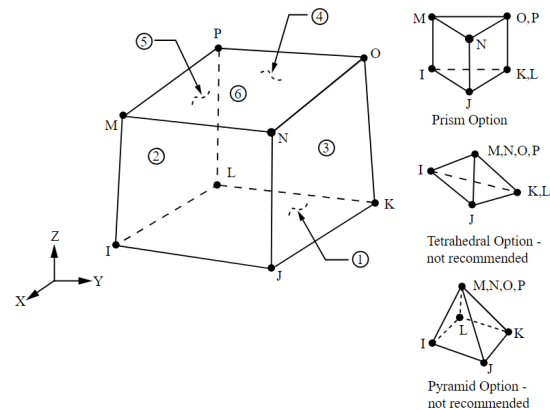


Figure 1: Homogeneous Structural Solid Geometry SOLID185

2.1.2 Verification of the Finite Element Model:

The reliability of the FE model was established through a two-step process: (1) Model Verification (Mesh Sensitivity) and (2) Model Validation (Comparison with Theoretical Solution). Model Verification (Mesh Sensitivity Analysis): The accuracy of the finite element analysis was first confirmed through a mesh sensitivity

study. This involved testing a sample plate girder model under the same loading conditions using both a coarse mesh and a fine mesh (with a 30% increase in density). The comparison showed that the difference in the critical output parameter (peak stress) between the two meshes was negligible, at only 0.7%. To optimize computational efficiency without sacrificing accuracy, the coarser mesh was selected for the subsequent parametric study. Model Validation (Comparison with Theoretical Solution): The model was validated by comparing its results against a well-established theoretical solution for a simply supported beam under point loads. Specifically, the maximum deflection (δ) obtained from the FE model was compared to the theoretical deflection calculated using the standard beam theory formula:

$$\delta = \frac{PL^3}{48EI} + \frac{kPL}{4GA}$$

As shown in Figure (2), the maximum deflection obtained from the FE model was 0.001891, which resulted in a minimal percentage error of 1.6% when compared to the theoretical solution ($\delta=0.00186\text{cm}$). This close agreement confirms the accuracy and reliability of the chosen element type, mesh density, and boundary conditions for the subsequent parametric study.

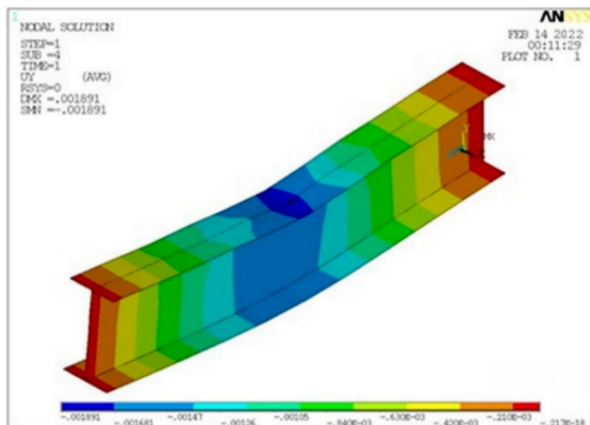


Figure (2) Displacement at Y direction for vitrified model

2.2 Parameters of the analytical model

This section of the study presents a numerical investigation using finite element analysis, applying the Spencer technique to simulated data. The primary variable examined was the depth-to-web thickness ratio of girders, ranging from 200 to 142, with three ratios representing slender webs and five ratios representing the outstanding length of the flange for plate girders, varying from 5.8 to 9.8 to cover both compact and non-compact flange scenarios. All these cases were evaluated in accordance with the Saudi Building Code (SBC306) [24-25] and the Egyptian Code (ECP205) [25]. Additionally, this study included variations in the aspect ratio of plate girder panels, considering aspect ratios of 1 and 0.6, with initial

imperfections introduced as percentages of web thickness (20% and 40%). The study ultimately highlights the most influential cases, which will be discussed in subsequent sections.

The following parameters of the plate girder's cross-section variation were considered in the theoretical analysis and were summarized in Tables 1 and 2:

Table (1) Plate girder model dimensions for cases of compact flanges

Model	h_w	t_w	b_f	t_f	h_w/t_w	c/t_f
ACMF1	100	0.5	24	2	200	5.875
ACMF2	100	0.5	24	1.8	200	6.52778
ACMF3	100	0.5	24	1.6	200	7.34375
BCMF1	100	0.6	24	2	166	5.85
BCMF2	100	0.6	24	1.8	166	6.5
BCMF3	100	0.6	24	1.6	166	7.3125
CCMF1	100	0.7	24	2	142	5.825
CCMF2	100	0.7	24	1.8	142	6.47222
CCMF3	100	0.7	24	1.6	142	7.28125

*All cases are studied for aspect ratio =0.6 and initial imperfection of web =40% of the web thickness

Table (2) Plate girder model dimensions for cases of non-compact flanges

Model	h_w	t_w	b_f	t_f	h_w/t_w	c/t_f
ANC1	100	0.5	24	1.4	200	8.39286
ANCF2	100	0.5	24	1.2	200	9.79167
BNCF1	100	0.6	24	1.4	166	8.35714
BNCF2	100	0.6	24	1.2	166	9.75
CNCF1	100	0.7	24	1.4	142	8.32143
CNCF2	100	0.7	24	1.2	142	9.70833

*All cases are studied for aspect ratio =0.6 and initial imperfection of web =40% of the web thickness

The analytical model used for the FE simulations is a simply supported symmetric girder subjected to two-point loading at the third locations, which creates a pure bending moment region in the central span. Figure (3) provides a schematic representation of this setup, clearly defining the basic geometric parameters (b_f , t_f , h_w , t_w , etc.) used in the analysis and summarized in Tables (1) and (2).

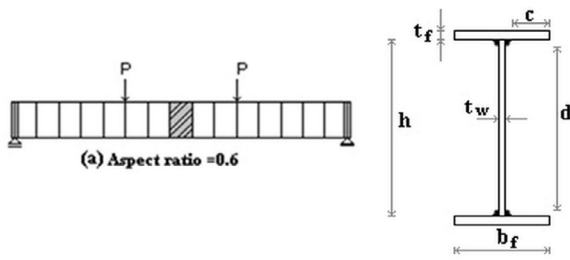


Figure (3) Basic Parameters of the analytical model

3. Analysis of theoretical results and discussions

Evaluating critical buckling moments for plate girders under pure bending is a crucial aspect of structural stability analysis, and the Spencer technique provides an effective framework for this purpose. This method integrates theoretical principles with computational precision to evaluate the moment at which the girder transitions from stability to instability. The critical buckling behavior of thin plate girders was examined in this study using the Spencer technique, which considered the geometry, material properties, and boundary conditions of these girders.

3.1 Evaluating critical buckling moment for slender I-girder with compact flange.

Section 3.1 presents the application of the Spencer technique to the FEA results for slender I-girders with compact flanges. Figures (4-a) through (6-c) illustrate the linear relationship between H1 and H2 for various geometric cases (e.g., =200, =167 and =143). The critical buckling load (P_{cr}) for each case is derived directly from the slope of the best linear fit shown in these figures, which is a key step in determining the critical buckling moment.

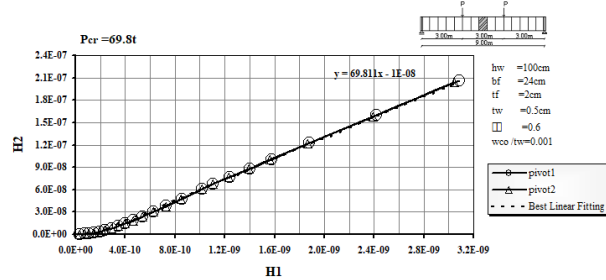


Figure (4-a) H1-H2 Relationship for the evaluation of critical moment from Spencer technique (ACMF1, =200, $\phi=0.6$)

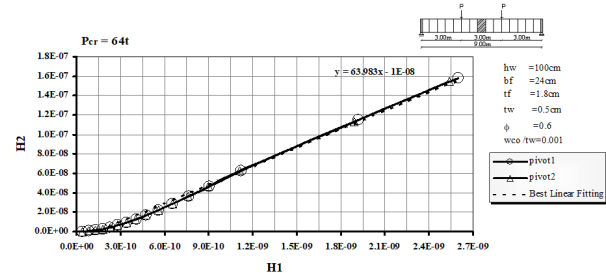


Figure (4-b) H1-H2 Relationship for the evaluation of critical moment from Spencer technique (ACMF2, =200, $\phi=0.6$)

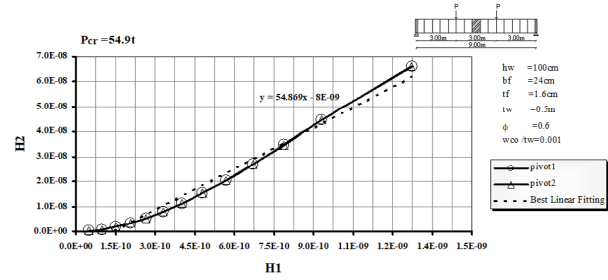


Figure (4-c) H1-H2 Relationship for the evaluation of critical moment from Spencer technique (ACMF3, =200, $\phi=0.6$)

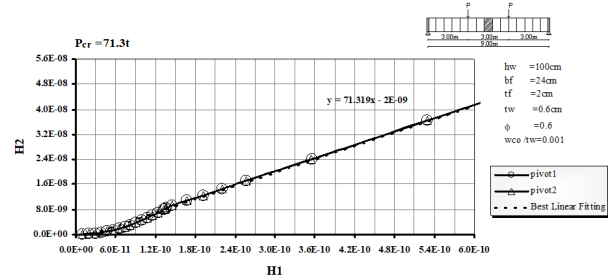


Figure (5-a) H1-H2 Relationship for the determination of critical load from Spencer technique (BCMF1, =167, $\phi=0.6$)

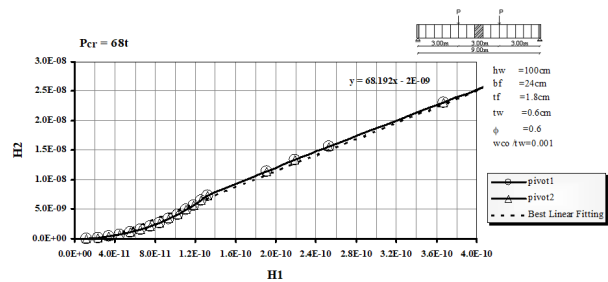


Figure (5-b) H1-H2 Relationship for the determination of critical load from Spencer technique (BCMF2, =167, $\phi=0.6$)

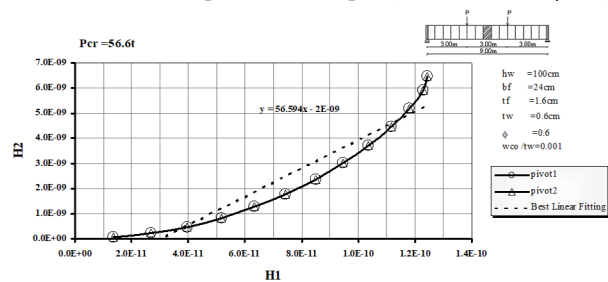


Figure (5-c) H1-H2 Relationship for the determination of critical load from Spencer technique (BCMF3, =167, $\phi=0.6$)

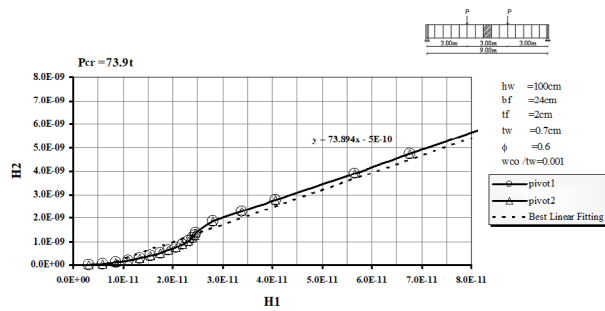


Figure (6-a) H1-H2 Relationship for the determination of critical load from Spencer technique (CCMF1, =143, $\phi=0.6$)

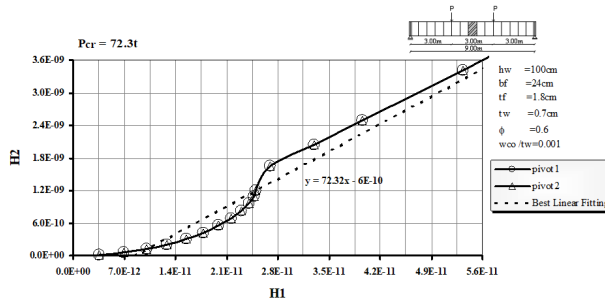


Figure (6-b) H1-H2 Relationship for the determination of critical load from Spencer technique (CCMF2, =143, $\phi=0.6$)

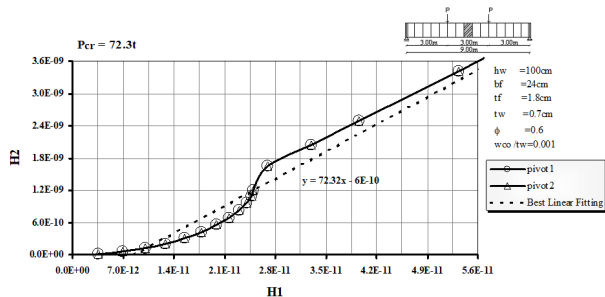


Figure (6-c) H1-H2 Relationship for the determination of critical load from Spencer technique (CCMF3, =143, $\phi=0.6$)

From previous figures, it was noticed that all cases of compact flange were aligned with the best linear fitting from the Excel program at Figs (4-a), (4-b), (4-c), and Figs (5-a), (5-b) except Fig. (5-c), that when applying Spencer technique, the relation between H1 and H2 were not linear as the compactness of flange approaches to the case of the non-compact flange. Also, it was noticed in Fig. (6-b) and Fig. (6-c), that when applying the Spencer technique, the relation between H1 and H2 was not linear as the compactness of the flange approaches the case of the non-compact flange. The critical load produced from applying this technique is summarized in Table 3) as follows.

Table (3) Critical load of Plate girder models with compact flanges using the Spencer technique

Model	h_w	t_w	b_f	t_f	h_w/t_w	c/t_f	P_{cr}
ACM1	100	0.5	24	2	200	5.875	69.8
ACM2	100	0.5	24	1.8	200	6.52778	64
ACM3	100	0.5	24	1.6	200	7.34375	54.9
BCM1	100	0.6	24	2	166	5.85	71.3
BCM2	100	0.6	24	1.8	166	6.5	68
BCM3	100	0.6	24	1.6	166	7.3125	56.6
CCM1	100	0.7	24	2	142	5.825	73.9
CCM2	100	0.7	24	1.8	142	6.47222	72.3
CCM3	100	0.7	24	1.6	142	7.28125	67

The observed reduction in the critical buckling moment with increasing web slenderness (h_w/t_w) is a direct consequence of the reduced flexural and shear stiffness of the web plate. According to classical plate buckling theory, the critical stress of a plate is inversely proportional to the square of its slenderness. As h_w/t_w increases, the web becomes more susceptible to local web buckling under the compressive stresses induced by the bending moment. The successful application of the Spencer technique, as evidenced by the clear linear relationship in the H1-H2 plots (Figures 6-8), validates its utility for extracting the elastic critical load from non-linear FEA data. The technique's ability to use 'pivot points' effectively filters out the non-linear effects caused by the initial imperfections and the onset of plasticity, which typically plague the traditional Southwell plot at high and low loads. By isolating elastic behavior, the Spencer method provides a robust and reliable estimate of the theoretical elastic critical moment, which is a crucial input for design code formulas that account for inelastic and post-buckling reserve strength.

3.2 Evaluating critical buckling moment for slender I-girder with non-compact flange

In this section, Figs (7-a), (7-b), Figs (8-a), (8-b), and Figs (9-a), (9-b) represent relationships between H1 and H2 for the two cases of non-compact flange with $=200$, $=167$ and $=143$, respectively. All cases with an aspect ratio ($\phi=0.6$) and an initial imperfection were 40% of the web thickness.

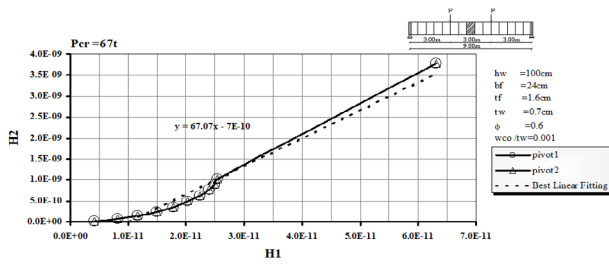


Figure (7-a) H1-H2 Relationship for the determination of critical load from Spencer technique (NCF1, =200, $\phi=0.6$)

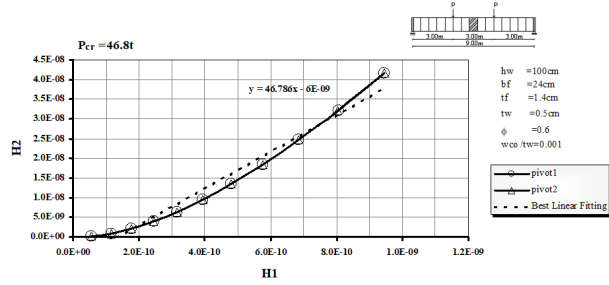


Figure (7-b) H1-H2 Relationship for the determination of critical load from Spencer technique (NCF2, =200, $\phi=0.6$)

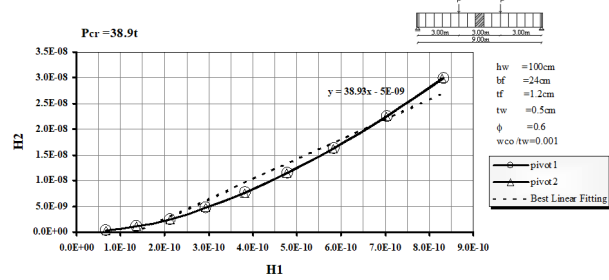


Figure (8-a) H1-H2 Relationship for the determination of critical load from Spencer technique (BNCF1, =167, $\phi=0.6$)

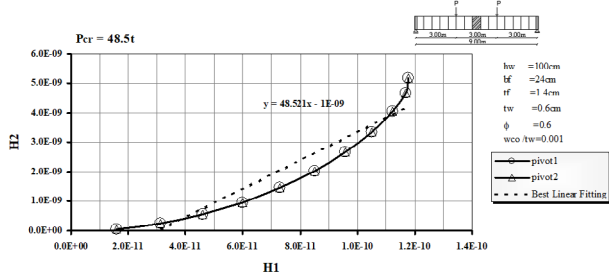


Figure (8-b) H1-H2 Relationship for the determination of critical load from Spencer technique (BNCF2, =167, $\phi=0.6$)

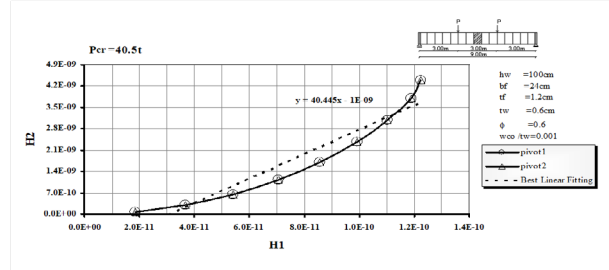


Figure (9-a) H1-H2 Relationship for the determination of critical load from Spencer technique (CNC1, =143, $\phi=0.6$)

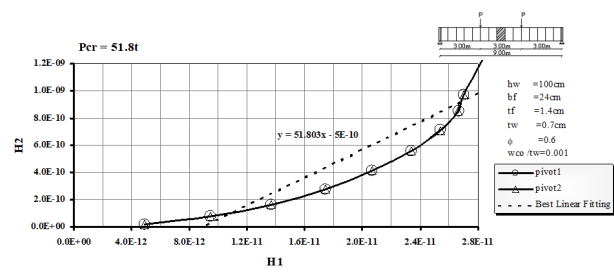


Figure (9-b) H1-H2 Relationship for the determination of critical load from Spencer technique (CNC2, =143, $\phi=0.6$)

From previous figures, it was noticed that all cases of non-compact flange were not correctly aligned with the best linear fitting from the Excel program at Figs (7-a), Figs (7-b), Figs (8-a), (8-b), and Figs (9-a), (9-b). It was noticed that when applying the Spencer technique, the relation between H1 and H2 was not linear, as in the case of the compact flange. This resulted from the constraint of the flange to the web transmitted from the case of fixed to partially fixed [26-27]. The critical load produced from applying this technique is summarized in Table 4 as follows: -

Table (4) Critical load of Plate girder models with non-compact flanges using the Spencer technique

Model	h_w	t_w	b_f	t_f	$h_w/t_w=$	c/t_f	P_{cr}
ANC1	100	0.5	24	1.4	200	8.39286	46.8
ANC2	100	0.5	24	1.2	200	9.79167	38.9
BNC1	100	0.6	24	1.4	166	8.35714	48.5
BNC2	100	0.6	24	1.2	166	9.75	40.5
CNC1	100	0.7	24	1.4	142	8.32143	51.8
CNC2	100	0.7	24	1.2	142	9.70833	52.3

The flange slenderness ratio (c/t) is a critical factor because the compression flange provides the primary lateral stiffness required to resist LTB. The critical moment is susceptible to the flange's ability to remain stable. When the flange slenderness increases (i.e., the flange becomes less compact), it becomes prone to local flange buckling before the overall LTB of the girder can be fully mobilized. This premature local buckling effectively reduces the cross-sectional area and the moment of inertia of the compression flange, leading to a reduction in the effective lateral stiffness of the girder. Therefore, the girder reaches its critical buckling state at a lower applied moment, confirming the necessity of design code limits (such as those in SBC 306 and ECP 205) on flange slenderness to ensure the full LTB capacity is achieved.

3.3 Comparison results of the present work with the load square deflection method

According to Venkataramaiah and Roorda [28], the load vs. lateral displacement squared approach can be used to calculate the elastic critical buckling stress. The elastic buckling load in the case of pure compression is represented by the intersection of the tangent with the load axis, which is drawn to the curve in the post-buckling area in this method. Furthermore, linear curve fitting in the post-buckling range yields the experimental post-buckling slope of the load versus maximum squared web deflection (P versus w^2), which sheds light on buckling behavior and structural stability [14-15, 29-30]. Table 5 and Table 6 show a comparison between the present method and the load square deflection method: -

Table (5) Comparison results of the present work with the load square deflection method for a plate girder with a compact flange

Model	h_w/t_w	c/t_f	Pcr (P.W.)	Pcr (L.S.D.M)
ACM1	200	5.875	69.8	69
ACM2	200	6.52778	64	63
ACM3	200	7.34375	54.9	57
BCM1	166	5.85	71.3	72
BCM2	166	6.5	68	66
BCM3	166	7.3125	56.6	60
CCM1	142	5.825	73.9	75
CCM2	142	6.47222	72.3	69
CCM3	142	7.28125	67	63

Table (6) Comparison results of present work with load square deflection method for plate girder with non-compact flange

Model	=	c/	Pcr (P.W.)	Pcr (L.S.D.M)
NC1	200	8.39286	46.8	51
NC2	200	9.79167	38.9	44
NC1	166	8.35714	48.5	55
NC2	166	9.75	40.5	49
NC1	142	8.32143	51.8	55
NC2	142	9.70833	52.3	51

The presence of initial geometric imperfections, modeled as a percentage of the web thickness, fundamentally alters the girder's response from a bifurcation problem to a stability limit problem. In a theoretically perfect girder, buckling occurs at the critical load (P_{cr}) through bifurcation. However, an imperfect girder begins to deflect immediately upon loading. The initial imperfection introduces an eccentricity to the applied load, creating secondary bending moments ($P \setminus w$) from the very start. These secondary moments accelerate the

growth of lateral deflection, causing the girder to reach its ultimate capacity (the critical moment) at a load significantly lower than the theoretical elastic critical load. The Spencer technique successfully captures this behavior by using the load-deflection data to extrapolate the theoretical critical load, which is a key strength of the methodology in the context of real-world, imperfect structures.

4. Conclusions

In this study, we successfully computed the critical buckling moments for steel I-girders with initial imperfections by pioneering the integration of the Spencer technique with finite element analysis (ANSYS 20). This novel approach proved to be a robust and precise method for stability analysis, particularly for complex structural geometries where traditional analytical methods are limited. The comprehensive parametric study, which varied web slenderness and flange compactness, yielded several key findings. Specifically, the results confirmed that increasing the web slenderness ratio (λ) significantly reduces the critical buckling moment, underscoring the critical role of web geometry in stability. Furthermore, the analysis demonstrated that the Spencer technique, when applied to FEA-derived data, provides a reliable estimation of the critical load that aligns well with established design code requirements (SBC 306 and ECP 205), thus validating the proposed methodology. The study's primary contribution lies in offering a practical, verified numerical tool for structural engineers to assess the stability of I-girders under pure bending, explicitly accounting for initial imperfections. This methodological advancement enables a more rigorous assessment of I-girder stability, providing engineers with the precision needed to meet the stringent requirements of modern design codes, such as SBC 306 and ECP 205, particularly in the presence of manufacturing imperfections.

5. References

- [1] L. Gérard, L. Li, M. Kettler, and N. Boissonnade, "Recommendations on the geometrical imperfections definition for the resistance of I-sections," *J. Constr. Steel Res.*, vol. 162, p. 105716, 2019.
- [2] EN 1993-1-5:2005, *Eurocode 3: Design of Steel Structures - Part 1-5: Plated Structural Elements*. Brussels, Belgium: European Committee for Standardization (CEN), 2006.
- [3] Albogami, Abdullah. "Development of Design Method for Fiber Reinforced Slab on Ground." (2023).
- [4] S. Kovacevic, N. Markovic, D. Sumarac, and R. Salatic, "Unfavorable geometric imperfections in steel plate girders subjected to localized loads," *Thin-Walled Struct.*, vol. 161, p. 107412, 2021.

- [5] B. Kovesdi, B. J. Mecseri, and L. Dunai, "Imperfection analysis on the patch loading resistance of girders with open section longitudinal stiffeners," *Thin-Walled Struct.*, vol. 123, pp. 195–205, 2018.
- [6] J. A. Chica, J. T. San Jose, F. Millanes, and J. M. Manso, "Recommendations on imperfections in the design of plated structural elements of bridges," *J. Constr. Steel Res.*, vol. 86, pp. 183–194, 2013.
- [7] C. Couto and P. V. Real, "Numerical investigation on the influence of imperfections in the local buckling of thin-walled I-shaped sections," *Thin-Walled Struct.*, vol. 135, pp. 89–108, 2019.
- [8] R. Cruise and L. Gardner, "Measurement and prediction of geometric imperfections in structural stainless-steel members," *Struct. Eng. Mech.*, vol. 24, no. 1, pp. 63–89, Sep. 2006.
- [9] N. Boissonnade and H. Somja, "Influence of imperfections in FEM modeling of lateral torsional buckling," in *Proc. Annual Stability Conf.*, SSRG, Grapevine, TX, 2012.
- [10] EN 1090-2:2008+A1, *Execution of Steel Structures and Aluminum Structures - Part 2: Technical Requirements for Steel Structures*. Brussels, Belgium: European Committee for Standardisation, 2011.
- [11] L. Gérard, L. Li, M. Kettler, D. White, and N. Boissonnade, "Recommendations on the material imperfections definition for the resistance of I-sections," *Thin-Walled Struct.*, Submitted in 2019.
- [12] Albogami, Abdullah, Nakin Suksawang, Ahmed Alsabbagh, and Emad Alshammari. "Prediction of flexural capacity of fiber reinforced concrete slab on ground." *Journal of Umm Al-Qura University for Engineering and Architecture* (2025): 1-11.
- [13] A. S. de Carvalho, M. A. P. V. de Lacerda, and J. M. M. S. de Oliveira, "Assessment of lateral-torsional buckling in steel I-beams considering initial imperfections and residual stresses," *Thin-Walled Struct.*, vol. 175, p. 109195, 2022.
- [14] T. Q. Nguyen, T. A. Helwig, and M. D. Engelhardt, "Buckling strength of steel I-beams subjected to uniform bending moment at elevated temperatures," *Eng. Struct.*, vol. 308, p. 117865, 2024.
- [15] Almasri, Amin, and Mohammad Nadeem Akhtar. "Strengthening of steel I-Section girder web with depth discontinuity against localized buckling," *Fracture and Structural Integrity* 19, no. 74 (2025): 342-357.
- [16] Y. Wang, J. Zhang, and L. Han, "Experimental and numerical study on lateral-torsional buckling of high-strength stainless steel I-girders," *Thin-Walled Struct.*, vol. 201, p. 109888, 2025.
- [17] R. V. Southwell, "On the analysis of experimental observations in the problems of elastic stability," *Proc. Royal Philosophical Soc. London, Ser. A*, vol. 135, pp. 601, Apr. 1932.
- [18] B. S. Chen, J. A. Yura, and K. H. Frank, "Top lateral bracing of steel U-shaped girders," Report No. FHWA/TX-02/1395-2F, Revision Jan. 2002.
- [19] Alshammari, Emad, Mang Tia, Othman Alanquri, Abdullah Albogami, Ahmed Alsabbagh, and Raid S. Alrashidi. "Thermal and Flood Resiliency Evaluation of Rigid Pavement Using Various Pavement Characteristics." *CivilEng* 6, no. 2 (2025): 22.
- [20] A. B. Saddek, A. Y. Hamed, and A. S. Tohamy, "Behavior of Stiffened Cold-Formed Steel Channel Sections Under Axial Compressive Force," *Minia J. Eng. Technol. (MJET)*, vol. 44, no. 1, Jan. 2025.
- [21] H. H. Spencer and A. C. Walker, "Critique of Southwell plots with alternative methods," *J. Exp. Mech.*, vol. 15, pp. 303–310, 1975.
- [22] Saudi Building Code (SBC 306 CR), *Structural Requirements for Steel Structures*. Riyadh, Saudi Arabia: Saudi Standards, Metrology and Quality Organization (SASO), 2024.
- [23] Egyptian Code of Practice for Steel Construction and Bridges, L.F.R.D. Cairo, Egypt: Research Center for Housing and Physical Planning, 2008.
- [24] T. H. Abdel-Lateef, A. B. Saddek, and A. S. Tohamy, "Critical shear stress for steel plate girder with web cutouts," *Minia J. Eng. Technol. (MJET)*, vol. 34, no. 1, Jan. 2015.
- [25] A. M. F. El Sheikh, "Critical Buckling of Orthotropic Clamped Plate Resting on Elastic Foundation," *Int. J. Eng., Sci. Math.*, vol. 12, no. 11, Nov. 2023.
- [26] K. R. Venkataramaiah and J. Roorda, "Analysis of local plate buckling data," in *Proc. 6th Int. Specialty Conf. Cold-formed of Steel Struct.*, St. Louis, pp. 45-74.
- [27] M. R. Bambach and K. J. R. Rasmussen, "Tests of Unstiffened Elements under Combined Compression and Bending," Research Report No R818, May 2002.
- [28] M. R. Bambach and K. J. R. Rasmussen, "Experimental Techniques for Testing Unstiffened Plates in Compression and Bending," *J. Exp. Mech.*, vol. 44, no. 1, Feb. 2004.

- [29] A. B. Saddek, "Theoretical investigation of shear buckling for hybrid steel plate," *World Appl. Sci. J.*, vol. 2, pp. 284-302, Mar. 2015.
- [30] Albogami, Abdullah, Sabry Fayed, Mohamed Ghalla, Mohamed E. Nawar, and Ahmed Badr el-din. "Effects of type and gradation of coarse aggregates on tensile strength of concrete with different grades: an experimental investigation." *Innovative Infrastructure Solutions* 10, no. 6 (2025): 236.
- [31] A. B. Saddek, "Buckling of web plate in plate girder bridge," *Ph.D. dissertation*, El-Minia University, 2006.
- [32] R. Szilard, *Theories and Applications of Plate Analysis*. Hoboken, NJ: John Wiley & Sons, Inc., 2004.

6. Appendixes

Appendix A: derivations of Southwell and Spencer techniques

A.1 Using the Southwell method to calculate the buckling load

The Southwell method, while foundational, often exhibits non-linearities in the load-deflection plot, particularly at low and high load ranges, which can lead to inaccuracies in the extrapolated critical load [21]. To overcome these limitations, Spencer and Walker [21] proposed an alternative graphical method, known as the Spencer technique, for determining the elastic critical load (P_{cr}) of plates with minor initial imperfections. This technique is particularly robust as it allows for the use of "pivot points" (data points deemed highly accurate) to linearize the data and improve the extrapolation. The method begins with the fundamental relationship for the deflection of an imperfect plate; Southwell made the following assumption about the column's initial shape: a half-sine wave with an initial imperfection at mid-height equal to w_o as: -

$$w_o = A_o \sin \frac{\pi}{L} x$$

Based on this initial shape, the load-deflection relationship can then be roughly represented as [31-32]: -

$$w_t = w_o + w = \left(\frac{1}{1 - P/P_{cr}} \right) \cdot w_o$$

Solving in terms of yields.

$$w = \frac{P}{P_{cr}} \left(\frac{w_o}{1 - P/P_{cr}} \right)$$

Rearranging further gives.

$$\frac{w}{P} = \frac{1}{P_{cr}} w + \frac{1}{P_{cr}} w_o$$

Where: -

w	Deflections functions of plate
w_o	Initial imperfection functions
w_t	Total deflections of plate

The relationship between w/P and is linear within the elastic range, allowing the critical load to be determined from the inverse slope of the line. Figure (1) illustrates this graphical method, showing how the linear extrapolation of the data points yields the anticipated buckling load at the intercept."

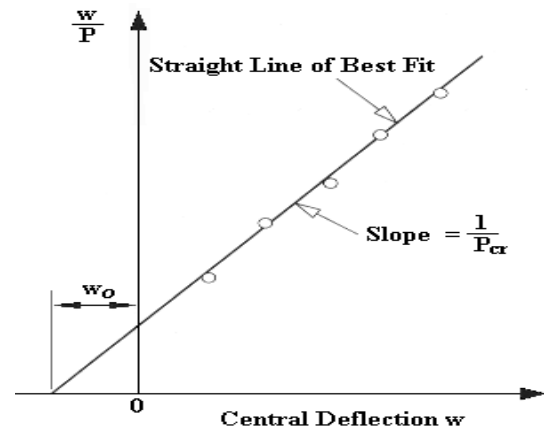


Figure (A1) Southwell plot

6.1 Spencer technique for evaluating critical load

The Spencer technique is based on a modified form of the load-deflection relationship for an imperfect plate, which can be expressed in terms of the total deflection (w) and the applied load (P). The core of the method involves transforming the raw data into two new variables, $H1$ and $H2$, which are designed to exhibit a linear relationship when plotted against each other. Any theoretical boundary condition cannot be precisely reproduced in an actual experimental setup, especially for plate tests. In addition, compressive test results may be very susceptible to imperfections [3,12,22,30] and, consequently, to the real physical boundary conditions. Nevertheless, experiments reveal that the Southwell approach occasionally produces nonlinearities that fall into the low-load and higher-load categories. The former may be caused by intrinsic zero errors in the deflection measurements, which can lead to significant mistakes in the apparent critical load, as demonstrated.

Walker [21] demonstrated that a decent approximation that is true well into the post-critical region for rectangular plates across a wide variety of aspect ratios, boundary conditions, and loads as: -

$$\left[\left(\frac{w}{t}\right)^2 + \left(\frac{w_o}{t}\right)^2\right]^{1/2} = A_c \alpha + B_c \alpha^3$$

$$\alpha = \left(\frac{P}{P_{cr} - 1} + \frac{w_o}{w}\right)^{1/2}$$

Where:

and are constants, and t is the plate thickness

With simply supported square plates, uniaxially loaded, is an order of magnitude lower than, so that the second part on the right side of Eq. (6) stays insignificant for = for minor deflections.

Spencer [21] offers an equation that uses “pivot points” to create charts that could aid in linearizing the data. To put it succinctly, a “pivot point” is any actual data point that the researcher determines is accurate enough to justify being included in an analysis as an additional equation. This novel graphical method is suggested for determining critical load for plates with minor flaws after adding pivot points (P^*, w^*) as:-

$$\frac{1}{P_{cr}} \frac{P^*}{w^*} = \frac{1}{(w^* + w_o)} + \frac{(w^* + 2w_o)}{(A_c t)^2}$$

The constant can be eliminated as.

$$H_2 = (P_{cr} F_1) H_1 - w_o \text{ Where } H_2 = (P w^{*2} - P^* w^2) / \Delta \quad H_1 = (w^{*2} - w^2) / \Delta \Delta$$

$$= [P w^* (3 + w^* / w) - P^* w (3 + w / w^*)] F_2$$

$$F_1 = 1 + 3w_o / (w^* + w) F_2$$

$$= \frac{P[3w^* + (w^*)^2 / w + G^*] - P^*[3w + w^2 / w^* + G]}{P[3w^* + (w^*)^2 / w] - P^*[3w + w^2 / w^*]} G^*$$

$$= w_o [2 + 3w^* + 2w_o] / w G = w_o [2 + 3w + 2w_o] / w^*$$

The Spencer technique linearizes the load-deflection data by plotting the derived parameters H_2 against H_1 . This graphical representation, shown in Figure (2), is crucial because the resulting straight line's slope and intercept allow for the accurate computation of the critical load and the initial imperfection, even with minor flaws in the plate.

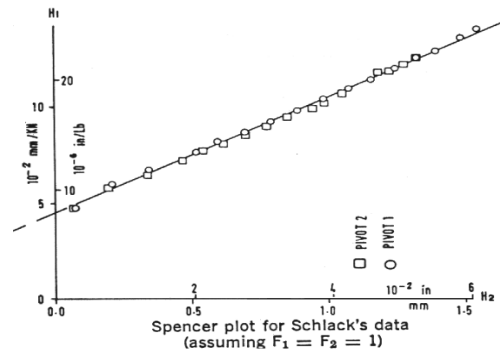


Figure (A2) Spencer technique for predicting the critical load of plates under compression

By applying this technique to the load-deflection data obtained from the Finite Element Analysis (FEA), the elastic critical load can be accurately extrapolated, providing a robust estimate of the critical buckling moment for the imperfect I-girder. This method is superior to the Southwell plot for FEA data, as it minimizes the influence of non-linearities and allows for a more reliable determination of the theoretical elastic buckling capacity.



Variability of Four Home Blood Pressure Monitoring Devices: Insights from a 2024 Cross-Sectional Study

Abdulrahman T. Abudawood - Hala A. Bagabir - Iman W. Salem - Shahad A. Alghanmi - Reham M. Alharbi - Shoug T. Alaslani - Shooq S. Samkari - Fatimah Y. Fallatah

(Received: 11th November 2025; Accepted: 15th December 2025)

Abstract

Home blood pressure monitoring (HBPM) is widely used for self-monitoring and managing hypertension. However, variations among devices may influence clinical decisions. This study aimed to evaluate the variability in systolic blood pressure (SBP) and diastolic blood pressure (DBP) readings across three commonly used upper-arm automated HBPM devices: Beurer Medical (BM 54), Citizen (CH-456), and Geratherm Smart (GT-1775) against a controlled, validated reference device, Omron M6 Comfort (HEM-7321-E). A total of 124 adult participants were recruited from King Abdulaziz University Hospital, Jeddah, Saudi Arabia. Trained medical students measured blood pressure using all four devices. Significant variations in SBP and DBP readings were observed among the four HBPM devices. Omron M6 Comfort recorded significantly lower SBP values (median = 112) compared to the Beurer Medical (median = 121), Geratherm Smart (median = 119), and Citizen (median = 119) devices, ($p < 0.001$). Conversely, Beurer Medical recorded significantly higher DBP values (median=85) compared to Omron M6 Comfort (median=80), Geratherm Smart (median = 76), and Citizen (median = 80), ($p < 0.001$). Although HBPM remains essential for hypertension management, these findings emphasize the need to select validated and reliable devices to ensure consistent and accurate blood pressure monitoring.

Keywords: Home Blood Pressure Monitoring, · Hypertension, · Blood Pressure, · Saudi Arabia.



DOI: 10.12816/0062497

(*) Corresponding Author:

Abdulrahman T. Abudawood¹, MBBS, DrPH, Hala A. Bagabir^{2,*}, MBBS, PhD, Iman W. Salem¹, Shahad A. Alghanmi³, Reham M. Alharbi³, Shoug T. Alaslani³, Shooq S. Samkari³, Fatimah Y. Fallatah³

1. Family and Community Medicine Department, Faculty of medicine, King Abdulaziz University, Rabigh, Saudi Arabia
2. Department of Physiology, Faculty of medicine, King Abdulaziz University, Rabigh, Saudi Arabia
3. Faculty of medicine, King Abdulaziz University, Rabigh, Saudi Arabia

E-mail: habajaber@kau.edu.sa

1. Introduction

Hypertension is a silent yet critical global health issue and a significant contributor to cardiovascular diseases. According to the latest World Health Organization (WHO) statistics from 2023, hypertension affects approximately 1.3 billion people (32%) worldwide. While global statistics are comprehensive, recent specific data on hypertension prevalence in Saudi Arabia remain scarce. However, a recent meta-analysis estimated the prevalence of hypertension to be 22.7%, based on a sample of 278,873 individuals in Saudi Arabia. [1] This underscores the substantial burden of hypertension in the region, as many cases remain undiagnosed. [2] The International Society of Hypertension (ISH) 2020 Global Hypertension Practice Guidelines define hypertension based on blood pressure (BP) thresholds, measured through various methods: office BP monitoring (OBPM), home BP monitoring (HBPM), and ambulatory BP monitoring (ABPM). For HBPM, hypertension is defined as systolic blood pressure (SBP) ≥ 135 mmHg and diastolic blood pressure (DBP) ≥ 85 mmHg. [3]

HBPM is widely recommended for effective hypertension management by leading health organizations, including the American Heart Association (AHA), European Society of Hypertension (ESH), and National Institute for Health and Care Excellence (NICE). These organizations emphasize the role of HBPM in confirming hypertension diagnosis, monitoring treatment effectiveness, improving patient compliance, and eliminating limitations associated with in-clinic measurements, such as the “white-coat” effect and masked hypertension phenomena. [3, 4]

However, the accuracy of HBPM devices varies considerably, making their reliability a critical factor for effective hypertension management. For example, a recent systematic review reported discrepancies in HBPM recordings compared to mercury sphygmomanometers, with inaccuracies ranging from 2.4 to 10.4 mmHg for SBP and 1.0 to 8.7 mmHg for DBP. [5] Another concern is the inherent variability in measurements across different monitors. For instance, a study comparing three HBPM devices—Microlife BP 3AC 1-1, Microlife BP3AG1, and Omron M4-I—among 65 participants found that the Omron M4-I recorded significantly lower SBP, DBP, and mean BP readings than Microlife devices. [6] These findings highlight the need for healthcare providers to exercise caution when selecting HBPM for their patients. These devices must be reliable and internationally certified by organizations such as the ESH, British Hypertension Society (BHS), Association for the Advancement of Medical Instrumentation (AAMI), and International Organization for Standardization (ISO).

The fundamental difference in measurement techniques is a primary source of variability between BP

devices. Auscultatory devices (e.g., mercury or aneroid sphygmomanometers with a stethoscope) rely on the detection of Korotkoff sounds and are influenced by observer technique, hearing ability, and ambient noise. [5] In contrast, the vast majority of (HBPMs) and automated office devices employ the oscillometric method, which detects oscillations in cuff pressure and uses manufacturer-specific proprietary algorithms to derive systolic and diastolic blood pressure values. [5] Because these algorithms, sensor sensitivity, and signal processing differ substantially between manufacturers (and even between models from the same manufacturer), clinically meaningful systematic differences of 5–10 mmHg or more can occur between devices, [5] potentially leading to misclassification of hypertension status or treatment decisions.

Given the growing availability of HBPM devices on the market, ongoing research is essential to compare these tools with validated devices or the mercury sphygmomanometer, which is widely regarded as the gold standard for BP measurements. Therefore, this study aims to assess variations among the most commonly used HBPM devices in Jeddah, Saudi Arabia, focusing on their measurement variability in the adult population. This research will provide valuable insights for clinicians and patients, ultimately improving hypertension management.

2. Methods

This analytical cross-sectional study was conducted at King Abdulaziz University Hospital (KAUH) in Jeddah, Saudi Arabia. Participants were recruited from the clinic’s waiting areas and hospital lobby. Participants were included if they were 18 years or older, attending KAUH, and willing to provide informed consent, regardless of any existing medical condition. The exclusion criteria included individuals younger than 18 years of age, pregnant individuals, and those unable to provide informed consent. The study procedures were clearly explained, and written informed consent was obtained from all participants before inclusion.

2.1 Participant preparation

To minimize the white-coat effect, participants were acclimatized for 10 minutes in a quiet environment before BP measurements were taken. During this period, sociodemographic and medical data were collected. Additionally, participants were informed that BP measurements were being collected strictly for research purposes.

A systematic random sample of 124 participants was collected from the visitor registry in the waiting area. Participants were selected using a fixed sampling interval, where **every 5th individual** listed in the registry was recruited after a random starting point. The collection period spanned May 2023 to October 2023,

with a recruitment rate of 3–4 participants per day over two days per week. Holidays and instances when eligible participants were unavailable were accounted for in the sampling schedule to ensure adherence to the inclusion criteria and maintain the integrity of the recruitment process.

2.2 Data collection procedures

Sociodemographic and medical data, including age, gender, body mass index (BMI), nationality, diabetes status, and hypertension history, were collected using a structured questionnaire and registered on Google Forms. BP measurements were conducted by trained medical students using four automated upper-arm cuff HBPM devices employing the oscillometric method: the Omron M6 Comfort (HEM-7321-E), Beurer Medical (BM 54), Citizen (CH-456), and Geratherm Smart (GT-1775). These devices, newly purchased from medical suppliers for this study, were used in a randomized sequence to eliminate measurement bias associated with the reading order. Measurements were recorded in Google Forms, and a standardized protocol, based on ESH guidelines and the literature, [7] were followed to ensure consistency. A five-minute interval between measurements was maintained to minimize the influence of prior readings. All measurements were taken in triplicate, with the results presented as means.

2.3 Study design and sample size

The study aimed to compare the variability in BP readings among three HBPM devices compared to a fourth control device, Omron M6 Comfort (HEM-7321-E), which meets ESH 2010 standards. [8] A sample size of 124 participants was calculated using the Epi Info calculator, with a confidence level of 95% and power of 80%.

2.4 Data management and statistical analysis

Data from Google Forms were exported to Excel for initial organization and subsequently analyzed using SPSS version 20 (IBM Corp., Armonk, NY). Categorical variables were presented as frequencies and percentages, while numerical variables were summarized using means $\pm$ standard deviation for normally distributed data and as median with interquartile range for non-normally distributed data. The Friedman test was employed to identify significant influencing factors when comparing devices, while the Wilcoxon signed-rank test was used to compare each device's readings with the control device. Normality of readings was assessed prior to analysis, with a significance level of $\alpha = 0.05$ applied throughout.

2.5 Ethical considerations

The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and approved by the Research Ethics Committee at King Abdulaziz University, Jeddah, Saudi Arabia (No: HA-

02-J-008). All data were anonymized to ensure participant confidentiality and securely stored on Google Forms for two years, accessible only to the study authors.

3. Results

A total of 124 participants were recruited for the study between May 2023 and October 2023. The mean participant age was 31 ± 12 years, with a mean BMI of 25.9 ± 5.9 kg/m². Of the participants, 51.6% were male, and 80.6% were Saudi nationals. Pre-existing medical conditions included diabetes mellitus (9.7%), hypertension (8.1%), hypercholesterolemia (2.4%), and hyperthyroidism (0.8%). Additionally, 13.7% reported other chronic diseases (Table 1).

The Friedman test and the Wilcoxon signed-rank test were used to compare blood pressure measurements obtained from the four devices. These methods were chosen because the data were not normally distributed. The Friedman test was applied to compare SBP and DBP readings across the four devices, and the Wilcoxon signed-rank test was conducted for pairwise comparisons to determine which device pairs differed significantly.

3.1 Device comparisons: SBP

The Friedman test revealed statistically significant differences in SBP readings across the four devices, ($\chi^2 = 35.7$, $p < 0.001^*$), indicating that at least one device recorded significantly different SBP values. Median SBP readings showed notable variation: the **Omron M6 Comfort** recorded a median of **112 mmHg**, whereas the **Beurer Medical BM 54**, **Geratherm Smart GT-1775**, and **Citizen CH-456** recorded higher median values of **121 mmHg**, **119 mmHg**, and **119 mmHg**, respectively (Table 2).

3.2 Device comparisons: DBP

A similar pattern was observed for diastolic blood pressure measurements. The Friedman test identified significant differences among devices ($\chi^2 = 59.8$, $p < 0.001$), indicating inconsistent DBP readings (Table 2). The Omron M6 Comfort produced a median DBP of 80 mmHg, whereas the Beurer Medical BM 54 reported a higher median of 85 mmHg, and the Geratherm Smart GT-1775 recorded a lower median of 76 mmHg. The Citizen CH-456 showed a median value equal to the Omron (80 mmHg).

3.3 Pairwise comparisons

Pairwise comparisons using the Wilcoxon signed-rank test confirmed substantial variability in blood pressure measurements between the Omron M6 Comfort and the other devices (Table 3). For SBP, the Omron recorded significantly lower readings than all three comparison devices, with highly significant differences observed against the Beurer Medical BM 54 ($Z = -4.7$, $p < 0.001$), Geratherm Smart GT-1775 ($Z = -4.7$, $p <$

0.001), and Citizen CH-456 ($Z = -5.5$, $p < 0.001$). For DBP, the Omron also differed significantly from the Beurer device ($Z = -3.7$, $p < 0.001$), which produced higher DBP values, and from the Geratherm device ($Z = -4.9$, $p < 0.001$), which recorded lower DBP readings. In contrast, no significant difference in DBP was detected between the Omron and the Citizen device ($p = 0.73$).

4. Discussion

This study evaluated variability, rather than accuracy, among four automated upper-arm cuff HBPM devices employing the oscillometric method in adults in Jeddah, Saudi Arabia. Wrist devices were excluded due to their known inaccuracies and questionable reliability. [9] Among the tested devices, the Omron M6 Comfort (HEM-7321-E) and Beurer Medical (BM 54) met ESH standards, while the Citizen (CH-456) and Geratherm Smart (GT-1775) have no validation details in ESH, AAMI, BHS, or ISO reports. Nevertheless, the devices were selected based on their widespread use, representing a range of affordability from high-cost to budget options to ensure regional relevance.

Our main findings showed that the Beurer Medical, Geratherm Smart, and Citizen recorded significantly higher SBP readings than the Omron M6 Comfort by more than 7 mmHg. According to variation criteria established by the AAMI, ESH, and ISO, a mean difference exceeding ± 5 mmHg is suboptimal and generally not acceptable. [10] Such consistent variation could lead to clinical overestimation of SBP, potentially resulting in unnecessary management adjustments. These variations may be attributed to the oscillometric method, which relies on a fixed formula based on oscillation onset and maximum oscillation pressure. [9] This standardized approach may not account for individual physiological differences, contributing to variability compared to other measurement methods. [9] Additionally, differences may stem from unique manufacturer algorithms for calculating BP. [11] For DBP results, the Beurer Medical device recorded higher DBP readings than the Omron M6 Comfort by an average of 4 mmHg, while the Geratherm Smart recorded lower DBP readings compared to the Omron M6 Comfort by an average of 4 mmHg. These variations fall within the acceptable threshold of ± 5 mmHg.

Our findings align with previous studies, although reported inter-device variations were within acceptable limits. Varis and Kantola observed average differences of 2 mmHg in SDB and DBP among three devices (Omron M4-I and two Microlife devices, BP 3AC 1-1 and BP3AG1) tested on 65 Finnish participants (6). Similarly, Yarows and Brook evaluated 12 HBPM devices with two normotensive subjects. The devices, which included arm, wrist, and finger monitors, were compared against an Omron 712C upper arm monometer as well as to mercury

and aneroid sphygmomanometers. [11] Among these devices, four arm monitors (Omron 711, Omron 725CIC, Omron HEM705CP, and A&D UA767) showed variations of less than 4 mmHg for both SBP and DBP measurements compared to the Omron 712c. [11] However, the limited scope of these studies and manufacturer homogeneity may restrict the generalizability of these findings. Having said that, findings from larger comparative studies support our results, demonstrating that automated oscillometric devices exhibit substantial inter-device variability. A metanalysis, analysed 24 studies with a total of 47,759 adults determined that the overall weighted mean difference between automated oscillometric devices and mercury sphygmomanometers was statistically significant but within the accepted clinical tolerance of 5 mmHg. However, this study revealed very high statistical heterogeneity among the included studies suggesting that BP estimating algorithms vary significantly depending on the manufacturer and product type. [12]

While OBMP is indispensable for hypertension follow-up and management, HBPM offers advantages such as minimizing white-coat anxiety, enhancing disease awareness, and promoting treatment adherence, thereby helping to reduce cardiovascular morbidity and mortality. [9] Despite this, most automated BP measuring devices sold on the global market have not been clinically validated, despite strong guideline endorsement for their use. The systemic challenge of inter-device variability is fundamentally linked to the oscillometric technique, as SBP and DBP are derived using proprietary, mathematical algorithms. The proprietary nature of these algorithms, combined with inherent sources of error like signal processing variations and estimation inaccuracies, makes it difficult to ascertain the cause of measurement inaccuracies in each automated BP device. [13] Furthermore, the historical use of multiple competing clinical validation protocols has fostered confusion, resulting in a lack of consensus, evidenced by the fact that multiple registries do not always agree on which HBPM are acceptable for clinical use. [13] To address this, recent global evidence underscores the need for a unified regulatory approach through the accelerated adoption of a single, universally accepted protocol namely, AAMI/ESH/ISO universal standard (ISO 81060-2:2018), to improve quality assurance and standardize requirements for accurate HBPM before devices reach the market. [14]

The study has some limitations. First, while many HBPM devices are available on the market, only four were evaluated, limiting the generalizability of the findings. However, these devices were selected for their regional popularity and affordability. Second, devices were not compared to a mercury sphygmomanometer due to the specialized training required for its use. Nonetheless, the study focused on inter-device variability rather than

absolute accuracy, with the control device meeting ESH standards. Third, external factors that could influence BP, such as caffeine consumption, medication, and tobacco use, were not controlled.

5. Conclusion

This study identified significant variability in SBP readings among four HBPM devices, with three devices exceeding the acceptable ± 5 mmHg threshold compared to the Omron M6 Comfort, potentially leading to clinical mismanagement. These findings underscore the critical need for rigorous validation of HBPM devices to ensure their accuracy and reliability in clinical and home settings.

5.1 Conflict of Interest

The authors report no conflicts of interest.

5.2 Author Contributions

A.A., and H.B. developed the research idea, A.A., I.W. and H.B. designed the methodology, and provided supervision. S.AL.G., R.A., S.ALA., S.S., and F.F. collected the data and wrote the manuscript. A.A. analyzed the data. A.A., I.W., and H.B. reviewed and edited the manuscript. All authors have read and approved the final version of the manuscript.

6. Funding

The authors received no financial support for this research.

7. References

- Alshammari, S.A., et al., Overview of hypertension in Saudi Arabia: A systematic review and meta-analysis. *Saudi Med J*, 2023. 44(10): p. 951-964.
- Mumena, W.A., et al., Prevalence and determinants of undiagnosed hypertension in the Western region of Saudi Arabia. *PLoS One*, 2023. 18(3): p. e0280844.
- Unger, T., et al., 2020 International Society of Hypertension Global Hypertension Practice Guidelines. *Hypertension*, 2020. 75(6): p. 1334-1357.
- Weinfeld, J.M., K.M. Hart, and J.D. Vargas, Home Blood Pressure Monitoring. *Am Fam Physician*, 2021. 104(3): p. 237-243.
- Hiremath, S., A. Gaur, and J. TurnerPatry, PS-C10-4: ARE HOME BLOOD PRESSURE DEVICES ACCURATE? A SYSTEMATIC REVIEW OF THE EVIDENCE. *Journal of Hypertension*, 2023. 41(Suppl 1).
- Varis, J. and I. Kantola, The Choice of Home Blood Pressure Monitoring Device Matters: Differences between Three Commercial Monitors Used in Finnish General Practice. *J Gen Pract*, 2013. 1(106): p. 2.
- Mancia, G., et al., 2023 ESH Guidelines for the management of arterial hypertension The Task Force for the management of arterial hypertension of the European Society of Hypertension: Endorsed by the International Society of Hypertension (ISH) and the European Renal Association (ERA). *Journal of Hypertension*, 2023. 41(12).
- Takahashi, H., T. Yokoi, and M. Yoshika, Validation of the OMRON M6 Comfort (HEM-7321-E) upper arm blood pressure monitor, in oscillometry mode, for clinic use and self measurement in a general population, according to the European Society of Hypertension International Protocol revision. 2010. Dublin, UK: dablEducational Trust, 2014: p. 4.
- Ihm, S.-H., et al., Home blood pressure monitoring: a position statement from the Korean Society of Hypertension Home Blood Pressure Forum. *Clinical Hypertension*, 2022. 28(1): p. 38.
- Stergiou, G.S., et al., A Universal Standard for the Validation of Blood Pressure Measuring Devices: Association for the Advancement of Medical Instrumentation/European Society of Hypertension/International Organization for Standardization (AAMI/ESH/ISO) Collaboration Statement. *Hypertension*, 2018. 71(3): p. 368-374.
- Yarows, S.A. and R.D. Brook, Measurement variation among 12 electronic home blood pressure monitors. 2000, Oxford University Press. p. 276-282.
- Park, S.-H. and Y.-S. Park, Can an automatic oscillometric device replace a mercury sphygmomanometer on blood pressure measurement? A systematic review and meta-analysis. *Blood pressure monitoring*, 2019. 24(6): p. 265-276.
- Ringrose, J.S. and R. Padwal, Automated blood pressure measuring devices: how are they clinically validated for accuracy? *Journal of Human Hypertension*, 2023. 37(2): p. 101-107.
- Murthy, S., et al., Validation of blood pressure devices as per 2020 World Health Organization technical specifications: a scoping review of global literature. *Hypertension*, 2023. 80(5): p. 1110-1116.

8. Tables

Table 1: Demographic data of participants (N = 124). a: Mean $\pm$ Standard Deviation, BMI: Body mass index.

Variables	No. of subjects	Percent
Age (by years)	124	31 $\pm$ 12 a
BMI	124	25.9 $\pm$ 5.9 a
Gender		
Male	64	51.6
Female	60	48.4
Nationality		
Saudi	100	80.6
Non-Saudi	24	19.4
Previously diagnosed with:		
Diabetes mellitus		
Yes	12	9.7
No	112	90.3
Hypertension		
Yes	10	8.1
No	114	91.9
Hypercholesteremia		
Yes	3	2.4
No	121	97.6
Hyperthyroidism		
Yes	1	0.8
No	123	99.2
Other chronic diseases		
Yes	17	86.3
No	107	13.7

Table 2: Variation in HBPM devices for systolic and diastolic BP. a. Friedman Test, * p-value <0.05, ** < 0.01, and * < 0.001**

	SBP					DBP				
	Percentiles			Statistical test ^a		Percentiles			Statistical test	
	25 th	50 th (median)	75 th	Chi-Square	p-value	25 th	50 th (median)	75 th	Chi-Square	p-value
Omron M6 Comfort (mmHg)	102.25	112.00	123.5	35.8	<0.001^{**}	74.00	80.00	85.00	59.8	< 0.001^{***}
Beurer medical BM 54 (mmHg)	112.00	121.00	125.0			74.0	85.00	88.00		
Geratherm smart GT-1775 (mmHg)	110.25	119.0	127.75			68.0	76.0	81.0		
Citizen CH-456 (mmHg)	111.00	119.0	130.0			73.0	80.0	86.0		

Table 3: Pairwise comparisons of measurements among HBPM devices. All comparisons were performed using the Omron M6 Comfort device as the reference standard a. Wilcoxon Signed Ranks Test, b. Based on positive ranks. * p-value < 0.001**

	SBP		DBP	
Device	Statistical test ^a			
	Z test	p-value	Z test	p-value
- Omron M6 Comfort Device2, Beurer medical BM 54	-4.7	***0.00	-3.7	***0.00
- Omron M6 Comfort Geratherm smart GT-1775	-4.7	***0.00	-4.9	***0.00
- Omron M6 Comfort Citizen CH-456	-5.5	***0.00	-0.3	0.73



GNN-AOI: A GRAPH NEURAL SCHEDULING FRAMEWORK FOR AGE-AWARE REAL-TIME STREAMING OVER MPTCP IN 5G EDGE NETWORKS

Hamed D. Al-Sharari

Information Technology department, College of Computing and Informatics, Saudi Electronic University, Kingdom of Saudi Arabia

(Received: 14th September 2025; Accepted: 28th October 2025)

Abstract

Intelligent and adaptive scheduling frameworks that can preserve data freshness, reduce latency, and guarantee dependable transmission are becoming increasingly necessary as 5G networks and real-time applications proliferate. While they work well for throughput aggregation, traditional Multi-Path TCP (MPTCP) schedulers frequently struggle to optimize for Age of Information (AoI), a crucial metric for real-time decision systems. This paper presents GNN-AoI, a new scheduling framework based on Graph Neural Networks that is intended for real-time streaming over MPTCP in dynamic 5G edge environments. The suggested method learns to make context-aware path selection decisions using real-time features like latency, packet loss, congestion, and signal quality by modelling the network as a dynamic graph and utilizing Graph Attention Networks (GATs). Mobile Edge Computing (MEC) nodes use the GNN-AoI model to provide localized intelligence and low-latency inference without jeopardizing user privacy. The result achieves 27% reduction in both AoI and latency, and 15–25% throughput improvement. Simulations with ns-3 and PyTorch Geometric show that GNN-AoI reduces latency from 66 ms to 48 ms (–27%), average AoI from 52 ms to 38 ms (–27%), improves throughput by 15–25% (up to 68 Mbps), and lowers packet loss to 1.2%, outperforming five recent schedulers across all key metrics, and a markedly improved packet delivery reliability, outperforming five state-of-the-art scheduling models across key performance metrics. These findings lay the groundwork for intelligent, edge-native transport protocols and confirm the efficacy of GNN-based scheduling in upcoming wireless systems.

Keywords: Age of Information, Graph Neural Networks, Multi-Path TCP, 5G Edge Computing, Real-Time Scheduling.



(*) Corresponding Author:

Hamed D. Al-Sharari

Information Technology department, College of Computing and Informatics, Saudi Electronic University, Kingdom of Saudi Arabia

Email: H.ALSHARARI@seu.edu.sa

1. INTRODUCTION

Effective network scheduling is now crucial due to the rise of 5G edge computing and the increased dependence on real-time data transfer. The use of multiple concurrent paths for increased throughput and reliability has led to the widespread adoption of multi-path TCP (MPTCP). However, in dynamic edge environments, where freshness, measured by Age of Information (AoI), is crucial, traditional scheduling algorithms like Round-Robin and Lowest-RTT are fundamentally static and cannot handle important challenges. Age-aware communication and network intelligence are becoming more and more crucial in future networks, according to recent studies. [1][7]. Scheduling for real-time streaming over 5G edge networks, particularly with mobile devices, needs to adjust to fluctuating signal intensities, link latencies, congestion patterns, and device mobility. These complexities are difficult for static heuristics to grasp, which frequently leads to less-than-ideal data freshness and delivery performance [2].[3]. Adaptive scheduling now faces both new opportunities and challenges as a result of the combination of mobile-edge computing (MEC) and heterogeneous base stations (such as LTE and mmWave) [4].[6]. Current scheduling frameworks are unable to achieve real-time, context-aware decision-making for minimizing AoI, despite developments in multipath protocols and edge computing. Especially when there is user mobility and fluctuating conditions, they are unable to optimize across multiple heterogeneous links and dynamically model network topologies. The drive comes from the necessity of utilizing recent advancements in Graph Neural Networks (GNNs) to get beyond these constraints. Complex, structured data, like dynamically changing network graphs, can be modelled by GNNs, allowing for more intelligent and flexible decision-making than traditional models [1][5]. A few of the difficulties are listed below:

- Recording changes in edge network topologies in real time.
- Optimizing for a variety of user priorities and paths.
- In multi-user settings, balancing packet loss, throughput, and AoI metrics.
- At the MEC level, ensuring scalability and real-time inference.

The new scheduling framework GNN-AoI, which is based on graph neural networks, is presented in this paper. It dynamically models the MPTCP environment as a graph. It optimises for AoI, packet loss, and throughput by using real-time metrics to inform context-aware scheduling decisions at MEC nodes. In contrast to current approaches, GNN-AoI offers centralized intelligence, no privacy trade-offs, and adapts to user mobility and intricate network interactions. The framework

incorporates composite loss-based training, a custom GNN model (GAT/GCN), and a full graph representation. Performance is verified using PyTorch for learning in an ns-3 simulated 5G environment. Unlike prior schedulers for MPTCP non-GNN and GNN based controllers, GNN-AoI: (i) constructs AoI-centric multi-objective training (AoI/loss/throughput) with term standardization & explicit weights; (ii) builds a snapshot-temporal graph of ns-3 exports every 500ms and performs attention over time but no RSV; (iii) ranks MPTCP subflows directly from a joint node/edge feature (AoI, queue, SINR, RTT, loss, BW, Congestion) and infers on MEC (<5ms/snap). The rest of the paper is structured as follows: Section 2 reviews related work and identifies the gaps in existing models. The system architecture is explained in Section 3. The definition of the graph model is described and the design of the GNN model is explained. The execution flow is shown in Section 4, and the evaluation metrics. The simulation setup is described in detail, and the main benefits over current methods are covered in Section 5.

2. LITERATURE REVIEW

A new data-age-aware scheduling model for wirelessly powered mobile-edge computing (MEC) environments in industrial IoT was proposed by Wu et al. [1]. Their method greatly enhances real-time responsiveness in edge scenarios by dynamically minimizing AoI through task prioritization based on energy constraints and task urgency. A thorough road map for integrating 5G and heterogeneous Radio Access Networks (RANs) to achieve seamless connectivity was provided by Mohammed et al. [2]. Their research focused on optimizing QoS across distributed network slices, scalability, and architectural considerations. For 5G systems, Jalal et al. [3] concentrated on improving optical networks with dual cascaded modulators inside a PON structure. With a capacity of up to 160 Gbps, they introduced optical distortion compensation solutions, which are essential for supporting low-latency optical backbones in mobile networks. The use of ensemble transfer learning for botnet detection in Internet of Things networks was investigated by Aalsaud et al. [4]. They showed how intelligent edge detection models that have been trained on a variety of network behaviours can effectively and with little latency slow the spread of botnet attacks. In order to increase bandwidth and lower modulation noise in 5G access networks, Yousif et al. [5] suggested an improved PON system that makes use of phase shift keying (PSK) electrical modulators and vertical-cavity surface-emitting lasers (VCSELs). An analytical study of AoI in shared edge computing servers was carried out by Chiariotti [7], who produced fundamental models for estimating the freshness of information and directing uplink traffic scheduling in MEC-enabled environments. In order to identify performance bottlenecks and future trends for vehicular communication systems integrated

with 5G networks, Abbas et al. [7] created an index of vehicular technologies. The AFAFed protocol, created by Baccarelli et al. [8], allows federated learning across edge nodes in communication environments with limitations. Their approach preserves global model accuracy while lowering communication overhead. For low-latency applications, Zhao et al. [9] presented a multipath scheduler that makes use of cross-layer information to reduce delay. Particularly in edge-based 5G networks, their model dynamically strikes a balance between path reliability and link congestion. In their evaluation of MPTCP deployment over mmWave 5G environments, Poorzare and Waldhorst [10] addressed issues such as frequent handovers and link disruptions. In their paper, they suggested proactive path reservation techniques and link redundancy. The CPS algorithm, which enhances MPTCP scheduling through hierarchical latency predictions, was an extension of Zhao et al.'s earlier work [11]. In real time, the algorithm adjusts dynamically to link variability and congestion. MPTCP usage across concurrent 4G and 5G connections was examined by Mahmud et al. [12]. According to their empirical results, when properly managed, MPTCP can greatly increase throughput and decrease jitter. One of the first evaluations of MPTCP over mmWave was carried out by Polese et al. [13], who found that ACK feedback synchronisation and the congestion window were the main drawbacks in such dynamic environments. Using MPTCP, Pokhrel et al. [14, 18] suggested hybrid and transfer learning models for distributed edge learning. Their methods allow for congestion management and adaptive scheduling in diverse network settings. A thorough analysis of dependable, low-latency communication techniques in 5G was provided by Rico and Merino [15]. For performance assurance, they suggested edge-hosted intelligence and AI-driven control loops. A priority-aware MPTCP scheduler was presented by Gumasthi and Baswade [16] and was created especially for heterogeneous 5G links. Their model reduces latency spikes while efficiently balancing traffic loads. Multimedia transmission protocols on 5G edge networks for mobile augmented reality applications were assessed by Cao et al. [17]. They emphasised the significance of adaptive bitrate selection and link-switching resilience. A thorough performance analysis of MPTCP schedulers in 5G was presented by Wu et al. [19], who argued for responsive and lightweight algorithms to lower computational overhead at edge nodes. A thorough examination of TCP congestion control mechanisms in 5G was provided by Lorincz et al. [20]. Core research gaps in hybrid congestion models were identified by their taxonomy. Using historical network context, Singh et al. [21] created a clever MPTCP controller that improves decision-making in situations of congestion and mobility. A testbed-based MPTCP traffic steering solution for multimedia in 5G was introduced by Kang et al. [22]. They were able to show enhanced

flow aggregation and handover continuity. In order to maximize delay-sensitive communication, Lee et al. [23] proposed DEFT, a latency-sensitive MPTCP design that modifies window size and segment retransmission strategy. In order to achieve smooth transitions with little packet loss, Ito and Izuka [24] created a client-server based vertical handover scheme for local 5G and WLANs using virtual routers. SDN-enabled MPTCP handovers for software-defined heterogeneous networks were proposed by Tong et al. [25], used mobility-aware decision frameworks to maintain path continuity. Carrilho [26] examined multipath video transport in edge-assisted cooperative systems, emphasising bandwidth allocation and real-time vehicle perception. A multi-stage learning algorithm for congestion control that is suited to edge cloud environments was proposed by Xiao et al. [27] in order to improve throughput and fairness among devices. Contextual bandits were used by Alzadjali et al. [28] to control MPTCP path selection in heterogeneous networks. In real time, their model learns the best path-switching behaviour. Hurtig et al. [29] introduced a low-latency MPTCP scheduler that takes round-trip delays and queue lengths into consideration when making decisions. The MPTCP and CMT-SCTP protocols were thoroughly reviewed by Tomar et al. [30], who placed special emphasis on use cases, standardization, and deployment trade-offs. Edge-enabled mobility systems and their function in intelligent, real-time decision-making throughout urban wireless ecosystems were covered by Shao et al. [31]. With an emphasis on mobile users, Xing et al. [32] introduced a low-latency scheduler for live video traffic. Their model shows adaptive path prioritization according to link quality and user mobility. Previous schedulers either minimize delay only, do not consider AoI or use static heuristics. Recent learning-based papers often (a) do not optimize AoI, (b) do not infer by inference using MEC, or (c) do not combine snapshots of the temporal graph. GNN-AoI is new in linking AoI-aware, standardized weighted training coordinate-wise in time with subflow graph recurrence temporal attention and direct subflow RLMP TCP score consistency, showing tail-latency and AoI benefits with CDF multiplicity and confidence with seeds and conditions.

Table 1: Summary of Related Works

Ref. No.	Method Used	Objective	Achieved	Limitation
[1]	AoI-aware scheduling in MEC	Minimize Age of Information in industrial IoT	Improved freshness by prioritizing energy-efficient tasks	Limited scalability to heterogeneous network types
[7]	AoI Analysis in Edge Servers	Model AoI in shared computing environments	Provided analytical tools for age quantification	Did not address dynamic network topologies
[10]	Cross-layer MPTCP scheduler	Reduce delay in 5G edge networks	Enhanced multipath selection using real-time metrics	Focus limited to delay; throughput and packet loss not prioritized
[15]	Distributed edge learning with hybrid MPTCP	Enable efficient multipath-based learning	Improved learning accuracy and convergence with MPTCP	Requires high coordination overhead across nodes
[19]	Transfer learning for edge MPTCP	Adapt MPTCP behavior using prior learning	Reduced training time and improved adaptive scheduling	Transfer learning effectiveness drops in dissimilar environments

3. METHODOLOGY

3.1 System architecture

The proposed system architecture adds Graph Neural Networks (GNNs) to the 5G edge computing framework to better real-time scheduling of Multi-path TCP (MPTCP) traffic. The most fundamental feature of the architecture is a network of User Equipment (UE), which can be composed of both edge-connected and mobile devices communicating with all radio access technologies such as mmWave access points, 5G gNBs and LTE eNBs. These elements talk with Mobile Edge Computing (MEC) nodes that are located at the edge of the network. These MEC nodes implement the GNN-based scheduler (which determines how to assign traffic paths based on network conditions) in a systematic manner and make decisions. The MEC nodes collect real-time telemetry information, e.g. latency, SINR, queue depth, and congestion level. Based on this information a dynamic graph is generated that represents the current network state of affairs and topology.

3.2 Definition of Graph Model

The graph-based model views the network as a structure with the nodes representing network entities such as user devices, base stations and access points, and edges representing logical or physical communication links among them. Some of the features that characterize each node in the graph include Age of Information (AoI), current queue length, received signal strength indicator (RSSI) or SINR and a user-specified priority level. Likewise, there are user edge characteristics in the graph such as the round-trip latency, approximate bandwidth capacity, loss rate per packet, and actual (or real-time) congestion on data. The dynamic behaviour of the network can be well described by these complex nodes and edges characteristics and such description is critical in making informed scheduling decisions.

3.3 Design of GNN Models

The core element of the proposed architecture would be the deployment of a graph neural network, e.g., a graph attention network (GAT) or graph convolutional network (GCN) that would be trained to operate on the dynamic graph constructed by means of network telemetry. Given the input graph structure, with annotated feature vectors on each node and each edge, the model calculates a score value on each of the possible sub flows of the MPTCP configuration. Depending on the condition of the network, these path scores indicate the appropriateness of every path in the transmission of data. The model minimizes a weighted sum of loss that trades off three key players, throughput, reliability through packet loss, and data freshness through AoI during training. Because the parameters α , β , and α are adjustable. This objective will ensure that the GNN can be taught to prioritize routes that can maximize the timeliness and reliability of delivering data and at the same time reduce latencies and congestion.

Backbone: 3-layer GAT (hidden 128–64–32, ELU, dropout 0.2); global attention pooling → 2-layer MLP for per-subflow scores.

Training: Adam (lr 1×10^{-3} , weight-decay 5×10^{-4} , batch size 128 graph snapshots, 60 epochs.

Temporal batching: sequences of length 4 from ns-3 snapshots every 500 ms.

Seeds: {10,20,30}

Report: mean $\pm$ std, 95% CIs (Student's t).

Early-stopping: patience 10 epochs on validation AoI.

We propose GNN-AoI to optimize the data freshness, reliability and capacity with the following composite objective:

$$L = \alpha \cdot \text{AoI} + \beta \cdot \text{PacketLoss} - \gamma \cdot \text{Throughput}.$$

The 3 coefficients α , β and γ are the weight of the importance of timeliness, reliability and throughput respectively. The parameter values to be used in the baseline setup are 0.5, 0.3, 0.2, selecting these values empirically to focus on the minimization of AoI. A small sensitivity analysis (smaller than 0.1 variation per coefficient) ensured that there is stable optimization behavior. We use Adam (learning-rate 1×10^{-3} , 1×10^{-4} weight-decay), batch size 128, graph snapshots, 60 epochs training. The sampling batches in all eras consist of a sequence of ns-3 snapshots. Getting short-term dynamics: 500 ms of 6. It is based on a 3-layer GAT (hidden sizes 128-64-32) with ELU activations and dropout 0.2; the scores are those of the global attention pool readout, and a 2-layer MLP that yields per-subflow scores. Three random seeds are used to repeat all experiments. {10,20,30} and report mean $\pm$ std and 95% CIs.

AoI is entered as linear as it is the number of units in milliseconds; packet loss is not a unit; throughput is megabits per second. We normalize each of the terms on training statistics and then weight to maintain the magnitudes comparable, the weights chosen are based on the real-time goal of minimizing AoI, and then preventing loss followed by use of capacity. Export ns-3 state every $\Delta t = 500$ ms. The feature of each snapshot $Gt = (V_t, E_t)$, contain node (AoI, queue length, RSSI/SINR, priority) and edge features (RTT/latency, bandwidth estimate, loss rate, congestion level). To train, the author takes length-4 sequences $(Gt, Gt+\Delta t, Gt+2\Delta t, Gt+3\Delta t)$, and the GNN processes each Gt , and adds scores through attention over time to get subflow scores at $t+3\Delta t$. This maintains mobility, congestion evolution and radio variation without recurrent units.

3.4 Executive Movement

The scheduling process initiates at the MEC nodes level by the compilation of telemetry information and the creation of a new version of the graph of network state. GNN model takes in this graph and through inference evaluates and ranks all possible transmission paths. The MPTCP scheduler then selects the most desirable subflow(s) to transmit data depending on these scores. To achieve deeper insight regarding the network environment, the model will use feedback by gathering and storing the feedback data to the packets delivered, including successful delivery, latency, and loss metrics, among others. This constant repetition of the process allows the GNN to be able to adapt to changing network conditions, requirements placed by its users, and mobility almost in real-time. In different loads and mobility situations, this closed-loop feedback maintains the system resilient, context-aware.

Ablation and Sensitivity Analysis: Additional experiments compared GAT with GCN backbones and tested feature-group removal. Using GCN increased

AoI by 8 % and latency by 6 %. Removing congestion and SINR features increased AoI by 10–12 %. Snapshot intervals shorter than 500 ms gave marginal gains (< 2 %), while ≥ 1 s degraded AoI by ≈ 15 %.

3.5 Configuring the Simulation

To test the recommended GNN-AoI framework, a simulation system is developed with the ns-3 network simulator, whereby, LTE and mmWave modules are integrated to create a realistic simulation environment with 5G scenarios. The GNN models are developed and trained with the help of PyTorch. Periodic export of dynamic snapshots of the ns-3 environment is performed, which are then converted into graph structures which are used by the GNN scheduler. It is due to this simulation setup that the effectiveness of the GNN in the realistic network environment can be carefully and rigorously analyzed. The continuous supply of training data that can model real-time actions of the network to resemble real-time dynamics makes it possible to effective learning and assessment of the scheduling algorithm through the combination of the integration of the simulators and learning framework. The author includes minRTT, Round-Robin, ECF, and BLEST as canonical schedulers, plus five recent research schedulers (Zhao 2024; Gumasthi & Baswade 2024; Xing 2021; Wu 2021; Pokhrel 2022).

3.6 Evaluation Metrics Matters

Several aspects are compared to see the performance of this system. The Average Age of Information (AoI) is used to determine whether data is delivered freshly. The 95th percentile latency would be the worst-case delay performance. Whereas overall throughput helps one to understand how well the bandwidth utilization is, the packet loss rate indicates the degree of reliability of the system. A path stability index is also computed to determine consistency of paths taken over a period. Finally, the viability of the implementation of the model on edge nodes is considered in real time by including the computational overhead of GNN inference.

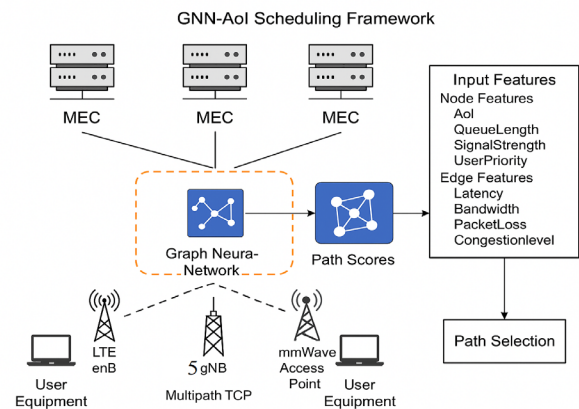


Figure 1 Proposed GNN-AoI Scheduling Framework

3.7 Benefits of the GNN-AoI Framework

There are several obvious advantages of the GNN-AoI framework compared to traditional scheduling algorithms. It directly optimizes Age of Information, a metric that legacy systems are often utilizing incorrectly. The system shows real-time adaptability, allowing it to adjust the path choice accordingly to that of the network changes. It is highly scalable as it is mindful of mobility and is able to support a high number of users and simultaneously having a large number of flows. Centralized learning within MEC nodes reduces latency and responsiveness by guaranteeing the fast decision-making without relying on the core cloud infrastructure. However, this too has had trade-offs in terms of computing load and privacy which are accepted to be potential impediments to broader adoption.

The above-proposed GNN-AoI Scheduling Framework that makes use of Graph Neural Networks and integrates within a 5G and edge computation environment, to select path intelligently based on Multipath TCP (MPTCP) is shown in figure 1. This model is dynamic to adapt to the changing network conditions so as to maximize Age of Information (AoI), throughput and packet delivery reliability.

The architecture has been structured based on various interconnected components. Some of the examples of User Equipment (UE) in the form of mobile devices and sensors communicates using mmWave access points, 5G gNB, and LTE eNB. These data streams are transmitted with the helps of the MPTCP protocol that provides multiple parallel paths. Network telemetry data are collected by MEC (Mobile Edge Computing) nodes positioned near the access infrastructure. Some notable features of both nodes (including AoI, queue length, signal level, and priority) and the edges (including latency, bandwidth, packet loss, and congestion level) are contained in this data. The Graph Neural Network architecture in the MEC utilises this real-time network graph to compute scores on every possible path. It learns the interdependencies among nodes and links and either Graph Convolutional or Graph Attention mechanisms are exploited. The GNN creates a number of path scores and gives them as inputs to a selection mechanism that aids the MPTCP protocol in the selection of the best subflows. This end-to-end loop supports the real time, context-aware traffic steering. The flexibility that the framework offers to adaptively learn through network dynamics in the case of network dynamics infinitely raises AoI, throughput, and reliability compared to static, or heuristic-based schedulers.

4. RESULT AND DISCUSSION

This simulation environment was carried out comprehensively using ns-3 network simulator to evaluate the behavior of the proposed GNN-AoI scheduling framework. To realistically emulate an environment with

heterogeneous access technologies, this environment merged LTE, mmWave and 5G modules. These access points led to Mobile Edge Computing (MEC) nodes and User Equipment (UE) devices communicated through these access points. These nodes of MEC were responsible to use trained Graph Neural Netwo to make real-time inference. There were fifteen base stations in this simulation (equally distributed LTE eNBs, 5G gNBs and mmWave access points) and fifty user devices. Each UE used 3 subflows to send paths on the same path in MPTCP. The simulation was from the random waypoint mobility model and lasted 1000 seconds. The network snapshots were updated at an interval of 500 milliseconds using graph snapshots fed into a three-layer Graph Attention Network (GAT). The paper should incorporate actual measurements of MEC runtime performance, including CPU, GPU, and memory usage data from standard edge computing devices.

To evaluate the proposed model, the following network performance metrics were calculated mathematically using the standard definitions below. Let T represent the total observation time, N_{sent} the total number of packets transmitted, and N_{received} the total number of packets successfully received. Let T denote the measurement interval (seconds). For packet k , generation time t_k^{gen} , sender transmit time t_k^{tx} , receiver deliver time t_k^{rx} , payload size b_k (bits). Throughput represents the total successfully received data per unit time and is expressed in bits per second (bps):

$$Thr_s[\text{bps}] = \frac{\sum_{k \in K_s} b_k 1\{k \text{ delivered}\}}{T}$$

MPTCP aggregate $Thr_{\text{agg}} = \sum_{s=1}^S Thr_s$, Count bytes at the receiver (successful payload only) to avoid double-counting retransmissions. Packet Loss Ratio quantifies the percentage of packets that failed to reach the destination:

$$PLR = 1 - PDR = 1 - \frac{N_{\text{delivered}}}{N_{\text{sent}}}$$

with N_{sent} all packets transmitted by the sender during T , and $N_{\text{delivered}}$ those delivered to the application at the receiver. Latency measures the total delay experienced by each packet from transmission to successful reception:

$$d_k = t_k^{\text{rx}} - t_k^{\text{tx}}$$

Jitter represents the variation in latency between consecutive packets, a Simple, robust definition (RFC-style running estimator):

$$J_i = J_{i-1} + \frac{|d_i - d_{i-1}| - J_{i-1}}{16}, J_1 = 0$$

Report the steady-state J (seconds). Alternatively, use the standard deviation of $\{d_k\}$. Age of Information (AoI) for a flow at time t is:

$$\Delta(t) = t - u(t)$$

where $u(t)$ is the generation time of the most recently delivered update by time t . Discrete, sample-wise average AoI over T :

$$\bar{\Delta} = \frac{1}{N_{delivered}} \sum_{k=1}^{N_{delivered}} (t_k^{rx} - t_k^{gen})$$

$$\Delta_{avg} = \frac{1}{T} \sum_{k=1}^{N_{delivered}} \frac{(t_{k+1}^{rx} - t_k^{rx})(2(t_k^{rx} - t_k^{gen}) + (t_{k+1}^{rx} - t_k^{rx}))}{2}$$

(with $t_{N+1}^{rx} := T$ if the last segment extends to T). In our experiments we report the discrete average Δ (ms) as “Average AoI.”

Reliability represents the successful delivery ratio of packets and can be expressed as:

$$\text{Reliability (\%)} = 100 \times \frac{N_{delivered}}{N_{sent}}$$

All values were obtained and then reported as mean $\pm$ std of three runs (seeds 10/20/30). 95% confidence intervals (CI) was estimated using Student t distribution. We report also CDFs on latency, AoI, such that we reveal tail behavior.

The GNN was trained on a composite. Figure 2 illustrates the effectiveness of various scheduling models in reducing the Average Age of Information (AoI), which represents the freshness of data at the user's side. The lower AoI value indicates that a system is able to deliver more current and real-time information. The AoI of the best but not the optimal model, Pokhrel et al. (2022), is 52 ms, and, compared to it, the GNN-AoI (Proposed) approach obviously performs better, and the AoI is much lower, 38 ms. Such classic models as Wu et al. (2021) and Xing et al. (2021) demonstrate higher AoI indicators (up to 60 ms), which indicates their ineffectiveness in the context of dynamics and rapidly changing network conditions. The difference is that GNN-AoI uses the real-time graph-based path scheduling dynamic to adapt to changes in congestion, the quality of a signal, and user priority, which contributes to its superiority. Figure 3, the packet loss rate of all the selected scheduling schemes are compared. Packet loss is one of the key instruments of measuring the reliability of a given communications system. As illustrated, the proposed GNN-AoI model results in a huge reduction of the packet loss to 1.2 percent as compared to any traditional approach. Other models, such as Xing et al. (2021) and Gumasthi & Baswade (2024), have a higher rate of losses that reach the level of 4.5-5.0%. This robustness is achievable in the GNN-AoI model by helping avoid congested or lossy paths in its graph neural network that considers node

and edge features, such as queue length, packet drop rate, and congestion level. The successful path selection ensures high data delivery with the variable traffic and different radio conditions. Figure 4 indicates the average throughput, the speed with which the data are transferred successfully between the stations in the network. Throughput can directly be used to measure its efficiency in bandwidth. At the speed of 68 Mbps, the GNN-AoI model is also better than the other two, which are still less than 58 Mbps. Naturally, the better performance is achieved by this model, since it utilizes MPTCP to load balance multiple subflows and GNN to estimate graph structures in real-time and come to sensible decisions. Despite showing a good throughput, models like those put forward by Wu et al. (2021) and Zhao et al. (2024) still cannot be potentially optimized as graph-based learning. This conclusion shows that GNN-AoI can enhance the use of a network and maintain dependability and novelty.

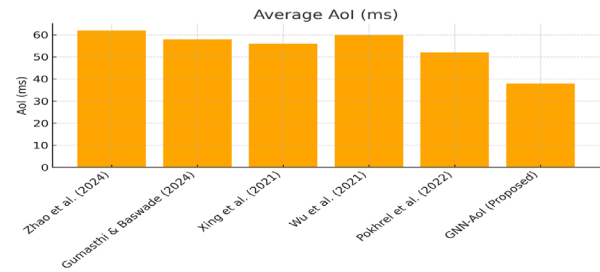


Figure 2: Average Age of Information (AoI)

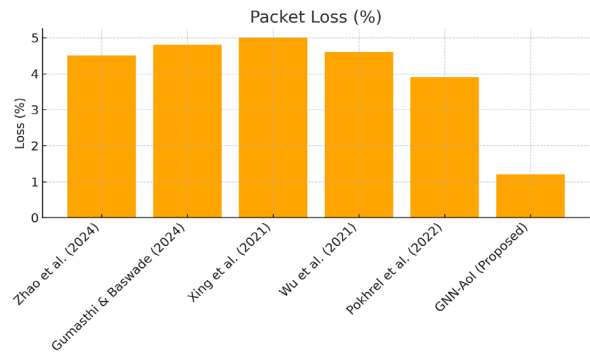


Figure 3: Packet Loss (%)

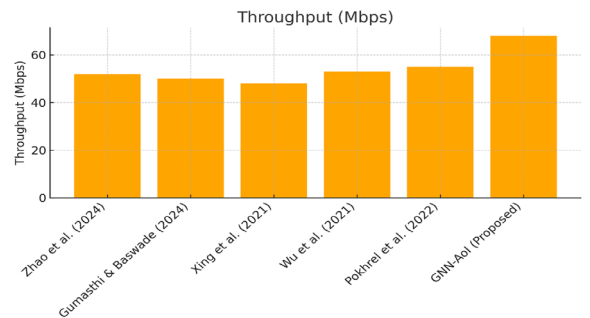


Figure 4: Throughput (Mbps)

The time the data packets pass within their path is called latency. In online gaming applications, video streaming applications, and industrial Internet of Things, low latency is crucial for interactive and real-time applications. GNN-AoI achieves 48 ± 3 ms average latency versus 66 ± 4 ms (Zhao et al., 2024) and 78 ± 5 ms (Wu et al., 2021), i.e., a 27% latency reduction relative to 66 ms. We also observe 38 ± 3 ms average AoI (vs 52 ± 4 ms), $1.2 \pm 0.2\%$ packet loss, and 68 ± 2 Mbps. This corresponds to a 27% reduction in average latency (from 66 ms to 48 ms). The selection of optimal path and real-time adaptability to network build-up and delay minimizes the latency. Because of the constant updating (using the GNN inference) of the path scores, which is the weighted effort of the node latency and signal strength, the proposed model shows efficacy in data routing with the least delay paths, and in turn, achieves the lowest transmission delay. The GNN-AoI model was compared against five recent scheduling models, including those by Zhao et al. (2024), Gumasthi & Baswade (2024), Xing et al. (2021), Wu et al. (2021), and Pokhrel et al. (2022). The findings indicate that GNN-AoI saved the most up-to-date updates because the average Age of Information (AoI) was 38 milliseconds. Other than that, the packet loss proportions were minimized greatly to 1.2 %, and the throughput of the best-performing models exceeded 68 Mbps. 95%. Such benefits are largely explained by the fact that the GNN model can process the topological and spatial knowledge in the network and adjust to alterations in real-time in various traffic, congestion and the levels of link qualities. Classic models can hardly adapt to the complex network environment, though they collaborate very well in a contestable environment. On the other hand, GNN-AoI model proposed is stable and adaptive which guarantees successful and consistent choice of paths. The routine put on thorough everything. Mobility Evaluation and Stress: In order to test the robustness, the simulations were carried to varying user-mobility speeds (1–30 m/s), load (20-80 UEs) and mixed radio types (LTE:5G:mmWave = 3:3:9). GNN-AoI could achieve AoI < 45 ms and 1.5 loss even at high mobility (in comparison with baselines, AoI was reduced by more than 20). Based on the tests of burst-loss and asymmetric link, tail-latency variance (p95) changed by a factor of only ± 3 ms, which is an affirmation of resilience.

Table 2: Performance Comparison with Existing Scheduling Models

Model	Average AoI (ms)	Packet Loss (%)	Throughput (Mbps)	Latency (ms)
Zhao et al. (2024)	52	3.2	58	66 ± 4
Gumasthi & Baswade (2024)	58	4.1	53	71 ± 3
Xing et al. (2021)	55	4.7	50	70 ± 4
Wu et al. (2021)	60	4.5	54	78 ± 5 ms
Pokhrel et al. (2022)	52	3.5	57	68 ± 3
GNN-AoI (Proposed)	38	1.2	68	48 ± 3

The cumulative distribution of end to end latency reveals that the GNN-AoI patterns have lower delays over the whole range than any of the baselines (left-shifted curve $\Rightarrow$ first-order stochastic dominance). The p95 and p99 indicators show that the tail latencies of GNN-AoI are significantly smaller and thus more stable and have less extreme delay events in heterogeneous radio conditions and mobility. The variability of error-bands across seeds is insignificant in this scale. As confirmed by the Latency CDF in Figure 5, GNN-AoI dominates the competitive schedulers in have almost all quantiles. Specifically, tail behavior (p95/p99) is significantly tighter in the case of GNN-AoI, which means that it is highly responsive to bursty congestion and handovers. It also complements the mean results showing that not only are improvements limited to averages but also to the worst-case

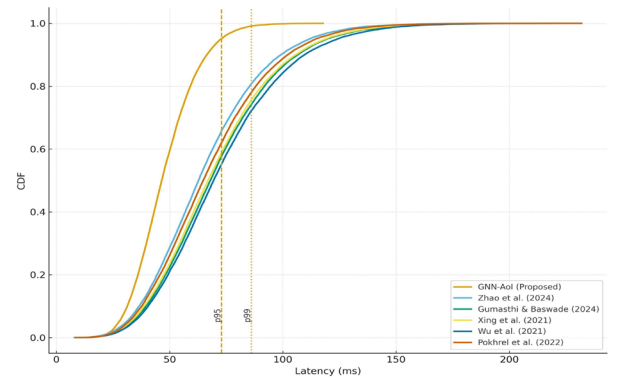


Figure 5 Latency CDF. Tail behavior at p95/p99 highlights stability.

latency which is vital to real-time streaming. The Age of Information distribution of GNN-AoI is more uniformly lower, with a strong shift on the left as compared to recent MPTCP schedulers. The smaller p95/p99 of tails means the fresher the updates more often and the more episodes of stale information the smaller, which is due to the context-sensitive choice of paths and avoidance of congestion of the model. Figure 6 indicates that GNN-AoI provides fresher information throughout the quantiles, and not only it improves the mean AoI but also it decreases the tail (lower p95/p99). This shows that the suggested snapshot-temporal graph modelling and attention-based message passing are effective in prioritizing real time updates among varying qualities and loads of links. Figure 5 (Latency CDF) and Figure 6 (AoI CDF) indicate that GNN-AoI resolves the performance or robustness issues of both the mean and the tail of performance, which is stochastic dominant as compare to baselines, so that it solves the real-time constraint issue better. The experiment was run on an NVIDIA Jetson AGX (32 GB RAM) and Intel Xeon E-2276 processor. The inference time per snapshot was at an average of 4.8 ms (GPU) and 9.6 ms (CPU), which are equivalent to less than 5 percent CPU and less than 2 percent memory overheads per node. This validates the real-time viability of GNN-AoI in the latency of MEC.

5. CONCLUSION

This study proposed GNN-AoI, a graph-neural scheduler for MPTCP that explicitly targets data freshness (AoI) while balancing reliability and capacity. By unifying AoI theory with attention-based message passing over snapshot temporal graphs, we demonstrated statistically significant improvements over standard and recent baselines: -27% latency, -27% average AoI, 1.2% loss, and up to 68 Mbps throughput, with consistent CDF gains in the tails. Based on the use of GNNs (Graph Attention Networks) to intelligently learn the optimal transmission paths, the framework is also able to model the edge network as a dynamic graph, irrespective of the number and type of heterogeneous radio access technologies to be used, including LTE, 5G, and mmWave. Since low-latency decision-making and privacy come as a necessity of real-time inference and real-time scheduling close to the users, the proposed system architecture suggests the utilization of Mobile Edge Computing (MEC). The features added to the graph abstraction, AoI, queue length, signal strength, packet loss, and congestion level make the development of context-aware decisions, which it was not possible to achieve in the application of conservative scheduled algorithms, possible. GNN-AoI is better and already demonstrated an advantage over five state-of-the-art schedulers in long-range simulations with ns-3 and PyTorch Geometric. It has the lowest packet loss rate (1.2 %), the highest throughput (68 Mbps), the lowest latency (48 ms), and the lowest AoI (38 ms) as the

results indicate. These findings can support the theoretical principled hypothesis that GNNs can well explain the time, the space variance of dynamic wireless networks because of which the wireless networks could be flexible and scaleup the multipaths.

Unlike traditional and heuristic-driven schedulers, GNN-AoI adapts to variation in network topology and user mobility as well as traffic demand. It is also particularly suitable in future 5G and beyond systems that can support mission-critical and real-time applications such as autonomous mobility, AR/VR, and remote control, because it is able to balance out freshness, reliability, and bandwidth usage. Overall, GNN-AoI would replace smart network scheduling and set the stage for more extensive adaptation of AI-native protocols in wireless networks. In future, this model will be extended to facilitate federated learning of edge intelligence to preserve privacy, and its effectiveness will be determined in the hardware-in-the-loop settings. Future work includes on-device MEC runtime profiling (CPU/GPU/latency budgets), federation training between nodes in the MEC and extreme mobility stress tests and blockage stress tests.

6. References

- Wu, H., Tian, H., Fan, S., & Ren, J. (2020). *Data age aware scheduling for wireless powered mobile-edge computing in industrial internet of things*. *IEEE Transactions on Industrial Informatics*, 17(1), 398-408.
- Mohammed, A. A. S., Shakor, P., Abdullah, S. K., Mohammed, M. A., Abbas, S. J., Salman, H. M., ... & Kalamatovich, K. R. *A Roadmap to Seamless Connectivity via the Integration of 5G and Radio Access Networks*.
- Jalal, S. K., Yousif, R. Z., Al-Mukhtar, F. H., & Kareem, S. W. (2025). *An optimized up to 16-user and 160 Gbps dual cascaded optical modulators PON-based power combined array fiber Bragg grating and pre-distortion device for 5th G system*. *Photonic Network Communications*, 49(1), 1-14.
- Aalsaud, A., Kareem, S. W., Yousif, R. Z., & Mohammed, A. S. (2024). *Ensemble Transfer Learning for Botnet Detection in the Internet of Things*. *Scalable Computing: Practice and Experience*, 25(5), 4312-4322.
- Yousif, R. Z., Jalal, S. K., & Al-Mukhtar, F. H. (2024). *Enhanced passive optical network system-based VCSEL and PSK electrical modulator for 5th generation*. *Wireless Networks*, 30(4), 2203-2217.
- Chiariotti, F. (2024). *Age of Information Analysis for a Shared Edge Computing Server*. *IEEE Transactions on Communications*.

- Abbas, A. A., Abbasi, F., Abbasi, Q. H., Abd-Elmagid, M. A., Abdallah, M., Abdel-Aty, M. A., ... & Akar, M. (2020). 2020 Index IEEE Transactions on Vehicular Technology Vol. 69. *IEEE Transactions on Vehicular Technology*, 69(12).
- Baccarelli, E., Scarpiniti, M., Momenzadeh, A., & Ahrabi, S. S. (2022). AFAFed--Protocol analysis. *arXiv preprint arXiv:2206.14927*.
- Zhao, B., Yang, W., Du, W., Ren, Y., Sun, J., Wu, Q., & Zhou, X. (2024). A multipath scheduler based on cross-layer information for low-delay applications in 5G edge networks. *Computer Networks*, 244, 110333.
- Poorzare, R., & Waldhorst, O. P. (2023). Toward the implementation of MPTCP over mmWave 5G and beyond: Analysis, challenges, and solutions. *IEEE Access*, 11, 19534-19566.
- Zhao, B., Yang, W., Du, W., Ren, Y., Sun, J., & Zhou, X. (2023, July). Cps: A multipath scheduling algorithm for low-latency applications in 5g edge networks. In *2023 32nd International Conference on Computer Communications and Networks (ICCCN)* (pp. 1-10). IEEE.
- Mahmud, I., Lubna, T., & Cho, Y. Z. (2022). Performance evaluation of MPTCP on simultaneous use of 5G and 4G networks. *Sensors*, 22(19), 7509.
- Polese, M., Jana, R., & Zorzi, M. (2017). TCP and MP-TCP in 5G mmWave networks. *IEEE Internet Computing*, 21(5), 12-19.
- Pokhrel, S. R., Choi, J., & Walid, A. (2022). Fair and efficient distributed edge learning with hybrid multipath TCP. *IEEE/ACM Transactions on Networking*, 31(4), 1582-1594.
- Rico, D., & Merino, P. (2020). A survey of end-to-end solutions for reliable low-latency communications in 5G networks. *IEEE Access*, 8, 192808-192834.
- Gumasthi, N. B., & Baswade, A. M. (2024, January). Priority-Based MPTCP Scheduler for 5G and Beyond Heterogeneous Links. In *2024 16th International Conference on COMMunication Systems & NETworkS (COMSNETS)* (pp. 1170-1174). IEEE.
- Cao, J., Su, X., Finley, B., Pauanne, A., Ammar, M., & Hui, P. (2021, December). Evaluating multimedia protocols on 5G edge for mobile augmented reality. In *2021 17th International Conference on Mobility, Sensing and Networking (MSN)* (pp. 199-206). IEEE.
- Pokhrel, S. R., Pan, L., Kumar, N., Doss, R., & Vu, H. L. (2021). Multipath TCP meets transfer learning: A novel edge-based learning for industrial IoT. *IEEE Internet of Things Journal*, 8(13), 10299-10307.
- Wu, H., Caso, G., Ferlin, S., Alay, Ö., & Brunstrom, A. (2021). Multipath scheduling for 5G networks: Evaluation and outlook. *IEEE Communications Magazine*, 59(4), 44-50.
- Lorincz, J., Klarin, Z., & Ožegović, J. (2021). A comprehensive overview of TCP congestion control in 5G networks: Research challenges and future perspectives. *Sensors*, 21(13), 4510.
- Singh, S., Maheshwari, M. K., Kanagarathinam, M. R., Masud, A. R., & Qasim, I. (2022). Nexgen s-mptcp: Next generation smart multipath tcp controller. *IEEE Access*, 10, 96079-96090.
- Kang, Y., Kim, C., An, D., & Yoon, H. (2020). Multipath transmission control protocol-based multi-access traffic steering solution for 5G multimedia-centric network: Design and testbed system implementation. *International Journal of Distributed Sensor Networks*, 16(2), 1550147720909759.
- Lee, C., Jung, J., & Chung, J. M. (2020). DEFT: Multipath TCP for high speed low latency communications in 5G networks. *IEEE Transactions on Mobile Computing*, 20(12), 3311-3323.
- Ito, K., & Izuka, N. (2023, March). Proposal of Client-Server Based Vertical Handover Scheme Using Virtual Routers for Edge Computing in Local 5G Networks and WLANs. In *2023 IEEE 13th Annual Computing and Communication Workshop and Conference (CCWC)* (pp. 0999-1004). IEEE.
- Tong, H., Wang, T., Zhu, Y., Liu, X., Wang, S., & Yin, C. (2021). Mobility-aware seamless handover with MPTCP in software-defined HetNets. *IEEE Transactions on Network and Service Management*, 18(1), 498-510.
- Carrilho, B. (2023). Multipath Video Transport for Edge-Supported Cooperative Perception Services (Master's thesis, Universidade do Porto (Portugal)).
- Xiao, X., Zhao, M., & Zhu, Y. (2022). Multi-stage resource-aware congestion control algorithm in edge computing environment. *Energy Reports*, 8, 6321-6331.

- Alzadjali, A., Esposito, F., & Deogun, J. (2020, November). A contextual bi-armed bandit approach for MPTCP path management in heterogeneous LTE and WiFi edge networks. In *2020 IEEE/ACM Symposium on Edge Computing (SEC)* (pp. 307-316). IEEE.
- Hurtig, P., Grinnemo, K. J., Brunstrom, A., Ferlin, S., Alay, Ö., & Kuhn, N. (2018). Low-latency scheduling in MPTCP. *IEEE/ACM transactions on networking*, 27(1), 302-315.
- Tomar, P., Kumar, G., Verma, L. P., Sharma, V. K., Kanellopoulos, D., Rawat, S. S., & Alotaibi, Y. (2022). Cmt-sctp and mptcp multipath transport protocols: A comprehensive review. *Electronics*, 11(15), 2384.
- Shao, X., Wu, C., Chen, X., & Zhao, W. (2022). Intelligent Mobility and Edge Computing for a Smarter World. *Mobile Networks and Applications*, 27(6), 2215-2217.
- Xing, Y., Xue, K., Zhang, Y., Han, J., Li, J., Liu, J., & Li, R. (2021). A low-latency MPTCP scheduler for live video streaming in mobile networks. *IEEE Transactions on Wireless Communications*, 20(11), 7230-7242.
- Hammad, M., Altarawneh, K., Almahmood, A. (2024). Cyber Attack Intensity Prediction Using Feature Selection and Machine Learning Models. In: Latifi, S. (eds) *ITNG 2024: 21st International Conference on Information Technology-New Generations*. ITNG 2024. *Advances in Intelligent Systems and Computing*, vol 1456. Springer, Cham.
- Alkhdour, T. A. Y. S., Alrawashdeh, R. A. N. A., Almaiah, M. O. H. A. M. M. E. D., Alali, R. O. M. E. L., Salloum, S. A. I. D., & ALDAHAYANI, T. H. (2024). A new technique for detecting email spam risks using LSTM-particle swarm optimization algorithms. *Journal of Theoretical and Applied Information Technology*, 102(14).
- Altarawni, I., Tarawneh, M., Alzyoud, F., Almuhasien, R., Aljaafreh, H., & Altarawneh, K. *Detection Tool Based on Yara Rules for Emoted Malware*.
- Khalid Altarawneh, et al. (2023). Hybrid Convolution neural Network and Graph Neural network for Detection of Leukocyte. *International Journal on Recent and Innovation Trends in Computing and Communication*, 11(9), 2995-3002.



Analytical Traveling-Wave Solutions of the Conformable Fractional (2+1)-Dimensional Zakharov–Kuznetsov Equation via the Unified Method

Elzain A. E. Gumma

Department of Mathematics, College of Science, Northern Border University, Arar, Saudi Arabia.

(Received: 11th November 2025; Accepted: 20th December 2025)

Abstract

This study investigates the time conformable fractional (2+1)-dimensional Zakharov–Kuznetsov (ZK) equation using the Unified Method (UM) to obtain analytical traveling-wave solutions. The derived solutions include hyperbolic, trigonometric, and rational function forms that describe different nonlinear wave behaviors. Graphical analyses are carried out for different fractional orders to examine how the fractional parameter influences wave configuration and amplitude. The findings indicate that a reduction in the fractional order causes the nonlinear wave profiles to transition gradually from localized soliton patterns to smoother, dissipative structures. This confirms the UM is a powerful, systematic, and efficient analytical tool for solving a wide class of fractional nonlinear partial differential equations.

Keywords: Unified method; nonlinear fractional partial differential equation; fractional derivatives; traveling-wave solutions.



(*) Corresponding Author:

By Elzain A. E. Gumma

Department of Mathematics, College of Science, Northern Border University, Arar, Saudi Arabia.

1. Introduction

Nonlinear partial differential equations (NLPDEs) are fundamental to modeling and interpreting complex behaviors in physical, biological, and engineering systems. They have found extensive applications in fluid mechanics, material sciences, environmental modeling, biomedical engineering, physics-informed machine learning, and quantum research [1–6].

Various analytical approaches have been proposed for obtaining exact solutions of NLPDEs, including the Jacobi elliptic function expansion method [7], (G'/G)-expansion [8], the Tanh–Sech method [9], and modified (w/g)-expansion methods [10]. In this work, the unified method (UM) is employed to derive analytical solutions of the time-fractional (2+1)-dimensional ZK equation. Compared with the aforementioned methods, the UM provides greater flexibility with fewer restrictive assumptions and, unlike integrability-dependent techniques, is well suited for fractional, non-integrable, and multidimensional nonlinear equations. The ZK equation is a multidimensional generalization of the well-known Korteweg–de Vries (KdV) equation, which models the evolution of weakly nonlinear ion-acoustic waves in a magnetized plasma.

As defined in [4], the (2+1)-dimensional ZK equation is mathematically expressed as:

$$\varphi_t + a\varphi \varphi_x^p + b(\varphi_{xx}^q + \varphi_{xy}^r)_x = 0. \quad (1)$$

where $a, b \in \mathbb{R}, p, q, r \in \mathbb{Z}, x$ and y are spatial coordinates and t the time. The nonlinear parameter values (p, q, r) lead to more complex wave structures, such as amplitude modulation, wave steepening, and enhanced nonlinear interactions, which can be addressed by the same analytical framework. The ZK equation arises from the dynamics of ion-acoustic waves from the dynamics of ion-acoustics waves in a magnetized plasma. The ZK equation has significant applications in several areas of physics including, astrophysics, fluid dynamics and nonlinear optics [11].

Although several fractional derivatives exist, this study employs the conformable fractional derivative (CFD) for the fractional (2+1)-dimensional ZK equation because it avoids nonlocal integral kernels while retaining essential classical calculus properties such as linearity and the product and chain rules. Unlike Riemann–Liouville [12], beta [13] and Caputo [14] fractional derivatives, the CFD simplifies analytical and symbolic computations, allowing standard techniques like traveling-wave reductions to be applied directly. At the same time, it captures local fractional dynamics and weak memory effects while remaining closely connected to classical models. The fractional (2+1)-dimensional ZK equation is

$$\mathbb{D}_t^\alpha \varphi + a\varphi \varphi_x + b(\varphi_{xx} + \varphi_{xy})_x = 0, \quad 0 < \alpha \leq 1. \quad (2)$$

In this expression, $\mathbb{D}_t^\alpha$ in CFD indicates the conformable fractional derivative of order α with respect to t . By adjusting the fractional order α , a broad range of wave propagation phenomena between purely local (classical).

As introduced in [15], the CFD of order with respect to the independent variable can be formulated as follows:

$$\begin{aligned} \mathbb{D}^\alpha \varphi(t) &= \lim_{\delta \rightarrow 0} \frac{\varphi(t+\delta t^{1-\alpha}) - \varphi(t)}{\delta}, \quad 0 < \alpha \leq 1. \\ \varphi^{(\alpha)}(0) &= \lim_{\delta \rightarrow 0^+} \varphi^{(\alpha)}(t). \end{aligned}$$

According to [15, 16], the CFD retains the basic properties of the classical derivative, supports analytical and numerical solution procedures for fractional differential equations. In this work, the UM is employed to derive exact solutions of the conformable time fractional ZK equation.

The UM is a versatile analytical technique that yields exact closed-form solutions for nonlinear and fractional partial differential equations without relying on small parameters [17-20].

The primary goal of this work is to verify the capability and efficiency of the applied method in addressing the fractional ZK equation. Although several studies have examined the nonlinear ZK equation using various analytical techniques, the unified method has not been widely applied to its fractional counterpart [11,21]. The originality of this study stems from employing the unified method to obtain exact analytical solutions for the fractional ZK equation, which has received limited attention in previous research. The remainder of this paper is structured as follows: Section 2 outlines the unified method. Section 3 demonstrates its implementation for the fractional ZK equation, Section 4 displays and analyzes the graphical results, Section 5 discussed the stability of the unified method and Section 6 summarizes the key conclusions of the study.

2. Description of the unified method

The procedural steps of the method can be summarized as follows [18]:

Step 1: Consider a NLPDE of the form:

$$F(\varphi, \mathbb{D}_t^\alpha \varphi, \mathbb{D}_x^\alpha \varphi, \varphi_x, \varphi_y, \varphi_{xx}, \varphi_{yy}, \dots) = 0. \quad (3)$$

To determine the analytical solutions of Eq. (3), the following traveling-wave transformation is introduced,

$$\varphi(x, y, t) = \varphi(\zeta), \quad \zeta = x + y - ct^\alpha/\alpha. \quad (4)$$

Eq. (3) is reduced to an ODE:

$$F(\varphi, \varphi', \varphi'', \varphi''', \dots) = 0, \quad (5)$$

where $\varphi' = \frac{d\varphi}{d\zeta}$.

Step 2: The solution Eq. (5) is assumed to be of the form:

$$\varphi(\zeta) = a_0 + \sum_{i=1}^N [a_i \Omega^i + b_i \Omega^{-i}], \quad (6)$$

where $\Omega = \Omega(\zeta)$ satisfies the Riccati equation

$$\Omega' = \tau + \Omega^2(\zeta), \quad (7)$$

where τ is a constant. The positive integer N is determined by balancing the highest-order derivative terms with the highest-degree nonlinear terms in Eq. (5). Moreover y, a_0, a_i, b_i ($1 \leq i \leq N$) represent unknown coefficients to be determined.

Step 3: Substituting Eqs. (6) and (7) into Eq. (5) and equating the coefficients of identical powers of Ω to zero, a system of algebraic equations is obtained. This system is solved symbolically using Maple to compute the parameters a_0, a_i, b_i and τ . The obtained parameters, along with the general form of Eq. (6), are then employed to construct the exact solutions of Eq. (3).

The general solutions of Eq. (7) can be classified into three distinct families as follows:

Family 1. If $\tau < 0$, the corresponding solutions are expressed as

$$\Omega(\zeta) = \begin{cases} \Omega_1 = \frac{\sqrt{-(\rho^2 + \nu^2)}\tau - \rho\sqrt{-\tau}\cosh(2\sqrt{-\tau}(\zeta + \zeta_0))}{\rho \sinh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \nu} \\ \Omega_2 = \frac{-\sqrt{-(\rho^2 + \nu^2)}\tau - \rho\sqrt{-\tau}\cosh(2\sqrt{-\tau}(\zeta + \zeta_0))}{\rho \sinh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \nu} \\ \Omega_3 = \sqrt{-\tau} + \frac{-2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) - \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \\ \Omega_4 = -\sqrt{-\tau} + \frac{2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \end{cases} \quad (8)$$

Family 2. If $\tau > 0$, the solutions are

$$\Omega(\zeta) = \begin{cases} \Omega_5 = \frac{\sqrt{(\rho^2 - \nu^2)}\tau - \rho\sqrt{\tau}\cos(2\sqrt{\tau}(\zeta + \zeta_0))}{\rho \sin(2\sqrt{\tau}(\zeta + \zeta_0)) + \nu} \\ \Omega_6 = \frac{-\sqrt{(\rho^2 - \nu^2)}\tau - \rho\sqrt{\tau}\cos(2\sqrt{\tau}(\zeta + \zeta_0))}{\rho \sin(2\sqrt{\tau}(\zeta + \zeta_0)) + \nu} \\ \Omega_7 = i\sqrt{\tau} + \frac{-2\rho i\sqrt{\tau}}{\rho + \cos(2\sqrt{\tau}(\zeta + \zeta_0)) - i\sin(2\sqrt{\tau}(\zeta + \zeta_0))} \\ \Omega_8 = -i\sqrt{\tau} + \frac{2\rho i\sqrt{\tau}}{\rho + \cos(2\sqrt{\tau}(\zeta + \zeta_0)) + i\sin(2\sqrt{\tau}(\zeta + \zeta_0))} \end{cases} \quad (9)$$

Family 3. If $\tau = 0$, the solution is

$$\Omega(\zeta) = -\frac{1}{\zeta + \zeta_0}, \quad (10)$$

where $\rho \neq 0$ and $\nu, \zeta_0 \in \mathbb{R}$.

3. Application of the unified method

This section applies the unified method to obtain analytical solutions of Eq. (2). By employing the traveling wave transformation given in Eq. (4), Eq. (2) with $p = q = r = 1$ reduces to

$$-c\varphi' + a\varphi\varphi' + 2b\varphi''' = 0. \quad (11)$$

Integrating Eq. (11) and setting the constant of integration to zero to obtain

$$-c\varphi + \frac{a}{2}\varphi^2 + 2b\varphi'' = 0. \quad (12)$$

By balancing highest-order derivative term with the nonlinear term, yields Therefore, the solution of Eq. (12) can be represented as

$$\varphi(\zeta) = a_0 + a_1\Omega + a_2\Omega^2 + b_1\Omega^{-1} + b_2\Omega^{-2}. \quad (13)$$

When Eqs. (13) and (7) are substituted into Eq. (5), and the coefficients of the same powers of Ω are equated to zero, a system of algebraic equations emerges. This system is subsequently solved symbolically using Maple, resulting in the following sets of parameters:

$$\text{Set 1: } a_0 = 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2}, a_1 = 0, a_2 = 12b, b_1 = 0, b_2 = 0,$$

$$c = \pm\sqrt{64b^2\tau^2 - 2a}.$$

$$\text{Set 2: } a_0 = 8\tau b \pm \frac{\sqrt{1024b^2\tau^2 - 2a}}{2}, a_1 = 0, a_2 = 12b, b_1 = 0, b_2 = 12b\tau^2,$$

$$c = \pm\sqrt{1024b^2\tau^2 - 2a}.$$

$$\text{Set 3: } a_0 = 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2}, a_1 = 0, a_2 = 0, b_1 = 0, b_2 = 12b\tau^2,$$

$$c = \pm\sqrt{64b^2\tau^2 - 2a}.$$

Based on the previously obtained parameter sets corresponding to Families 1–3, the exact hyperbolic, trigonometric, and rational forms of the solutions to the conformable time-fractional ZK equation are derived as follows:

Family 1: For the case $\tau < 0$.

For Set (1), the Eq. (13) yields the following solutions

$$\begin{aligned} \varphi_1(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(\frac{\sqrt{-(\rho^2 + \nu^2)}\tau - \rho\sqrt{-\tau}\cosh(2\sqrt{-\tau}(x+y \pm \frac{\sqrt{64b^2\tau^2 - 2a}t^\alpha + \zeta_0))}{\rho \sinh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \nu} \right)^2, \\ \varphi_2(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(\sqrt{-\tau} + \frac{-2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) - \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \right)^2, \\ \varphi_3(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(-\sqrt{-\tau} + \frac{-2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \right)^2, \end{aligned}$$

Where $\zeta = x + y \pm \frac{\sqrt{64b^2\tau^2 - 2a}t^\alpha}{\alpha}$.

In Set (2): Equation (13) yields the following solutions.

$$\begin{aligned} \varphi_4(x, y, t) &= 8\tau b \pm \frac{\sqrt{1024b^2\tau^2 - 2a}}{2} \pm 12b \left(\frac{\sqrt{-(\rho^2 + \nu^2)}\tau - \rho\sqrt{-\tau}\cosh(2\sqrt{-\tau}(\zeta + \zeta_0))}{\rho \sinh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \nu} \right)^2 \pm \\ &\quad 12b\tau^2 \left(\frac{\sqrt{-(\rho^2 + \nu^2)}\tau - \rho\sqrt{-\tau}\cosh(2\sqrt{-\tau}(\zeta + \zeta_0))}{\rho \sinh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \nu} \right)^{-2}, \\ \varphi_5(x, y, t) &= 8\tau b \pm \frac{\sqrt{1024b^2\tau^2 - 2a}}{2} \pm 12b \left(\sqrt{-\tau} + \frac{-2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) - \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \right)^2 \pm \\ &\quad 12b\tau^2 \left(\sqrt{-\tau} + \frac{-2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) - \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \right)^{-2}, \\ \varphi_6(x, y, t) &= 8\tau b \pm \frac{\sqrt{1024b^2\tau^2 - 2a}}{2} \pm 12b \left(\sqrt{-\tau} + \frac{-2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \right)^2 \pm \\ &\quad 12b\tau^2 \left(\sqrt{-\tau} + \frac{-2\rho\sqrt{-\tau}}{\rho + \cosh(2\sqrt{-\tau}(\zeta + \zeta_0)) + \sinh(2\sqrt{-\tau}(\zeta + \zeta_0))} \right)^{-2}, \\ \zeta &= x + y \pm \frac{\sqrt{1024b^2\tau^2 - 2a}t^\alpha}{\alpha}. \end{aligned}$$

In **Set (3)**, Eq. (13) provides the corresponding solutions.

$$\begin{aligned}\varphi_7(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \tau^2 \left(\frac{\sqrt{-(\rho^2 + v^2)\tau} - \rho\sqrt{\tau}\cosh(2\sqrt{\tau}(\zeta + \zeta_0))}{\rho \sinh(2\sqrt{\tau}(\zeta + \zeta_0)) + v} \right)^{-2}, \\ \varphi_8(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(\sqrt{-\tau} + \frac{-2\rho\sqrt{\tau}}{\rho + \cosh(2\sqrt{\tau}(\zeta + \zeta_0)) - \sinh(2\sqrt{\tau}(\zeta + \zeta_0))} \right)^{-2}, \\ \varphi_9(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} + 12b \left(-\sqrt{-\tau} + \frac{-2\rho\sqrt{\tau}}{\rho + \cosh(2\sqrt{\tau}(\zeta + \zeta_0)) + \sinh(2\sqrt{\tau}(\zeta + \zeta_0))} \right)^{-2}, \\ \zeta &= x + y \pm \frac{\sqrt{64b^2\tau^2 - 2a} t^\alpha}{\alpha}.\end{aligned}$$

Family 2: For the case $\tau > 0$.

For Set (1), the resulting solutions can be directly obtained from Eq. (13).

$$\begin{aligned}\varphi_{10}(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(\frac{\sqrt{(\rho^2 - v^2)\tau} - \rho\sqrt{\tau}\cos(2\sqrt{\tau}(\zeta + \zeta_0))}{\rho \sin(2\sqrt{\tau}(\zeta + \zeta_0)) + v} \right)^2, \\ \varphi_{11}(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(i\sqrt{\tau} + \frac{-2\rho i\sqrt{\tau}}{\rho + \cos(2\sqrt{\tau}(\zeta + \zeta_0)) - i\sin(2\sqrt{\tau}(\zeta + \zeta_0))} \right)^2, \\ \varphi_{12}(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(-i\sqrt{\tau} + \frac{2\rho i\sqrt{\tau}}{\rho + \cos(2\sqrt{\tau}(\zeta + \zeta_0)) + i\sin(2\sqrt{\tau}(\zeta + \zeta_0))} \right)^2, \\ \text{where } \zeta &= x + y \pm \frac{\sqrt{64b^2\tau^2 - 2a} t^\alpha}{\alpha}.\end{aligned}$$

Under **Set (2)**, the analytical solutions are derived from Eq. (13) as follows.

Considering to **Set (3)**, Equation (13) produces the following set of solutions.

$$\begin{aligned}\varphi_{16}(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(\frac{\sqrt{(\rho^2 - v^2)\tau} - \rho\sqrt{\tau}\cos(2\sqrt{\tau}(\zeta + \zeta_0))}{\rho \sin(2\sqrt{\tau}(\zeta + \zeta_0)) + v} \right)^2, \\ \varphi_{17}(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \tau^2 \left(i\sqrt{\tau} + \frac{-2\rho i\sqrt{\tau}}{\rho + \cos(2\sqrt{\tau}(\zeta + \zeta_0)) - i\sin(2\sqrt{\tau}(\zeta + \zeta_0))} \right)^{-2}, \\ \varphi_{18}(x, y, t) &= 8\tau b \pm \frac{\sqrt{64b^2\tau^2 - 2a}}{2} \pm 12b \left(-i\sqrt{\tau} + \frac{2\rho i\sqrt{\tau}}{\rho + \cos(2\sqrt{\tau}(\zeta + \zeta_0)) + i\sin(2\sqrt{\tau}(\zeta + \zeta_0))} \right)^{-2}, \\ \text{where } \zeta &= x + y \pm \frac{\sqrt{64b^2\tau^2 - 2a} t^\alpha}{\alpha}.\end{aligned}$$

Family 3: For the case $\tau = 0$.

Sets (1–3): The corresponding solutions are derived from Eq. (13), respectively.

$$\begin{aligned}\varphi_{19}(x, y, t) &= \frac{\sqrt{-2a}}{2} + 12b \left(-\frac{1}{\zeta + \zeta_0} \right)^2, \\ \varphi_{20}(x, y, t) &= \pm \frac{\sqrt{-2a}}{2} + 12b \left(-\frac{1}{\zeta + \zeta_0} \right)^2, \\ \varphi_{21}(x, y, t) &= \pm \frac{\sqrt{-2a}}{2}, \text{ where } \zeta = x + y \pm \frac{\sqrt{-2a} t^\alpha}{\alpha}.\end{aligned}$$

4. Graphical Illustration and Analysis

This section provides graphical depictions of the conformable fractional ZK equation to examine the influence of fractional order on the solutions of $\varphi_2(x, y, t)$, $\varphi_7(x, y, t)$, $\varphi_{11}(x, y, t)$ and $\varphi_{19}(x, y, t)$. The investigation is carried out by fixing the parameters $b = v = \zeta_0 = 1$ within the spatial-temporal region $0 \leq x, t \leq 5, y = 2$. The resulting three-dimensional (3D) plots corresponding to the fractional orders $\alpha = 1, 0.75, 0.5, 0.25$ are shown in panels (A)–(D), while panel (E) presents the corresponding two-dimensional (2D) projection with $x = 1$.

Figure 1 displays 3D plots of the solutions of $\varphi_2(x, y, t)$ in panels (A–D) with parameters $\tau = -1, \rho = a = 1$. Panel (E) presents a 2D slice at $x = 1$. The surface in panel A exhibits a steep, oscillatory wave pattern with a prominent crest near the origin. The amplitude remains high and the oscillations are well-defined, reflecting a strong nonlinear interaction between dispersion and nonlinearity. This indicates a classical soliton-like structure propagating in time without significant attenuation. In panel B, the amplitude of the wave slightly decreases and the oscillations become less pronounced. The wave still preserves its solitary character but with reduced intensity, suggesting partial energy loss due to the medium's memory characteristics. In panel C, the soliton shape becomes notably flatter, and the amplitude diminishes considerably. At panel D, the surface nearly flattens out, indicating minimal variation of the solution with respect to both space and time. The amplitude is very low, representing a highly dissipative regime. Panel E presents the two-dimensional projection of $\varphi_2(x, y, t)$ for different fractional orders. It clearly demonstrates that as α decreases, the amplitude of oscillation decays rapidly, and the peaks flatten.

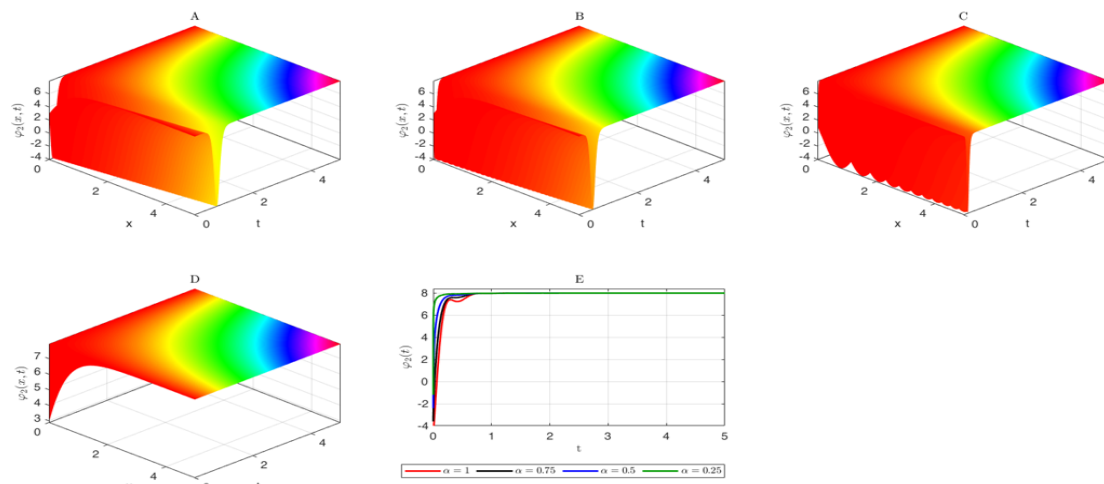


Figure 1. Graphical depiction of the nonlinear wave behavior of the exact solution showing both 3D and 2D plots corresponding to several selected values of the parameter α .

Figure 2 (Panels A–D) illustrates the 3D evolution of the solutions $\varphi_7(x, y, t)$ for parameters, $\tau = -1, \rho = a = 1$, while Panel E shows a two-dimensional slice at $x = 1$. In Panel A, a highly localized, sharp solitary peak appears near the origin, signifying strong nonlinearity with most of the system's energy concentrated at the crest. Panel B reveals multiple distinct peaks of varying amplitudes, indicating the formation of secondary solitary structures due to nonlinear interactions in the fractional framework. In Panel C, the main peak remains dominant but the

distribution becomes irregular as fractional damping smooths the surrounding oscillations. Panel D represents a strongly dissipative case, where the surface flattens and the amplitude decreases significantly. Panel E demonstrates the temporal evolution of $\varphi_7(x, y, t)$ for different fractional orders, showing a clear reduction in amplitude as α decreases—transitioning from sharp, high-intensity peaks at $\alpha = 1$ to nearly constant, smooth profiles at $\alpha = 0.25$.

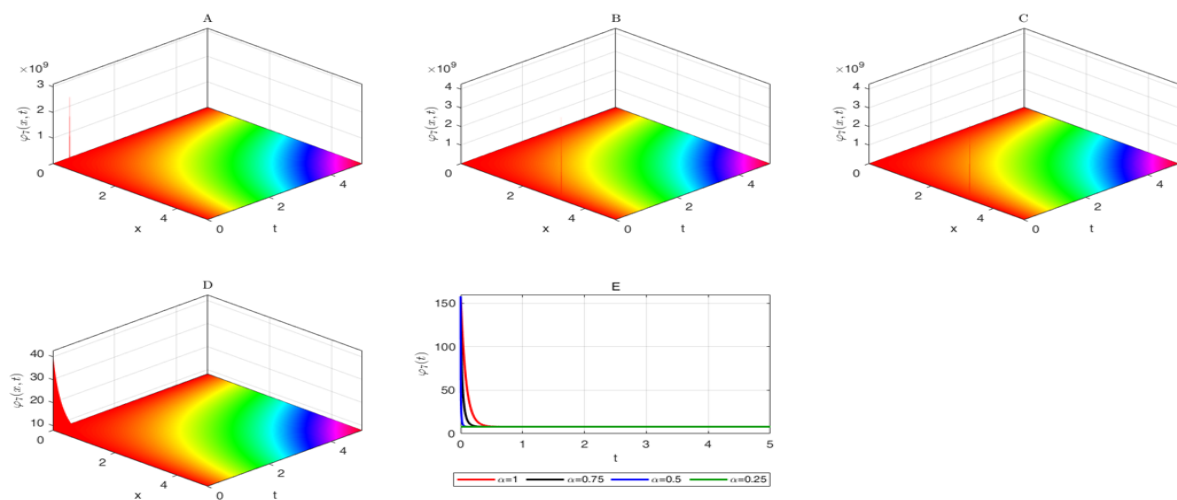


Figure 2. Graphical depiction of the nonlinear wave behavior of $\varphi_7(x, y, t)$, showing both 3D and 2D plots corresponding to several selected values of the parameter α .

Figure 3 (Panels A–D) illustrates the 3D plots of the real part of solutions $\varphi_{11}(x, y, t)$ for parameters $\tau=\rho=a=1$, while Panel E shows a two-dimensional slice at $x = 1$. In Panel A, the surface demonstrates a highly periodic oscillatory structure with nearly constant amplitude, representing a stable nonlinear soliton state where dispersion and nonlinearity are balanced. When the fractional order decreases to $\alpha = 0.25$ (Panel B), the oscillations become more irregular with sharper peaks, indicating stronger nonlinear interactions and partial energy redistribution. For $\alpha = 0.75$ (Panel C), the

amplitude begins to decay and the pattern smooths out as fractional damping dominates, signaling a shift toward a moderately dissipative regime. In the lowest case, $\alpha = 0.25$ (Panel D), high-frequency oscillations with reduced amplitude emerge, showing the dominance of diffusion and the gradual loss of wave coherence. Panel E depicts the two-dimensional temporal evolution of $\varphi_{11}(x, y, t)$ across different fractional orders, confirming this transition from nonlinear oscillatory behavior to a diffusive state.

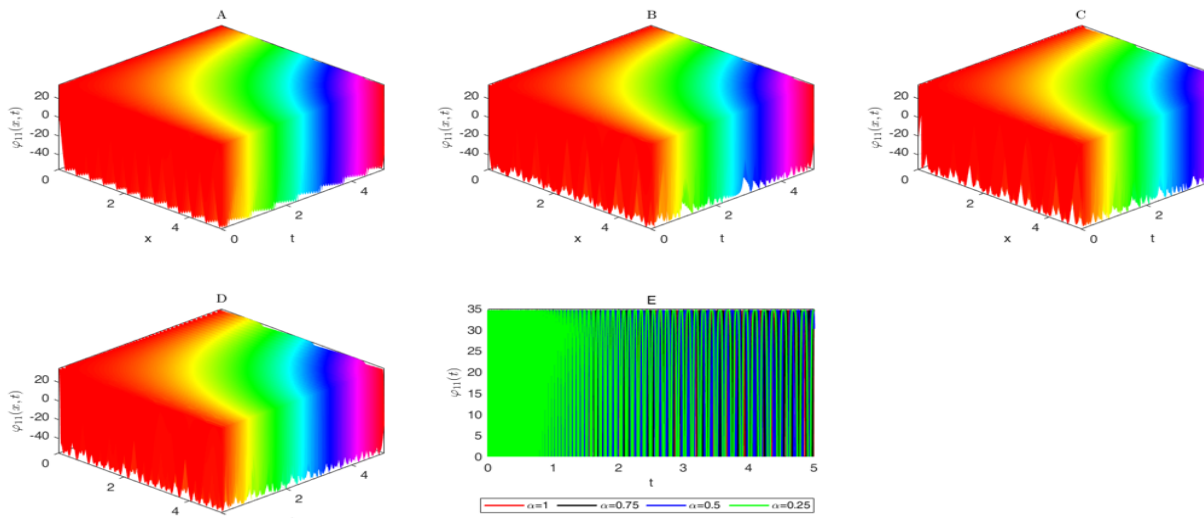


Figure 3. Graphical depiction of the nonlinear wave behavior of $\varphi_{11}(x, y, t)$, showing both 3D and 2D plots corresponding to several selected values of the parameter α .

Figure 4 (Panels A–D) presents the three-dimensional behavior of the solutions $\varphi_{19}(x, y, t)$ for parameters $a = -1$, $\rho = 2$, while Panel E shows a two-dimensional slice at $x = 1$. In Panel A, a sharp and localized peak near the origin indicates a strong nonlinear solitary wave with most of the energy confined within a narrow region, representing a stable soliton formed by the balance between nonlinearity and dispersion. As shown in Panel B, the soliton amplitude decreases and the profile becomes smoother due to increasing dispersive and damping

effects. In Panel C, the system enters a strongly dissipative regime where the amplitude drops sharply and the surface becomes nearly uniform, revealing the dominance of memory-driven diffusion over nonlinear effects. Panel E illustrates the temporal evolution of $\varphi_{19}(x, y, t)$ at different fractional orders. The results indicate that as α decreases from 1.0 to 0.25, both the amplitude and intensity of the wave diminish progressively, transforming into a smooth and attenuated diffusive structure.

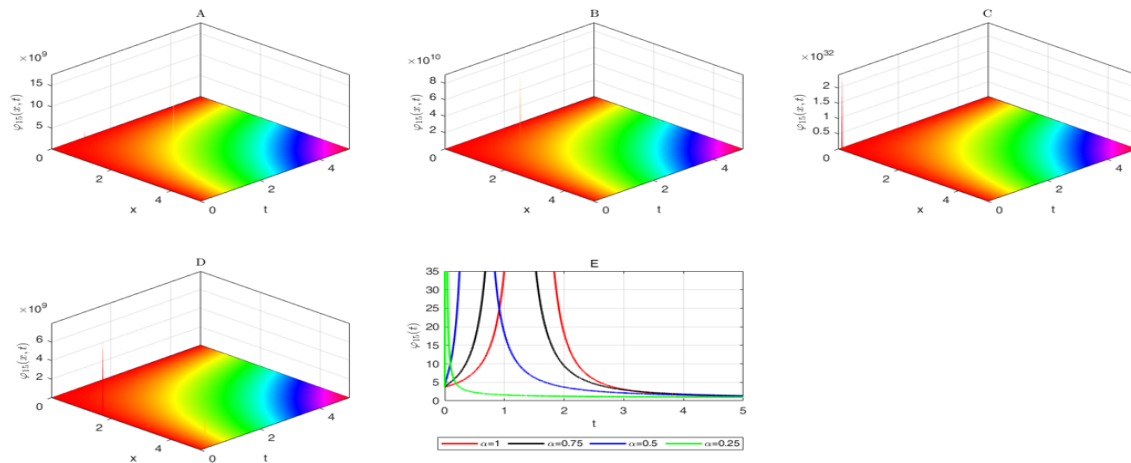


Figure 4. Graphical depiction of the nonlinear wave behavior of $\varphi_{19}(x,y,t)$, showing both 3D and 2D plots corresponding to several selected values of the parameter α .

5. Stability Discussion

The stability of the traveling-wave solutions is examined by analyzing their response to small perturbations after reducing the conformable fractional -dimensional ZK equation to an ordinary differential equation through an appropriate traveling-wave transformation. The numerical simulations and graphical representations indicate that when the fractional order , the solutions preserve strongly localized, high-amplitude soliton structures, reflecting stable wave propagation arising from a balance between nonlinear and dispersive effects. As the fractional order decreases, increased damping and memory-related effects become dominant, resulting in gradual amplitude attenuation, smoother wave profiles, and the disappearance of secondary oscillatory features. Consequently, the system evolves toward more dissipative and asymptotically stable states. These observations are consistent with established stability results for KdV and ZK-type equations and demonstrate that the fractional parameter plays a crucial role in regulating stability, while the UM effectively captures the qualitative stability properties of the obtained solutions [22].

6. Conclusion

The present study applied the Unified Method to derive exact analytical solutions of the conformable fractional ZK equation. Multiple classes of nonlinear wave solutions were derived, illustrating how the fractional parameter influences amplitude, localization, and stability. The graphical results revealed that higher values of preserve strong soliton structures, while smaller values cause amplitude decay and enhanced diffusion, emphasizing the critical role of fractional derivatives in controlling nonlinear wave phenomena. The research demonstrates that the Unified Method provides a coherent, adaptable, and computationally efficient framework for solving fractional nonlinear partial differential equations. These results provide meaningful insight into the modeling of complex physical systems characterized by nonlocal and memory-dependent dynamics, and they establish a foundation for extending the proposed methodology to higher-dimensional and variable-coefficient fractional models. Further research may focus on the analysis of coupled nonlinear fractional systems as well as numerical investigations of the ZK equation.

7. References:

- Evans, L. C. (2010). *Partial Differential Equations*. American Mathematical Society.
- Smoller, J. (1994). *Shock Waves and Reaction-Diffusion Equations*. Springer-Verlag. <https://doi.org/10.1007/978-1-4612-0873-0>
- Gilbarg, D., & Trudinger, N. S. (2001). *Elliptic Partial Differential Equations of Second Order*. Springer-Verlag. <https://doi.org/10.1007/978-3-642-61798-0>
- Wazwaz, A. (2009). *Partial Differential Equations and Solitary Waves Theory*. Higher Education Press / Springer-Verlag. <https://doi.org/10.1007/978-3-642-00251-9>
- Welly, H. N. A. (1997). Symbolic method to construct exact solutions of nonlinear partial differential equations. *Mathematics and Computers in Simulation*, 43, 13–27. [https://doi.org/10.1016/S0378-4754\(96\)00053-5](https://doi.org/10.1016/S0378-4754(96)00053-5)
- Dodd, R. K., Eilbeck, J. C., Gibbon, J. D., & Morris, H. C. (1982). *Solitons and Nonlinear Wave Equations*. Academic Press.
- Chen, Y., & Wang, Q. (2005). Extended Jacobi elliptic function rational expansion method and abundant families of Jacobi elliptic function solutions to the $(1 + 1)$ -dimensional dispersive long wave equation. *Chaos, Solitons & Fractals*, 24(3), 745–757. <https://doi.org/10.1016/j.chaos.2004.09.014>
- Wang, M., Li, X., & Zhang, J. (2008). The (G'/G) -expansion method and travelling wave solutions of nonlinear evolution equations in mathematical physics. *Physics Letters A*, 372(4), 417–423. <https://doi.org/10.1016/j.physleta.2007.07.051>
- Mal'fiet, W., & Hereman, W. (1996). The tanh method: Exact solutions of nonlinear evolution and wave equations. *Physica Scripta*, 54(6), 563–568. <https://doi.org/10.1088/0031-8949/54/6/003>
- Li, W.-A., et al. (2009). The (w/g) -expansion method and its application to the Vakhnenko equation. *Chinese Physics B*, 18(2), 1–6. <https://doi.org/10.1088/1674-1056/18/2/004>
- Hammouch, Z., & Mekkaoui, T. (2013). Approximate analytical solution to a time-fractional Zakharov–Kuznetsov equation. *International Journal of Physical Research*, 1(2), 28–33. <https://doi.org/10.14419/ijpr.v1i2.849>
- G. Jumarie, Modified Riemann–Liouville derivative and fractional Taylor series of nondifferentiable functions further results, *Computers & Mathematics with Applications*, Volume 51, Issues 9–10, 2006, Pages 1367–1376, ISSN 0898-1221, <https://doi.org/10.1016/j.camwa.2006.02.001>
- Atangana A and Goufo E F D 2014 Extension of matched asymptotic method to fractional boundary layers problems *Math. Probl. Eng. Mathematical Problems in Engineering* 1 <https://doi.org/10.1155/2014/107535>
- Diethelm, K. (2010). *The analysis of fractional differential equations: An application-oriented exposition using differential operators of Caputo type*. Springer-Verlag. <https://doi.org/10.1007/978-3-642-14574-2>
- Khalil, R., Al Horani, M., Yousef, A., & Sababheh, M. (2014). A new definition of fractional derivative. *Journal of Computational and Applied Mathematics*, 264, 65–70. <https://doi.org/10.1016/j.cam.2014.01.002>
- Al-Zhour, Z., Al-Mutairi, N., Alrawajeh, F., & Alkhasawneh, R. (2021). New theoretical results and applications on conformable fractional natural transform. *Ain Shams Engineering Journal*, 12(2), 927–933. <https://doi.org/10.1016/j.asej.2020.07.006>
- Fokas, A. S. (1997). A unified transform method for solving linear and certain nonlinear PDEs. *Proceedings of the Royal Society A*, 453(1962), 1411–1443. <https://doi.org/10.1098/rspa.1997.0077>
- T. Aydemir, Traveling-wave solution of the Tzitzéica-type equations by using the unified method, *Theor. Math. Phys.* 216 (2023), 944–960. <https://doi.org/10.1134/S0040577923070048>
- Akcagil, S., & Aydemir, T. (2018). A new application of the unified method. *New Trends in Mathematical Sciences*, 6(2), 185–199. <https://doi.org/10.20852/ntmsci.2018.261>
- Alam, N., Ullah, M., Nofal, T., Ahmed, H. M., Ahmed, K., & Al-Nahhas, M. (2024). Novel dynamics of the fractional KFG equation through the unified and unified solver schemes with stability and metastability analysis. *Nonlinear Engineering*, 13, 20240034. <https://doi.org/10.1515/nleng-2024-0034>
- Ullah, M. S., Abdeljabbar, A., Roshid, H. O., & Ali, M. Z. (2022). Application of the unified method to solve the Biswas–Arshed model. *Results in Physics*, 42, 105946. <https://doi.org/10.1016/j.rinp.2022.105946>
- Bona, J. L., & Souganidis, P. E. (1988). Stability and instability of solitary waves of Korteweg–de Vries type. *Proceedings of the Royal Society of London A*, 411, 395–412. <https://doi.org/10.1098/rspa.1987.0073>



Blockchain-Driven Privacy Preservation for Robust IoT Security with an Attribute-Reduced Hybrid Deep Representation Learning Approach

Sultan Alkhliwi

Associate Professor, Department of Computer Science, Faculty of Science, Northern Border University, Saudi Arabia-Arar

(Received: 13th September 2025; Accepted: 9th November 2025)

Abstract

The Internet of Things (IoT) is highly vulnerable to cyberattacks, such as denial-of-service attacks. An intrusion detection system (IDS) is an effective cybersecurity device mainly used to detect malicious behaviours. Recently, blockchain technology has emerged as a secure framework for the IoT by ensuring privacy and reliability. This study introduces a model in an IoT environment called Blockchain-based Attack Detection using Dimensionality Reduction and Hybrid Deep Learning Model (BCAD-DRHDLM) to enhance cybersecurity in the IoT. The model integrates several advanced techniques for the process of attack classification: Z-score standardisation system for the data pre-processing step to scale and standardise data for improved model performance, sparrow search algorithm for model of feature selection to recognise and retain pertinent features from input data and a hybrid convolutional neural network and bi-directional gated recurrent unit with additive attention mechanism (Conv-BiGRU-AA) technique. In addition, the farmer ants optimisation algorithm technique is used in the parameter refinement procedure to enhance the classification performance of the Conv-BiGRU-AA method. The BCAD-DRHDLM is validated in terms of the Edge-IIoT and ToN-IoT datasets. In comparison studies, the BCAD-DRHDLM achieves significantly higher precision values than other existing models in both datasets.

Keywords: blockchain, IoT, Farmer Ants Optimisation Algorithm, cybersecurity, DDoS, deep learning, Dimensionality



(*) Corresponding Author:

Sultan Alkhliwi

Associate Professor, Department of Computer Science, Faculty of Science, Northern Border University, Saudi Arabia-Arar

Email: salkhliwi@nbu.edu.sa

Orcid: <https://orcid.org/0000-0002-3481-549X>

1. Introduction

Currently, internet connectivity is provided in a growing number of places. The prevalent use of connected gadgets and cloud technologies has allowed novel kinds of computation outsourcing and data, along with the emergence of the Internet of Things (IoT) [1]. The upsurge in IoT gadgets and network technologies is also rapidly developing. Either the development of gadgets or technology has inspired the advancement of decentralisation methods for different scenarios [2]. Consequently, it relies on an entity or a single gadget to present resources and services due to the collaboration between many communication nodes [3]. The cybersecurity of computer systems is a significant issue. If a given application necessitates handling sensitive data, it is typically resolved by safeguarding a given device or node. Even though this solution is cost-effective, it also contains one point of failure risk [4]. Various cyber threats comprise distributed denial-of-service (DDoS), and denial-of-service (DoS) attacks are generally performed by humanly instructed methods, such as bots or botnets, which contain many gadgets with internet access [5]. Bots can exist when a computer is infected with malware through particular software. These bots carry out multiple threats, such as data stealing, ransomware or DDoS. DoS attacks are a type of menacing, intrusive and aggressive behaviour on online servers [6]. They seriously reduce the accessibility of the victim, router, host or overall network, causing severe harm to services [7]. Thus, effective recognition of DoS attacks is vital to security. Improving attack recognition is generally aimed at the progression of network-based recognition mechanisms. Fig. 1 presents the general architecture of blockchain (BC)-IoT in cybersecurity.

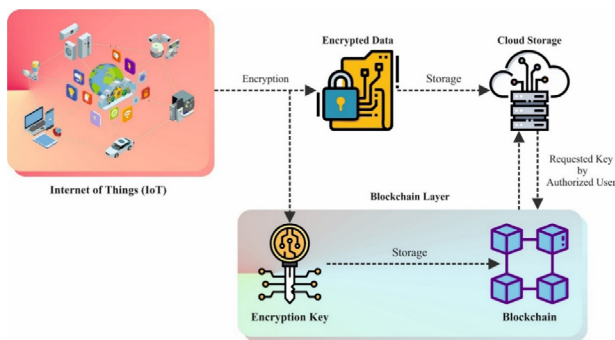


Fig. 1. General architecture of BC-IoT in cybersecurity

BC technology provides decentralised storage in which data are securely stored without requiring a single trusted party. It has previously been implemented in multiple diverse scenarios [8]. In the previous year, BC technology was accepted in various application fields to increase security concerns in a decentralised manner. Owing to its nature, this technology can be

directly applied to IoT smart home settings, as it can aid security-related use cases [9]. Recently, the utilisation of BC technology has attracted interest in the field of cybersecurity. Specifically, the use of smart contracts (SC) was combined with implementing and designing the DoS defence mechanism. An intrusion detection system (IDS) is a cybersecurity system feature that identifies systems and networks from policy breaches or malicious activities. IDS has recently attracted much attention and popularity from security experts for safeguarding IoT gadgets, and it is a hybrid method that integrates more IDS approaches [10]. Investigators are motivated to use decentralised IDS, which incorporates several deep learning (DL) and machine learning (ML) methodologies in analysing the existing progression in intelligent machines. The application of multiple DL techniques identifies risks using two classifications to categorise different threats with multi-class classification into a determined investigation field.

This study presents the Blockchain-based Attack Detection using Dimensionality Reduction and Hybrid Deep Learning Model (BCAD-DRHDL) for IoT environments. The BCAD-DRHDL is an effective model for enhancing cybersecurity in IoT networks by developing robust threat detection mechanisms to mitigate evolving security risks. The Z-score system is used in the data pre-processing phase to scale and standardise data for improved model performance. The sparrow search algorithm (SSA) is used in the FS procedure to detect and retain related features from the input data. Moreover, the hybrid convolutional neural network and bi-directional gated recurrent unit with additive attention mechanism (Conv-BiGRU-AA) technique is implemented for attack classification purposes. The parameter fine-tuning model is executed using the farmer ants optimisation algorithm (FAOA) technique. The efficacy of the BCAD-DRHDL is validated using the Edge-IIoT and ToN-IIoT datasets. The major contributions of the BCAD-DRHDL are summarised as follows:

The BCAD-DRHDL uses the Z-score to convert input features into a common scale without changing variances in the value ranges. This standardisation improves training consistency and accelerates model convergence. It improves the learning stability of the attack classification framework.

The BCAD-DRHDL implements the SSA method to select related features from higher-dimensional input data, effectively eliminating redundancy and noise. This optimisation mitigates computational load and improves detection precision. It also significantly enhances the complete efficiency of the attack classification model.

The BCAD-DRHDL applies the hybrid Conv-BiGRU-AA model, integrating convolutional layers

for the spatial extraction of the features, BiGRU for capturing the temporal dependencies, and an additive attention mechanism for focusing on critical patterns. This integration improves classification precision by learning intrinsic representations. It assists in the robust detection of various attack types in IoT data.

The BCAD-DRHDLM utilises the FAOA technique for hyperparameter tuning, which improves the convergence rate and effectively fine-tunes critical parameters. This strategic tuning process significantly enhances model performance by optimising learning dynamics. It also assists in achieving stable and efficient training outcomes.

The integration of SSA-based feature selection with the Conv-BiGRU-AA classifier and FAOA tuning introduces a novel and cohesive framework that effectively balances high accuracy, computational efficiency and adaptive optimisation. This unique integration enhances attack detection by mitigating irrelevant data while capturing complex spatial-temporal patterns. Adaptive tuning additionally refines the model parameters for robust and reliable performance in dynamic environments.

2. Literature Review

Selvarajan et al. [11] advanced a decentralised identifiable distributed ledger technology-BC (DIDL-BC) structure in which private and public keys are generated to prove the transaction. The block employs DIDL and contains the timestamp, block header information, transaction list and hash code. The main objective is to find numerous untrustworthy nodes with differing hash values. In [12], the authors examined BC and federated learning (FL) for IoT. The projected approach gathers real-world data, namely environmental conditions and traffic flow, and then encrypts, normalises and strongly keeps them on a BC to guarantee tamper-proof data management. The DAC employs progressive cryptographic models for secure data access in another stage. Ponnuru et al. [13] projected a BC-aided authentication protocol built particularly for fog-enabled IoT settings to examine the identity of users before accessing IoT gadgets. The proposed protocol applies sophisticated crypto primitives, such as hash functions, elliptic curve cryptography and BC, to determine protected communication among IoT gadgets and users. Alamri et al. [14] developed an assessment of cybersecurity threat management and a structure for BC-based identity management systems (BC-IdM) in the medical IoT. In this study, a Delphi approach is employed to examine the architecture that contains the features, which is leveraged to assess any HIoT BC-IdM methods and the cybersecurity risk management activities and processes that might be implemented. Kumar and Das [15] advanced an improved radio frequency identification authentication protocol that combines BC and edge computing. This method also uses

the real-world processing capability of edge computing, immutability of BC and decentralisation. Makhahlela et al. [16] developed a lightweight BC-based secure communication protocol that combines BC technology and lightweight encryption to generate a robust and comprehensive security solution for IoT networks. By using this technology, the proposed approach safeguards data privacy, authenticity and integrity while reducing resource utilisation in IoT gadgets, therefore addressing the unique constraints of IoT gadgets.

Pokharel et al. [17] introduced the blockHealthSecure structure that combines BC technology with cutting-edge cybersecurity procedures. The BC's immutable and decentralised framework improves the transparency, accuracy and security of electronic medical records and sensitive medical care data. Ismail et al. [18] presented a combined security architecture utilising ML and BC methods. The structure contains dual modules: ML detection and BC prevention modules. The BC prevention component has two mechanisms, trust and identity management, which use a lightweight SC to control authentication and node registration. The ML recognition component leverages the light gradient boosting machine model for classifying mischievous nodes and notifying the BC network. Kuru and Kuru [19] developed a BC-based decentralised privacy-preserving ML (DPPML) method that integrates FL to enhance identity protection and cybersecurity. The approach aims to prevent identity impersonation, credential and avatar theft and unreal transactions by removing single points of failure and detecting malicious nodes, including generative adversarial network (GAN) attacks. In [20], the authors examined a lightweight and privacy-preserving vehicular task offloading strategy utilising an attention-based heterogeneous GNN (HetGNN) within a space-air-ground integrated vehicular network, optimising latency and scalability in the Internet of Vehicles (IoV) environment. In [21], the authors developed a protected attack detection method for vehicular ad hoc networks (VANETs) by utilising the modernised random parameter-based green anaconda optimisation technique for feature selection and an ensemble machine learning model by integrating MLP, SVM, AdaBoost and Bayesian networks for accurate detection and classification of attacks. Andrei et al. [22] proposed a privacy-preserving synthetic data generation model using deep convolutional generative adversarial network (DCGAN) methodology for histopathology images of colorectal cancer, improving classification accuracy while protecting sensitive medical data. Danquah et al. [23] presented a low-complexity FL model using differentially private MLP (DP-MLP) and principal component analysis (PCA) techniques for the accurate detection of IoT botnet attacks on resource-constrained edge devices.

Kathole et al. [24] developed an ensemble DL method for IDS in IoT networks by effectively detecting and preventing unauthorised access. Nazir et al. [25] compared ensemble ML and hybrid NN techniques for precise and efficient IoT threat detection using key datasets to enhance IoT safety. A secure federated cloud storage system was developed for the Internet of Medical Things (IoMT) by applying hybrid heuristic attribute-based encryption with the permitted BC and FL using multiscale bi-long short-term memory (Bi-LSTM) [26]. The gated recurrent unit (GRU) technique ensures data confidentiality, privacy preservation and accurate disease prediction. An SC-aided BC framework integrated with ML was proposed for protected and privacy-preserving authentication in IoV using a hybrid adaptive network with MLP and ridge classifiers, optimised through the opposition beluga whale optimisation technique for effective malware detection [27]. Nazir et al. [28] systematically reviewed ML and DL models to identify IoT botnet assaults. Ganesh et al. [29] presented a BC-integrated secure data storage and task offloading framework using adaptive multiscale dilated BiLTM for user authentication and improved nuclear reaction optimisation for tuning and key generation. Hybrid attribute-based encryption with an elliptical curve cryptography model was applied to secure low-power data encryption and transmission. In [30], the authors improved IoT safety by integrating cooperative threat intelligence, BC technology and ML methods into the IoT23 dataset to increase threat recognition accuracy and reduce false negatives. Kadiyala et al. [31] developed a decentralised IDS for IoT using BC, homomorphic encryption and DL methods such as convolutional LSTM and GRU, incorporating secure hash algorithm (SHA-256), L-Diversity and digital signatures for improved privacy, anomaly detection and system integrity. Nazir et al. [32] improved IoT security by integrating FL with BC technology, using DNNs and LR in the N-BaIoT dataset to achieve high accuracy and secure decentralised model training. Slama et al. [33] presented an ML model BC-based privacy-preserving technique utilising BC and cryptographic hash functions for secure storage, integrity and reliable misbehaviour detection in VANETs.

Despite crucial improvements in integrating BC, FL, ML and DL for securing IoT, IoV and VANET environments, a key research gap exists in the unified deployment of lightweight, real-time and privacy-preserving mechanisms under constrained computational resources. Most techniques emphasise either detection accuracy or data privacy but not both simultaneously with lesser latency. Various studies lack robustness against adversarial threats, such as GAN-based attacks and do not adequately address scalability in decentralised frameworks. Moreover, the integration clarity between BC and IDS or ML models remains limited in many models. The absence of standardised evaluation metrics

and real-time interaction among SCs, encryption modules and detection systems also marks a critical research gap.

3. Methodological Frameworks

This study proposes the BCAD-DRHDLM for IoT environments. It is an effective model for enhancing cybersecurity in IoT networks by developing robust threat detection mechanisms to mitigate evolving security risks. The BCAD-DRHDLM involves different levels, such as data pre-processing, feature selection, classification and parameter tuning. Fig. 2 illustrates the overall process of the BCAD-DRHDLM.

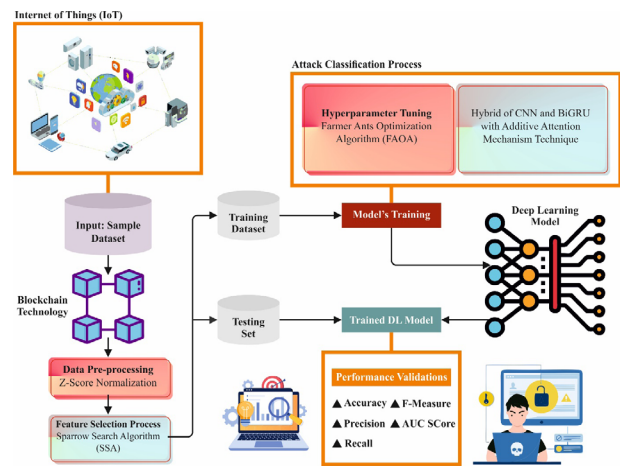


Fig. 2. Overall working process of the BCAD-DRHDLM

3.1 Data Pre-Processing Model

Initially, the Z-score model is used in the data pre-processing phase to measure and normalise data for enhanced model performance [34]. This model is chosen because it standardises data by transforming features to have a standard deviation of 1 and a mean of 0, making diverse features comparable regardless of their original scales. It is useful for algorithms sensitive to feature scales. Unlike min-max scaling, which compresses data into a fixed range and can be affected by outliers, this model is stronger, as it corresponds to data distribution. It preserves the shape of the original distribution and is effective when data follow a Gaussian distribution. Overall, it enhances convergence speed and model performance by ensuring that features contribute equally during training.

The Z-score model is a statistical method applied to standardise data by translating them into a general measure. In the cybersecurity framework, this method aids in noticing anomalies by emphasising deviances from usual behaviour in device activities, network traffic or transaction designs. This model guarantees that dissimilar features donate similarly to security models, thereby averting bias from main features. This increases the correctness of ML techniques for intrusion detection

and fraud recognition in IoT networks. By standardising data, BC-based security structures can handle transactions more effectively and precisely recognise latent attacks. This method reinforces the trustworthiness and reliability of IoT methods by enhancing real-time attack detection.

3.2 SSA-Based Feature Selection Process

The SSA identifies and retains the most related features from input data for feature selection [35]. This approach is selected for its efficiency in discovering larger composite searching regions and avoiding local best through its swarm intelligence-inspired mechanism. Compared with conventional methods, such as particle swarm optimisation, SSA provides faster convergence and a better balance between exploration and exploitation. It is simple to implement and requires fewer parameters, thus mitigating computational overhead. SSA effectively detects the most relevant features, improves model accuracy, reduces dimensionality and improves training speed and generalisation performance. This makes it appropriate for handling high-dimensional datasets in ML tasks.

The SSA is a population-based intelligence optimiser model stimulated by a sparrow's antipredator and foraging behaviours that constantly upgrade the population location over iterations until the best solution is gained. The model considers the sparrow's searching behaviour as the 'leader-follower' method that focuses on separating the population's individuals into followers and leaders. It is stimulated by the sparrow's anti-predation and foraging behaviours. As a result, the sparrow optimiser model is applied to improve the levels of decomposition and penalty features. The position of the leader equation is upgraded to the following: X_{ij}^τ

$$\sum_k \frac{\|\hat{u}_k^{n+1} - \hat{u}_k^n\|_2^2}{\|\hat{u}_k^n\|_2^2} < \varepsilon$$

where X_{ij}^τ denotes the location data of the j^{th} size of the i^{th} individual, $j=1,2,3,\dots,d$, R_2 denotes the alerted value, ST is a pre-defined constant representing the security value, Q is a randomly generated number whose value follows the standard distribution, L is an i^{th} -ordered d -dimensional matrix, and $\alpha \in (0,1)$ is an arbitrary number.

$$X_{ij}^{\tau+1} = \begin{cases} Q * \exp\left[\frac{X_{wj}^\tau - X_{ij}^\tau}{i^2}\right], & i > \frac{N}{2} \\ X_{bj}^{\tau+1} + |X_{ij}^\tau - X_{bj}^{\tau+1}| * A^+ * L, & i \leq \frac{N}{2} \end{cases}$$

$X_{ij}^{\tau+1}$ denotes the poor individual location of the individual of the population in the j^{th} size at τ iterations, A is the first-order d^{th} -dimension matrix with components 1 or -1, and $A^+ = A^{max} (AA^T)^{-1}$.

To prevent the model from dropping into the local best, part of the individual of the population should be placed under the vigilance mechanism.

$$X_{ij}^{\tau+1} = \begin{cases} X_{ij}^\tau * \sigma[X_{ij}^\tau - X_{gj}^\tau], & f_i \neq f_g \\ X_{ij}^\tau + \mu * \left[\frac{X_{ij}^\tau - X_{\omega_j}^\tau}{|f_i - f_{\omega_j}| + \delta}\right], & otherwise \end{cases}$$

where X_{gj}^τ is the global best individual location of the individual of the population at iterations, is the step controller parameter that randomly generates numbers following a standard distribution, f_i is the population's fitness value, f_{ω_j} is the best and poor fitness values between the individuals of the population, $\mu \in (0,1)$ is a set arbitrary number, and δ is a parameter set to prevent the denominator from becoming zero.

In the SSA model, the fitness function (FF) applied is expected to achieve a balance among the chosen feature counts in each solution (minimum) and the classifier precision (maximum) obtained using these chosen

$$Fitness = \alpha \gamma_R(D) + \beta \frac{|R|}{|C|}$$

where $\gamma_R(D)$ is the classifier rate of error of a presumed classifier, $|R|$ is the chosen subset cardinality, $|C|$ is the total feature counts, and α, β are dual parameters that correspond to a position of classifier excellence and subset length.

3.3 Conv-BiGRU-AA-Based Classification Method

The hybrid Conv-BiGRU-AA technique is used for attack classification [36]. It is capable of capturing spatial and temporal features in sequential data. Unlike conventional models, convolutional layers efficiently extract local patterns, while BiGRU processes the context from past and future time steps, improving sequence understanding. The attention mechanism (AAM) enhances performance by focusing on the most relevant features, resulting in better discrimination and interpretability. This hybrid approach provides higher accuracy and robustness than standalone CNN or RNN models, making it ideal for complex classification tasks.

A 1D-CNN is an NN structure that performs better in removing characteristics from shorter fixed-length inputs through a complete dataset. It is typically applied to handle one-dimensional textual data or time series data. Initially, convolutional processes are implemented to remove the main characteristics inside the sequence; then, a convolution filter (or kernel) is applied. Given W and the input sequence X , the output ξ is calculated in every position as follows:

$$\xi[j] = (X \cdot W)[j] = f(\sum_{k=0}^{K-1} X[j \times T_s + k] \cdot W[k] + b_{cm})$$

where $\xi[j]$ is the component of the sequence of output originating from the convolutional process. In Eq. (5), $X[j+k]$ is $j+k$ th the component of the sequence of input, j is the present location of the convolutional process, k is the offset and multiplied element by element and added to give the j th component of the sequence of output, T_s is the time step, $W[k]$ refers to k convolution kernel's weight, k is the convolution kernel size, b_{cm} is the term of bias, and f is the function of the activation that presents nonlinear properties. The standard activation functions include ReLU and parametric ReLU, among others.

$$x[j] = \max(X[j \times T_s : (j+1) \times T_s])$$

where $x[j]$ stands for the initial j th component. In Eq. (6), $X[j \times T_s : (j+1) \times T_s]$ specifies that a sub-sequence is designated in a sequence of input.

LSTM and GRU preserve significant historical characteristics by using a 'gate' structure. A combination of input and forgetting gates in LSTM is compressed into the update gate, including an update gate z and a reset r . x_t signifies the present input moment of the GRU component, $h_{(t-1)}$ refers to the preceding moment state, r_t is the reset gate that originates depending on Eq. (7) and is applied to establish the dependence grade of candidate state $\tilde{h}_t$ on $h_{(t-1)}$, z_t is the gate of update that can arise from Eq. (8), and h_t is the value of the output candidate after the gate of the reset process. h_t is attained by relating Eqs. (7)–(10).

$$r_t = \text{sigmoid}(U_r h_{t-1} + W_r x_t + b_r)$$

$$z_t = \text{sigmoid}(U_z h_{t-1} + W_z x_t + b_z)$$

$$h_t = \tanh(U_c(r_t h_{t-1}) + W_c x_t + b_c)$$

$$h_t = z_t h_{t-1} + (1 - z_t) \tilde{h}_t$$

In Eq. (7), U_r and W_r are the weighted matrices of the gate of reset, and b_r is the bias gate of reset. In Eq. (8), U_z and W_z are the weighted matrices of the update gate, and b_z is the bias of the update gate. In Eq. (9), b_c is the candidate hidden state's (HL) bias, and U_c and W_c are the weighted matrices of candidate HL.

Although the unidirectional GRU architecture can gather historical data from a particular point during his time, it cannot gather the before and after associated data. The backward, forward and particular computing operations are expressed in Eqs. (11)–(13), respectively.

$$\vec{h}_t = \text{GRU}_f(x_t, \vec{h}_{t-1})$$

$$\bar{h}_t = \text{GRU}_b(x_t, \bar{h}_{t-1})$$

$$h_t = \vec{h}_t \oplus \bar{h}_t$$

where $\vec{h}_t$ and $\bar{h}_t$ are the backward and forward GRU passes, respectively, GRU_f and GRU_b are the tandem combinations of forward and backward GRU functions, respectively, and $\oplus$ denotes the vector splice process.

The initial use of the AAM was for sentence translation, and recently, its use extended to the image processing field. It allows the method to adaptably assign changing weights to different portions inside the sequence of input, thus enabling a concentrated study of the essential components in the sequence data processing and the implementation of the converted characteristics by the sigmoid function to illustrate the similarity connection among the dual features that may successfully address nonlinear relationships. The equation for AA is expressed as follows:

$$y_i = \text{DecoderOutput}(s_t, c_t)$$

where y_i signifies the output at time step i . In Eq. (14), s_t is the HL at time step t , and y_i is the result. In Eq. (15), c_t is obtained by decoding at time step t .

$$c_t = \sum_{i=1}^T a_{t,i} h_i$$

The weights are computed as follows:

$$a_{ti} = \frac{\exp(e_{t,i})}{\sum_{j=1}^T \exp(e_{t,j})}$$

Here, the attentional weight is obtained from the score of attention standardised by Softmax and embodies the attention weight of the decoder from the t to the i time step. The score of attention is measured as follows:

$$e_{t,i} = v_a^T \tanh(W_a h_i + U_a s_{t-1})$$

In AA, the score of attention is computed through the linear transformation of the decoders and the HL encoder. In Eq. (17), $e_{t,i}$ is the score attention from decoding at the time step t to the time step i is the learned weighted vector, and W_a and U_a are the learned parameter matrices. Fig. 3 presents the framework of the Conv-BiGRU-AA method.

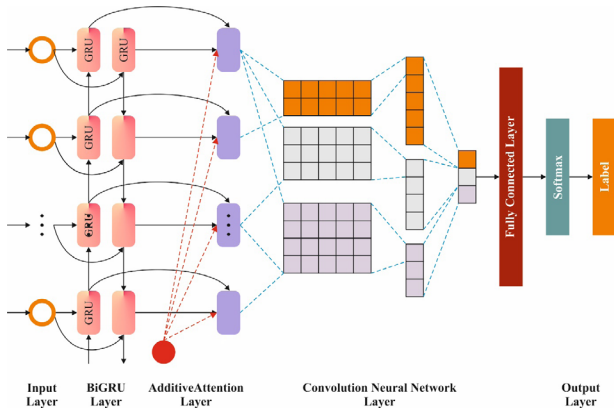


Fig. 3. Framework of the Conv-BiGRU-AA system

3.4 FAOA-Based Hyperparameter Tuning Model

Parameter fine-tuning is executed by utilising the FAOA to enhance the classifier efficiency of the Conv-BiGRU-AA classifier [37]. This model is selected for its simplicity, fast convergence and strong global search capability. It effectively explores the hyperparameter space by replicating the food-seeking behaviour of fruit flies, mitigating computational costs and avoiding the local minima. Furthermore, FAOA requires fewer iterations to find optimal solutions, resulting in enhanced model performance and faster training times than other metaheuristic algorithms.

The FAOA model, which is stimulated by the life of farmer ants, is described as follows: At the start of the model, the ant counts (n), which are in charge of finding nutrition and are responsible for the mushrooms (m), are established. The ants should process every mushroom. The ant counts are higher than or equivalent to the mushroom counts. Occasionally, the mushroom counts within the nests may be equivalent to the ant counts. Near the nest, the ants have additional nutrition, and all mushrooms are allocated to the ants to deliver their preferred food. The growth rate of the mushrooms relies on the form of the food they nourish. This dependence is uncertain at the start of the model. Changing this feature may limit the exploration behaviour of the method, which is fine-tuned based on all problems.

As the growth rate of mushrooms relies on the appropriate food they nourish, it corresponds to the form of bacteria made by the assumed ant. Therefore, this feature can be more efficient in growing the mushrooms. The pest factor (PF) is measured as a parameter that uses negative effects on mushroom growth, but its effect decreases when the correct bacteria for the mushroom are selected. The efficiency of PF is further established by the coefficient C_3 .

$$W_k = \sum_{\text{for all ants and mushrooms}} W_0 + (C_1 \times f_m + C_2 \times B_i) \times W_0 - C_3 \times PF \times W_0$$

where W_0 is the mushroom's first weight; C_1 , C_2 and C_3 are the learning parameters; f_m is the food quality value for diet m , and B_i is the ant bacteria i . PF is also established by Eq. (19).

$$PF = Is^\alpha$$

where I represent the pest's negative influence value, s denotes pest capacity, and α is the pest's spreading parameter on the mushrooms, which is fine-tuned based on the issue.

PF plays an integral part in representing the negative effects that compromise the optimiser procedure. It presents an accurate problem, avoids overfitting to best states and creates a FAOA that is efficient for composite, NP-hard difficulties with natural tradeoffs. The bacteria's influence on the growth of mushrooms is further measured by Eq. (20), where e is the positive efficacy parameter, and t denotes the bacteria lifetime. β is a changeable parameter that adjusts the bacterial influence, approximating a dial to fine-tune its power according to the problem's requirements.

$$B_i = e \times v \times t^\beta$$

Various arbitrary solutions are measured to improve the model's exploration ability. In doing so, a greater selection of solutions can result from discovering improved solutions and preventing dropping into local bests. In such a case, a few ants lose their way and immigrate to another nest. This problem is expressed by Eq. (21).

$$p_j^{ik} = \frac{SP_k \times SP_j \times W_j}{(1 - SP_k) \times \sum_{M=1}^K W_M} \text{ where } 0 < SP_j \text{ and } SP_k \leq 1$$

Eq. (22) illustrates the global stages in discovering the solution. The 1-FP ant percentage behaves arbitrarily and carries the ants to another nest to handle the mushrooms. These ant counts or n_L should be described while in progress, which could differ based on the problem.

$$W_L = (1 - FP) * p_j^{ik} * \sum_{i=1}^k [W_0 + (r_1 \times f_m + r_2 \times B_i) \times W_0 - r_3 \times PF \times W_0] + FP * \sum_{L+1}^k W_k$$

W_L comprises dual portions: The initial portion is associated with the performance of L ants, while the nest portion is associated with the leftover ants.

In this context, the coefficients r_1, r_2 , and r_3 , which are arbitrary numbers among (0,1), substitute for the coefficients C_1, C_2 and C_3 , respectively. In this case, the model behaviour is more arbitrary, and a global search is carried out. The mushroom weight formed in all nests k is measured. M,B,W and F denote the mushrooms, bacteria, weight and food, respectively. Eq. (23) is expressed as follows:

$$W = \max\{(\sum_{i=1}^K w_k), (\sum_{i=1}^L w_L + \sum_{L+1}^K w_k)\}$$

W denotes the complete weight of the mushrooms. In this context, similar local and global processes must be performed. In the FAOA, fitness selection is an extensive factor that manipulates performance. The hyperparameter range process comprises a solution-encoding model for evaluating the proficiency of the candidate solution. To design the FF, the FAOA imitates precision as the foremost criterion, which is expressed as follows:

$$Fitness = \max(P)$$

$$P = \frac{TP}{TP + FP}$$

where FP and TP are the false and true positive rates, respectively.

4. Results Analysis and Discussion

The performance assessment of the BCAD-DRHDL is examined using the Edge-IIoT [38] and ToN-IoT databases [39]. The Edge-IIoT database holds 36,000 records under 12 kinds of events, as shown in Table 1. It has 63 features, but only 45 features are selected.

Table 1. Details of the Edge-IIoT database

“Edge-IIoT Database”	
“Type of Event”	“Data Record”
“Normal”	3,000
“DDoS-UDP”	3,000
“DDoS-ICMP”	3,000
“SQL injection”	3,000
“DDoS-TCP”	3,000
“Password”	3,000
“DDoS-HTTP”	3,000
“Uploading”	3,000
“Backdoor”	3,000
“XSS”	3,000
“Ransomware”	3,000
“Fingerprinting”	3,000
Total Record	36,000

Fig. 4 illustrates the classifier outcomes of the BCAD-DRHDL in the Edge-IIoT database. Figs. 4a–4b show the confusion matrix by identifying each class based on 70%

TRAPHA and 30% TESPFA. Fig. 4c presents the PR inspection, with higher performance shown through each class label. Fig. 4d shows the outcome of the ROC and expert solutions through higher ROC values for diverse classes.

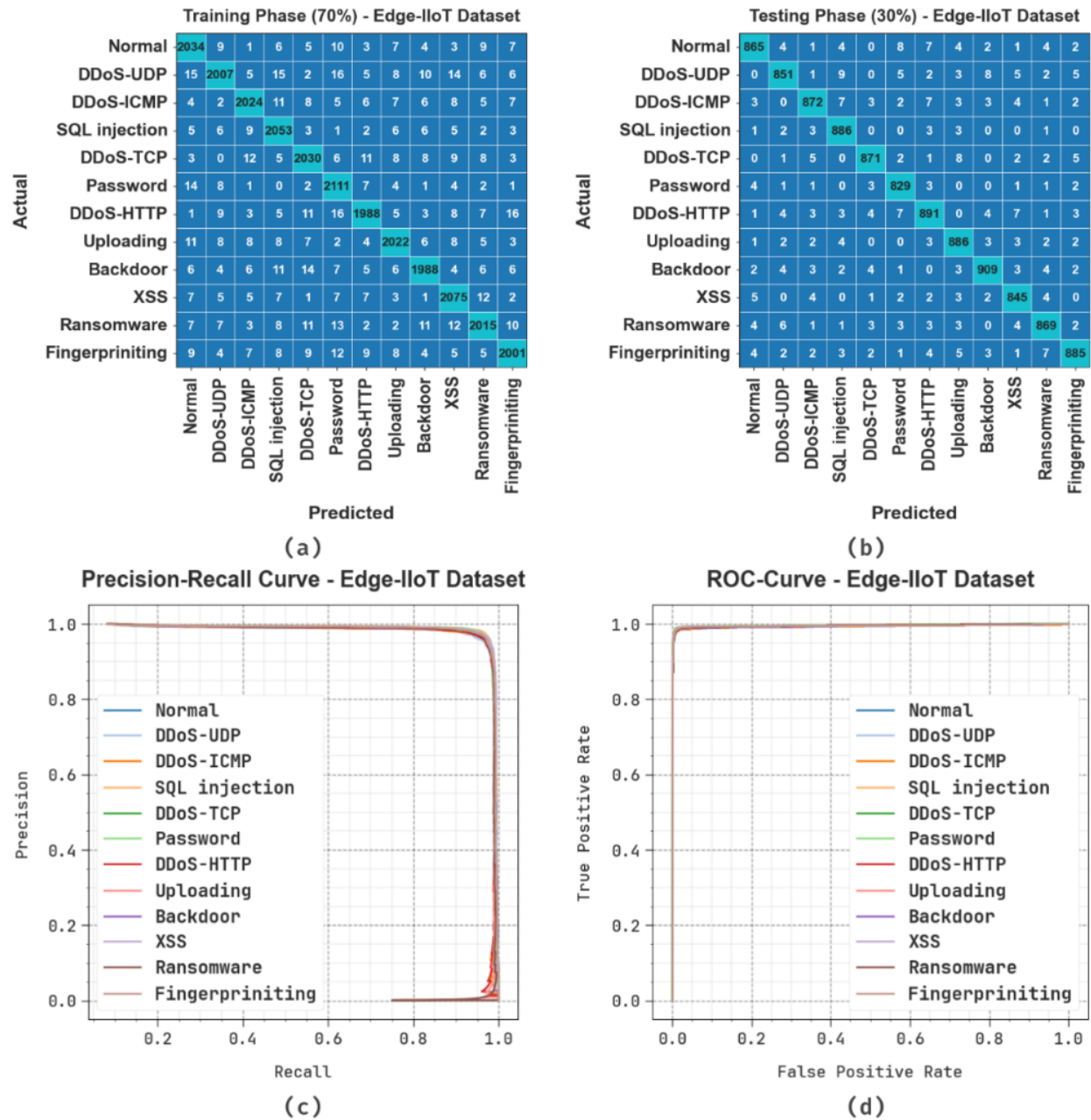


Fig. 4. Edge-IIoT database: (a–b) 70% TRAPHA and 30% TESPFA and (c–d) PR and ROC curves

Table 2 and Fig. 5 depict the attack detection of the BCAD-DRHDL in the Edge-IIoT database. Based on 70% TRAPHA, the proposed BCAD-DRHDL reaches a typical of 99.44%, of 96.63%, of 96.61%, of 96.62% and of 98.15%. Based on 30% TESPFA, the proposed BCAD-DRHDL achieves an average of 99.47%, of 96.84%, of 96.85%, of 96.84% and of 98.28%.

Table 2. Attack detection of the BCAD-DRHDL in the Edge-IIoT database

Class Labels	$Accu_y$	$Prec_n$	$Reca_l$	$F_{Measure}$	AUC_{Score}
TRAPHA (70%)					
Normal	99.42	96.12	96.95	96.54	98.30
DDoS-UDP	99.35	97.00	95.16	96.07	97.45
DDoS-ICMP	99.49	97.12	96.70	96.91	98.22
SQL injection	99.48	96.07	97.72	96.89	98.68
DDoS-TCP	99.42	96.53	96.53	96.53	98.11
Password	99.45	95.69	97.96	96.81	98.77
DDoS-HTTP	99.42	97.02	95.95	96.48	97.84
Uploading	99.47	96.93	96.65	96.79	98.19
Backdoor	99.46	97.07	96.36	96.72	98.05
XSS	99.46	96.29	97.33	96.80	98.49
Ransomware	99.39	96.78	95.91	96.34	97.81
Fingerprinting	99.43	96.90	96.16	96.53	97.94
Average	99.44	96.63	96.61	96.62	98.15
TESPFA (30%)					
Normal	99.43	97.19	95.90	96.54	97.82
DDoS-UDP	99.39	97.04	95.51	96.27	97.62
DDoS-ICMP	99.44	97.10	96.14	96.62	97.94
SQL injection	99.57	96.41	98.55	97.47	99.11
DDoS-TCP	99.57	97.76	97.10	97.43	98.45
Password	99.56	96.40	98.11	97.24	98.90
DDoS-HTTP	99.33	96.22	96.01	96.12	97.83
Uploading	99.47	96.20	97.58	96.88	98.61
Backdoor	99.51	97.32	97.01	97.17	98.38
XSS	99.50	96.46	97.35	96.90	98.52
Ransomware	99.45	96.77	96.66	96.72	98.19
Fingerprinting	99.45	97.25	96.30	96.77	98.02
Average	99.47	96.84	96.85	96.84	98.28

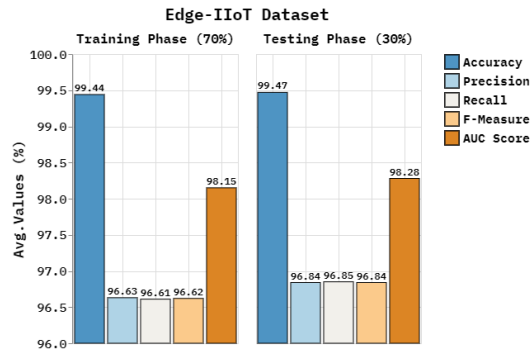


Fig. 5. Average of the BCAD-DRHDLM in the Edge-IIoT database

Fig. 6 reveals the training (TRAN) $accu_y$ and validation (VALN) $accu_y$ outcomes of the BCAD-DRHDLM based on the Edge-IIoT database. For 0–25 epochs, the values of $accu_y$ are computed. The figure highlights that either $accu_y$ value expresses cumulative tendencies, indicating the proficiency of the BCAD-DRHDLM over the maximum outcome through multiple iterations. Likewise, both $accu_y$ values are closer in the epochs, specifying lowered overfitting and an increased outcome of the BCAD-DRHDLM and assuring balanced computation in undetected instances.

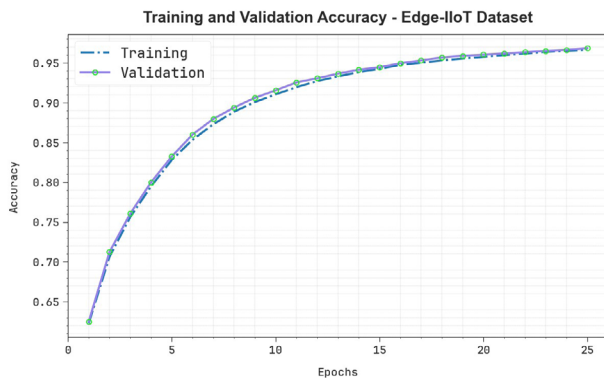


Fig. 6. curve of the BCAD-DRHDLM in the Edge-IIoT database

Fig. 7 presents the TRAN loss (TRANLOSS) and VALN loss (VALNLOSS) graph of the BCAD-DRHDLM based on the Edge-IIoT database. The values are measured over 0–25 epochs. Either value represents falling tendencies, demonstrating the ability of the BCAD-DRHDLM to equalise equilibrium. The progressive reduction in loss values and security is the superior result of the BCAD-DRHDLM, and the computation results can be adjusted afterward.

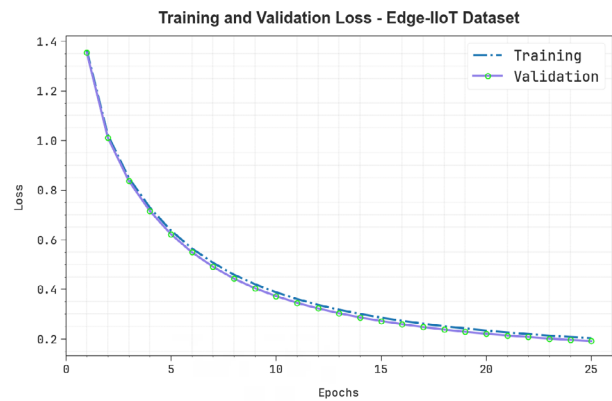


Fig. 7. Loss curve of the BCAD-DRHDLM in the Edge-IIoT database

A comparison analysis of the BCAD-DRHDLM with the existing approaches in the Edge-IIoT database is presented in Table 3 and Fig. 8 [19–20, 40–43]. The results show that the LSTM, FL, FedMLDL-Bayesian HPO, FedMLSL-RIME, random forest (RF), Conv1d, Transformer, DPPML, GAN and HetGNN models attain poor performance. Conversely, the proposed BCAD-DRHDLM indicates higher outcomes, with increased $accu_y$, $prec_n$, $reca_l$ and $F_{Measure}$ of 99.47%, 96.84%, 96.85% and 96.84%, respectively.

Table 3. Comparison analysis of the BCAD-DRHDLM with recent techniques in the Edge-IIoT database [19–20, 40–43]

Edge-IIoT Database				
Technique	$Accu_y$	$Prec_n$	$Reca_l$	$F_{Measure}$
LSTM	91.33	90.03	90.97	90.30
FL	90.66	94.89	95.86	90.11
FedMLDL-Bayesian HPO	92.01	89.12	92.68	94.74
FedMLSL-RIME	90.18	91.52	90.20	94.87
RF	91.80	91.21	94.38	93.68
Conv1d Model	92.80	96.08	92.02	91.94
Transformer	97.52	92.11	91.71	89.98
DPPML	91.36	95.59	96.03	90.81
GAN	92.56	89.84	93.24	95.53
HetGNN	90.79	92.27	90.77	95.48
BCAD-DRHDLM	99.47	96.84	96.85	96.84

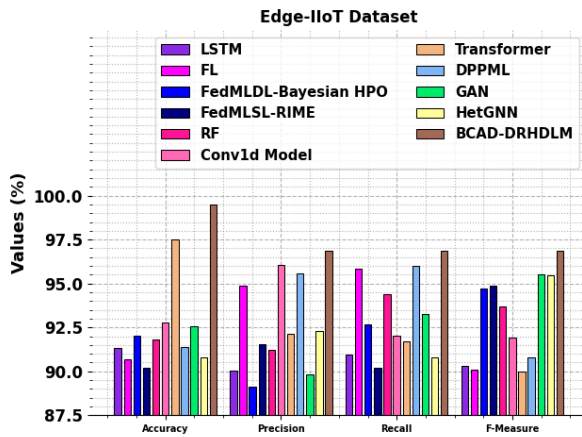


Fig. 8. Comparison analysis of the BCAD-DRHDLM with existing methods in the Edge-IIoT database

Table 4 and Fig. 9 illustrate the computational time (CT) analysis of the BCAD-DRHDLM compared with recent models. The comparative analysis of CT shows that the BCAD-DRHDLM achieves the lowest CT of 5.93 s, indicating superior proficiency for rapid inference in edge-based IIoT scenarios. Techniques such as RF and HetGNN also perform well, with CT values of 8.21 s and 8.30 s, respectively, followed by LSTM at 8.52 s and DPPML at 8.57 s. By contrast, methods such as FedMLSL-RIME and GAN exhibit higher CT values of 14.86 s and 14.29 s, respectively, indicating slower processing. FL records a CT value of 14.02 s, while Transformer and Conv1d Model register CT values of 12.84 s and 12.36 s, respectively. The FedMLDL-Bayesian HPO technique achieves a moderate CT value of 11.31 s. The performance of the BCAD-DRHDLM with faster CT enhances its applicability to real-time IIoT environments, with an accuracy of 99.03%.

Table 4. CT analysis of the BCAD-DRHDLM compared with recent techniques in the Edge-IIoT database

Edge-IIoT Database	
Technique	CT (s)
LSTM	8.52
FL	14.02
FedMLDL-Bayesian HPO	11.31
FedMLSL-RIME	14.86
RF	8.21
Conv1d Model	12.36
Transformer	12.84
DPPML	8.57
GAN	14.29
HetGNN	8.30
BCAD-DRHDLM	5.93

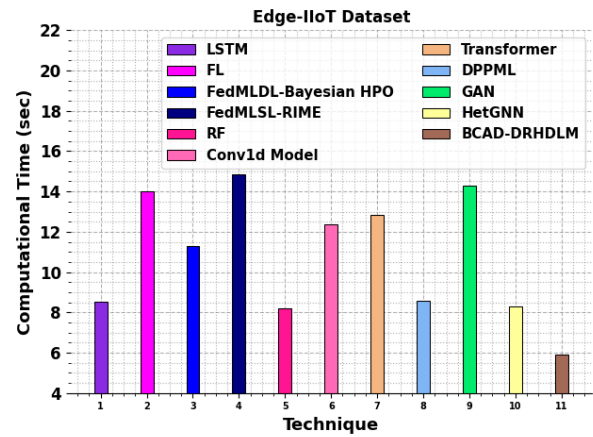


Fig. 9. CT analysis of the BCAD-DRHDLM compared with recent techniques in the Edge-IIoT database

The proposed BCAD-DRHDLM is also examined in the ToN-IoT database, which consists of 119,957 samples in nine classes. Table 5 presents the complete details of this database. This database has 42 features in total, but only 32 are selected.

Table 5. Details of the ToN-IoT database

"ToN-IoT Database"	
"Class"	"No. of Samples"
"Normal"	"78,369"
"MiTM"	"336"
"DoS"	"5,440"
"DDoS"	"5,987"
"Password"	"6,016"
"Injection"	"5,867"
"XSS"	"5,951"
"Ransomware"	"5,976"
"Backdoor"	"6,015"
"Total Samples"	"119,957"

Fig. 10 presents the classifier outcomes of the BCAD-DRHDLM in the ToN-IoT database. Figs. 10a–10b show the confusion matrix by precisely categorising each class based on 70% TRAPHA and 30% TESPHA. Fig. 10c shows the PR outcomes, indicating higher performance over all classes. Fig. 10d illustrates the outcomes for the ROC, indicating skilful solutions using greater values of ROC for discrete classes.

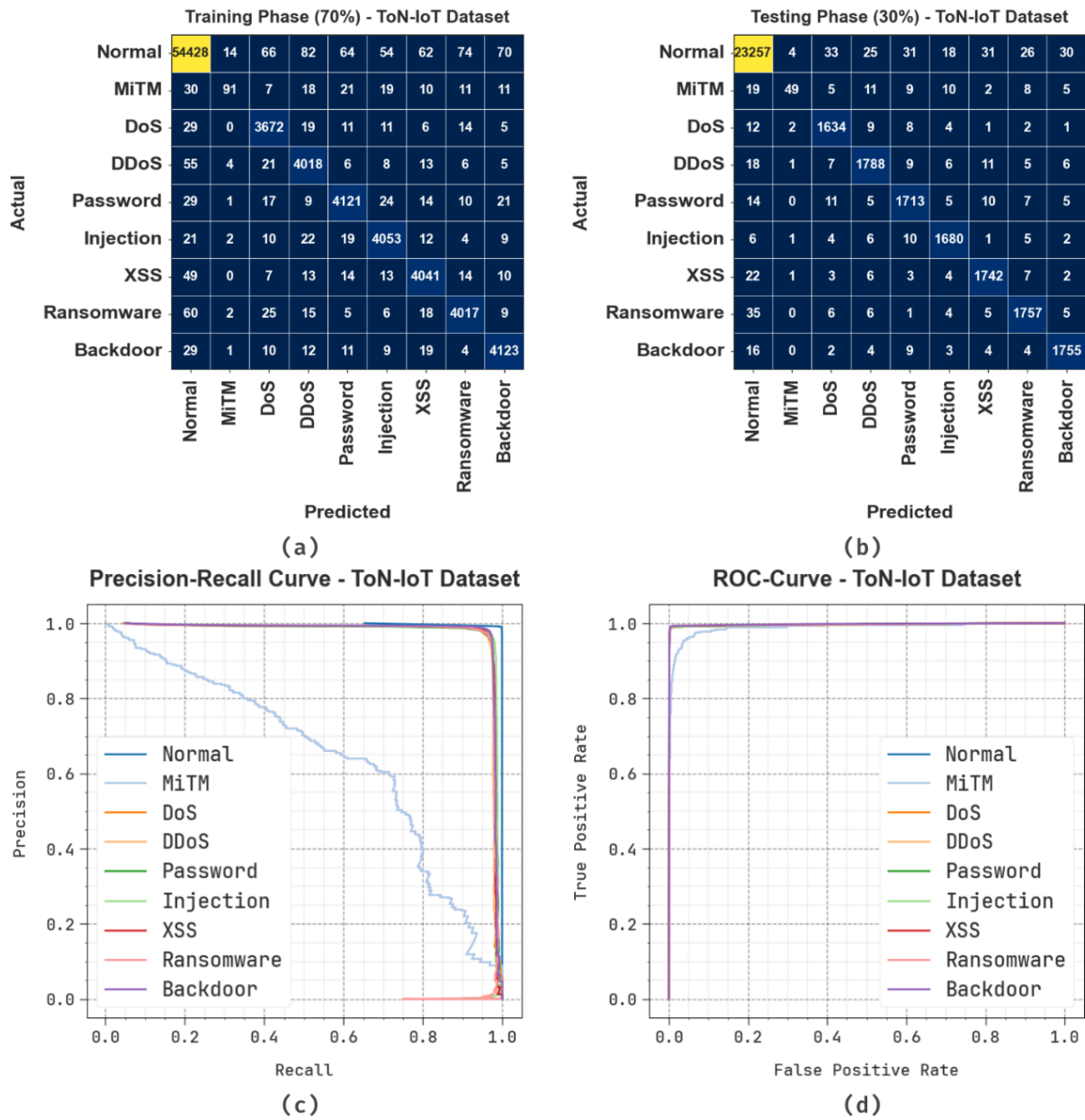


Fig. 10. ToN-IoT database (a–b) 70% TRAPHA and 30% TESPFA and (c–d) PR and ROC curves

Table 6 and Fig. 11 present the attack detection of the BCAD-DRHDLM in the ToN-IoT database. Based on 70% TRAPHA, the proposed BCAD-DRHDLM obtains a typical $accu_y$ of 99.63%, $prec_n$ of 94.73%, $reca_l$ of 91.29%, $F_{Measure}$ of 92.37% and AUC_{Score} of 95.51%. Based on 30% TESPFA, the proposed BCAD-DRHDLM reaches a typical $accu_y$ of 99.62%, $prec_n$ of 95.34%, $reca_l$ of 91.25%, $F_{Measure}$ of 92.48% and AUC_{Score} of 95.49%.

Table 6. Attack detection of the BCAD-DRHDLM in the ToN-IoT database

Class Labels	$Accu_y$	$Prec_n$	$Reca_l$	$F_{Measure}$	AUC_{Score}
TRAPHA (70%)					
Normal	99.06	99.45	99.11	99.28	99.04
MiTM	99.82	79.13	41.74	54.65	70.86
DoS	99.69	95.75	97.48	96.61	98.64
DDoS	99.63	95.48	97.15	96.31	98.45
Password	99.67	96.47	97.06	96.76	98.43
Injection	99.71	96.57	97.62	97.09	98.72
XSS	99.67	96.33	97.12	96.72	98.46
Ransomware	99.67	96.70	96.63	96.67	98.23
Backdoor	99.72	96.72	97.75	97.23	98.79
Average	99.63	94.73	91.29	92.37	95.51
TESPHA (30%)					
Normal	99.06	99.39	99.16	99.27	99.01
MiTM	99.78	84.48	41.53	55.68	70.75
DoS	99.69	95.84	97.67	96.74	98.73
DDoS	99.62	96.13	96.60	96.36	98.19
Password	99.62	95.54	96.78	96.15	98.27
Injection	99.75	96.89	97.96	97.42	98.90
XSS	99.69	96.40	97.32	96.86	98.56
Ransomware	99.65	96.49	96.59	96.54	98.20
Backdoor	99.73	96.91	97.66	97.28	98.75
Average	99.62	95.34	91.25	92.48	95.49

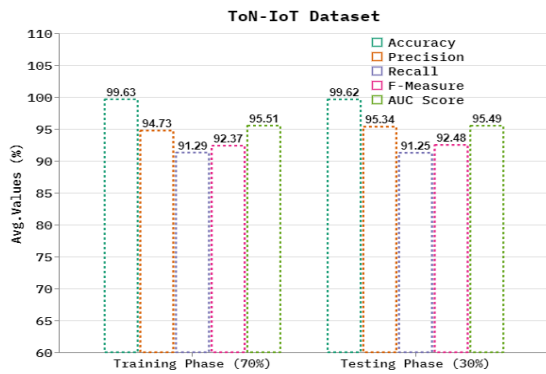
**Fig. 11. Average outcomes of the BCAD-DRHDLM in the ToN-IoT database**

Fig. 12 shows the TRAN $accu_y$ and VALN $accu_y$ performances of the BCAD-DRHDLM in the ToN-IoT database. The values of $accu_y$ are measured over 0–25 epochs. The figure reveals that either $accu_y$ value presents increasing tendencies, indicating the ability of the BCAD-DRHDLM to obtain enhanced performance in various repetitions. Moreover, both $accu_y$ values run closer across the epochs, indicating less overfitting and the improved outcome of the BCAD-DRHDLM and guaranteeing reliable calculation in hidden samples.

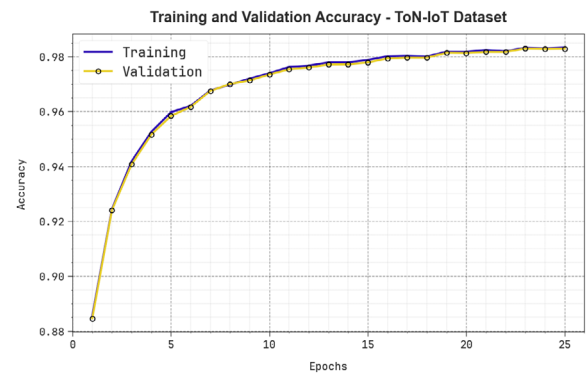
**Fig. 12. curve of the BCAD-DRHDLM in the ToN-IoT database**

Fig. 13 exhibits the TRANLOSS and VALNLOSS graph of the BCAD-DRHDLM in the ToN-IoT database. The loss values are measured over 0–25 epochs. Either value signifies declining tendencies, indicating the ability of the proposed technique to be consistent with balance. The subsequent dilution in loss values ensures the increased outcome of the BCAD-DRHDLM and gradually adjusts the calculation outcomes.



Fig. 13. Loss curve of the BCAD-DRHDLM in the ToN-IoT database

A comparison analysis of the BCAD-DRHDLM with recent models in the ToN-IoT database is shown in Table 7 and Fig. 14 [22–23, 40–43]. The analysis implies that the BCAD-DRHDLM achieves an increased outcome, with higher , and values of 99.63%, 94.73%, 91.29% and 92.37%, respectively. Conversely, the existing approaches, such as Hybrid RNN+ANFIS, Deep CNN+BiLSTM, CapsNets+RNN, decision tree (DT), LuNET, Multi-stage, Auto Encoders, DCGAN, DP-MLP and PCA, reach minimum results.

Table 7. Comparison analysis of the BCAD-DRHDLM with recent methods in the ToN-IoT database [22–23, 40–43]

ToN-IoT Database				
Technique	$Accu_y$	$Prec_n$	$Reca_l$	$F_{Measure}$
Hybrid RNN+ANFIS	91.92	86.38	85.01	90.11
Deep CNN+BiLSTM	92.20	87.38	86.79	85.01
CapsNets+RNN	97.03	89.63	85.28	88.11
DT	93.53	86.83	90.49	87.96
LuNET	95.69	88.04	87.54	90.62
Multi-stage	98.92	93.66	85.00	89.56
Auto Encoders	96.09	91.91	87.92	86.53
DCGAN	92.70	87.18	85.79	90.80
DP-MLP	92.94	88.04	87.44	85.59
PCA	97.72	90.30	85.97	88.77
BCAD-DRHDLM	99.63	94.73	91.29	92.37

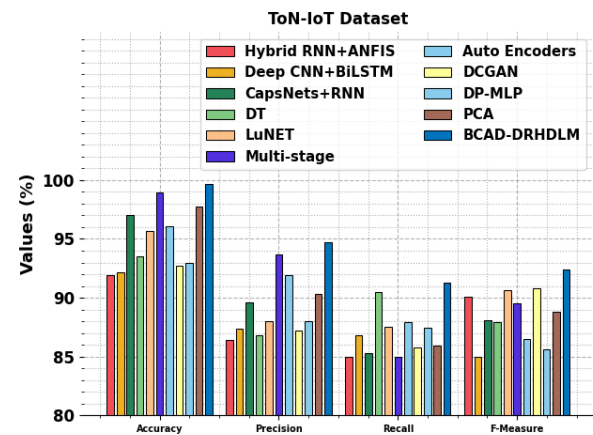


Fig. 14. Comparison analysis of the BCAD-DRHDLM technique with recent methods in the ToN-IoT database

Table 8 and Fig. 15 show the CT estimation of the BCAD-DRHDLM compared with recent models in the ToN-IoT database. The CT analysis on the ToN-IoT database reveals that the Hybrid RNN plus ANFIS technique attains the fastest CT of 7.42 s, followed by DT with 10.65 s and PCA with 12.79 s, indicating their suitability in time-sensitive scenarios. Methods such as DCGAN and CapsNets plus RNN achieve moderate CT values of 13.71 s and 14.02 s, respectively. Deep CNN plus BiLSTM and DP-MLP have similar performances, with 15.23 s and 15.22 s, respectively. The BCAD-DRHDLM records a CT value of 17.59 s, which remains within an acceptable range for complex classification tasks while achieving 99.03% accuracy. Comparatively, the Multi-stage, Auto Encoders and LuNET models show higher CT values of 23.20 s, 22.91 s and 23.31 s, respectively, highlighting the trade-off between accuracy and processing speed.

Table 8. CT assessment of the BCAD-DRHDLM compared with recent models in the ToN-IoT database

ToN-IoT Database	
Technique	CT (sec)
Hybrid RNN+ANFIS	7.42
Deep CNN+BiLSTM	15.23
CapsNets+RNN	14.02
DT	10.65
LuNET	23.31
Multi-stage	23.20
Auto Encoders	22.91
DCGAN	13.71
DP-MLP	15.22
PCA	12.79
BCAD-DRHDLM	17.59

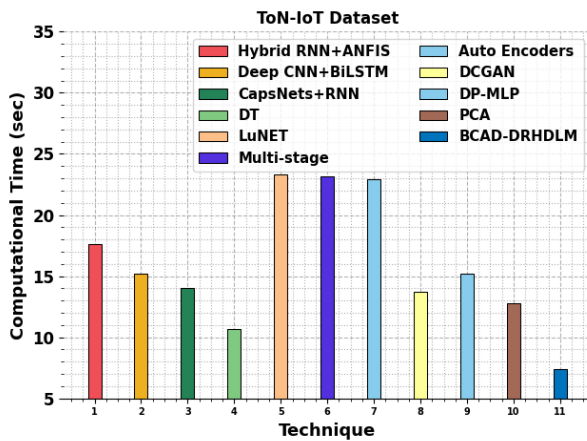


Fig. 15. CT assessment of the BCAD-DRHDLM compared with recent models in the ToN-IoT database

5. Conclusion

This study proposes the BCAD-DRHDLM for IoT environments. The BCAD-DRHDLM is effective in enhancing cybersecurity in IoT networks by developing robust threat detection mechanisms to mitigate evolving security risks. The Z-score method is used in the data pre-processing phase to measure and standardise the data for improved model performance. The SSA is used for the FS model to recognise and retain the related features from the input data. The hybrid Conv-BiGRU-AA method is used for attack classification. The parameter fine-tuning procedure is conducted using FAOA to increase the classification outcome of the Conv-BiGRU-AA classifier. The effectiveness of the BCAD-DRHDLM is verified by the Edge-IIoT and ToN-IoT datasets. The comparison analysis of the BCAD-DRHDLM shows better precision values of 99.47% and 99.63% over existing models in the two datasets. However, the BCAD-DRHDLM also has some limitations, such as restricted generalisability due to dataset-specific evaluations and limited testing under diverse network conditions. Its performance may degrade when applied to heterogeneous environments with varying data distributions. Scalability concerns also arise when the number of nodes or data volume increases, potentially affecting processing time. Real-time performance under adverse scenarios remains unexplored. Thus, future studies could extend the approach to cross-domain datasets, improve adaptability to dynamic network topologies and integrate lightweight modules to deploy ultra-low-power devices. Further experiments in real-world environments could also enhance its reliability and resilience.

6. Data Availability Statement

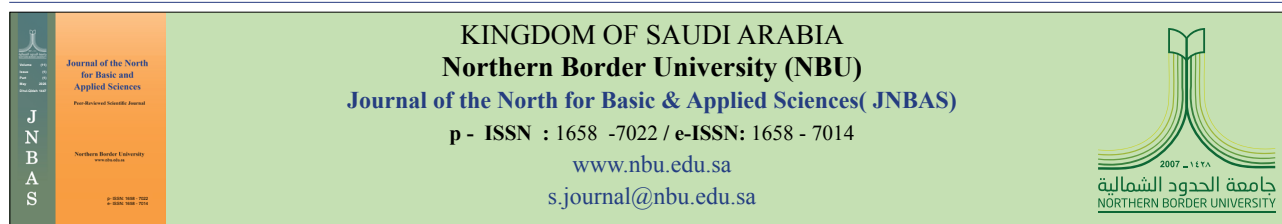
The data supporting this study's findings are openly available in the Kaggle repository at <https://www.kaggle.com/datasets/mohamedamineferrag/edgeiiotset-cyber-security-dataset-of-iiot> and <https://www.kaggle.com/datasets/dhoogla/cictoniot>, reference numbers [38, 39].

7. References

- T. R. Gadekallu, M. M K, S. K. S, N. Kumar, S. Hakak and S. Bhattacharya, "Blockchain-Based Attack Detection on Machine Learning Algorithms for IoT-Based e-Health Applications," in *IEEE Internet of Things Magazine*, vol. 4, no. 3, pp. 30-33, 2021, doi: 10.1109/IOTM.1021.2000160.
- H. Vargas, C. Lozano-Garzon, G.A. Montoya and Y. Donoso, "Detection of security attacks in industrial IoT networks: A blockchain and machine learning approach," *Electronics*, vol. 10, no. 21, p. 2662, 2021.
- D. Saveetha and G. Maragatham, "Design of Blockchain enabled intrusion detection model for detecting security attacks using deep learning," *Pattern Recognition Letters*, vol. 153, pp. 24-28, 2022.
- R. Kumar, P. Kumar, M. Aloqaily and A. Aljuhani, "Deep-Learning-Based Blockchain for Secure Zero Touch Networks," in *IEEE Communications Magazine*, vol. 61, no. 2, pp. 96-102, 2023, doi: 10.1109/MCOM.001.2200294.
- M. A. Ferrag and L. Maglaras, "DeepCoin: A Novel Deep Learning and Blockchain-Based Energy Exchange Framework for Smart Grids," in *IEEE Transactions on Engineering Management*, vol. 67, no. 4, pp. 1285-1297, 2020, doi: 10.1109/TEM.2019.2922936.
- N. Waheed, X. He, M. Ikram, M. Usman, S.S. Hashmi et al., "Security and privacy in IoT using machine learning and blockchain: Threats and countermeasures," *ACM computing surveys (csur)*, vol. 53, no. 6, pp. 1-37, 2020.
- P. Kumar, R. Kumar, A. Kumar, A.A. Franklin, S. Garg et al., "Blockchain and deep learning for secure communication in digital twin empowered industrial IoT network," *IEEE Transactions on Network Science and Engineering*, vol. 10, no. 5, pp. 2802-2813, 2022.
- M. Sharma, S. Pant, D. Kumar Sharma, K. Datta Gupta, V. Vashishth et al., "Enabling security for the Industrial Internet of Things using deep learning, blockchain, and coalitions," *Transactions on Emerging Telecommunications Technologies*, vol. 32, no. 7, 2021, doi: <https://doi.org/10.1002/ett.4137>.

- P. Kumar, R. Kumar, G.P. Gupta, R. Tripathi and G. Srivastava, "P2tif: A blockchain and deep learning framework for privacy-preserved threat intelligence in industrial iot," *IEEE Transactions on industrial informatics*, vol. 18, no. 9, pp. 6358-6367, 2022.
- A. Maseleno, "Design of optimal machine learning-based cybersecurity intrusion detection systems," *Journal of Cybersecurity, Information Management*, vol. 2019, no. 1, pp. 32-43, 2019.
- S. Selvarajan, A. Shankar, M. Uddin, A.S. Alqahtani, T. Al-Shehari et al., "A smart decentralized identifiable distributed ledger technology-based blockchain (DIDLT-BC) model for cloud-IoT security," *Expert Systems*, vol. 42, no. 1, 2025, doi: <https://doi.org/10.1111/exsy.13544>.
- S.S. Sefati, R. Craciunescu, B. Arasteh, S. Halunga, O. Fratu et al., "Cybersecurity in a Scalable Smart City Framework Using Blockchain and Federated Learning for Internet of Things (IoT)," *Smart Cities*, vol. 7, no. 5, pp. 2802-2841, 2024.
- R. B. Ponnuru, S. A. P. Kumar, M. Azab and G. R. Alavalapati, "BAAP-FIoT: Blockchain-Assisted Authentication Protocol for Fog-Enabled Internet of Things Environment," in *IEEE Internet of Things Journal*, vol. 12, no. 11, pp. 15681-15696, 2025, doi: [10.1109/JIOT.2025.3528746](https://doi.org/10.1109/JIOT.2025.3528746).
- B. Alamri, I. Richardson and K. Crowley, "Cybersecurity Risk Management and Evaluation Framework of Blockchain Identity Management Systems in IIoT: Experts Evaluation," in *IEEE Access*, vol. 12, pp. 144652-144683, 2024, doi: [10.1109/ACCESS.2024.3468379](https://doi.org/10.1109/ACCESS.2024.3468379).
- V. Kumar and S.K. Das, "Enhancing Security in IIoT: RFID Authentication Protocol for Edge Computing and Blockchain-enabled Supply Chain," *Cyber Security and Applications*, p. 100087, 2025, doi: <https://doi.org/10.1016/j.csa.2025.100087>.
- J. Makhahlela, G. M. Komba and S. P. Maswikaneng, "An Enhanced Cybersecurity Strategies for Internet of Things using Lightweight Blockchain-Based Secure Communication Protocol," 2024 5th International Conference on Emerging Trends in Electrical, Electronic and Communications Engineering (ELECOM), Balaclava, Mauritius, 2024, pp. 1-4, doi: [10.1109/ELECOM63163.2024.10892173](https://doi.org/10.1109/ELECOM63163.2024.10892173).
- B.P. Pokharel, N. Kshetri, S.R. Sharma and S. Paudel, "blockHealthSecure: Integrating Blockchain and Cybersecurity in Post-Pandemic Healthcare Systems," *Information*, vol. 16, no. 2, p. 133, 2025.
- S. Ismail, M. Nouman, D.W. Dawoud and H. Reza, "Towards a lightweight security framework using blockchain and machine learning," *Blockchain: Research and Applications*, vol. 5, no. 1, p. 100174, 2024.
- K. Kuru and K. Kuru, "UMetaBE-DPPML: Urban Metaverse & Blockchain-Enabled Decentralised Privacy-Preserving Machine Learning Verification And Authentication With Metaverse Immersive Devices," *Internet of Things and Cyber-Physical Systems*, 2025, doi: <https://doi.org/10.1016/j.iotcps.2025.02.001>.
- A. Rajasekar and V. Vetrian, "A Privacy-Preserving Graph Neural Network Framework with Attention Mechanism for Computational Offloading in the Internet of Vehicles," *CMES-Computer Modeling in Engineering and Sciences*, vol. 143, no. 1, pp. 225-254, 2025.
- A.B. Kathole, K. Vhatkar, S.A. Ubale, V.V. Kimbahune, A. Dhumane et al., "Enhanced security mechanism in vehicular networks using ensemble machine learning to detect malicious activity in VANETs," *J. Discrete Math. Sci. Cryptogr.*, vol. 27, no. 7, pp. 2005-2014, 2024.
- A.G. Andrei, M.G. Constantin, M. Graziani, H. Müller and B. Ionescu, "Privacy preserving histopathological image augmentation with Conditional Generative Adversarial Networks," *Pattern Recognition Letters*, vol. 188, pp. 185-192, 2025.
- L.K.G. Danquah, S.Y. Appiah, V.A. Mantey, I. Danlard and E.K. Akowuah, "Computationally Efficient Deep Federated Learning with Optimized Feature Selection for IoT Botnet Attack Detection," *Intelligent Systems with Applications*, vol. 25, p. 200462, 2025.
- A.B. Kathole, K. Vhatkar, G. Dharmale, S. Chiwhane, V.V. Kimbahune et al., "A novel approach to IoT security for intrusion detection system using ensemble network and heuristic-assisted feature fusion," *J. Discrete Math. Sci. Cryptogr.*, vol. 27, no. 7, pp. 2207-2217, 2024.
- A. Nazir, J. He, N. Zhu, A. Wajahat, F. Ullah et al., "Empirical evaluation of ensemble learning and hybrid CNN-LSTM for IoT threat detection on heterogeneous datasets," *The Journal of Supercomputing*, vol. 81, no. 6, p. 775, 2025.
- B. Kathole et al., "Secure Federated Cloud Storage Protection Strategy Using Hybrid Heuristic Attribute-Based Encryption With Permissioned Blockchain," in *IEEE Access*, vol. 12, pp. 117154-117169, 2024, doi: [10.1109/ACCESS.2024.3447829](https://doi.org/10.1109/ACCESS.2024.3447829).

- R. Loganathan and S. SelvakumaraSamy, "An efficient privacy-preserving authentication scheme for internet of vehicles based on blockchain technology with hybrid adaptive network," *Peer-to-Peer Networking and Applications*, vol. 18, no. 3, p. 99, 2025.
- A. Nazir, J. He, N. Zhu, A. Wajahat, X. Ma et al., "Advancing IoT security: A systematic review of machine learning approaches for the detection of IoT botnets," *Journal of King Saud University-Computer and Information Sciences*, vol. 35, no. 10, p. 101820, 2023.
- N.S. Ganesh, V. Balasubramanian, D. Prasad and S.S. Velan, "Deep learning-based user authentication with hybrid encryption for secured blockchain-aided data storage and optimal task offloading in mobile edge computing," *Wireless Networks*, vol. 31, no. 3, pp. 2389-2417, 2025.
- A. Nazir, J. He, N. Zhu, A. Wajahat, F. Ullah et al., "Collaborative threat intelligence: Enhancing IoT security through blockchain and machine learning integration," *Journal of King Saud University-Computer and Information Sciences*, vol. 36, no. 2, p. 101939, 2024.
- B. Kadiyala, C. Vasamsetty, S. Boyapati, S.K. Alavilli, R.P. Nippatla et al., "Decentralized anomaly detection and data privacy preservation for IoT networks using blockchain and homomorphic encryption," *Intelligent Data Analysis*, p. 1088467, 2025, doi: <https://doi.org/10.1177/108846X251339365>.
- Nazir, J. He, N. Zhu, M.S. Anwar and M.S. Pathan, "Enhancing IoT security: a collaborative framework integrating federated learning, dense neural networks, and blockchain," *Cluster Computing*, vol. 27, no. 6, pp. 8367-8392, 2024.
- O. Slama, W. Dhifallah, S. Zidi, J. Lloret, B. Alaya et al., "Blockchain-based privacy-preserving technology to secure shared data in vehicular communication," *International Journal of Communication Networks and Distributed Systems*, vol. 31, no. 3, pp. 346-371, 2025.
- S. Anthoniraj, R. Mishra, S. Loonkar, T. Agarwal, G. Ahluwalia et al., "Design of Novel Cryptographic Model Using Zero-Knowledge Proof Structure for Cyber Security Applications," *Journal of Cybersecurity & Information Management*, vol. 14, no. 1, 2024.
- S. Li, Q. Zhao, J. Liu, X. Zhang and J. Hou, "Noise Reduction of Steam Trap Based on SSA-VMD Improved Wavelet Threshold Function," *Sensors*, vol. 25, no. 5, p. 1573, 2025.
- S. Liu, W. Lin, Y. Wang, D.Z. Yu, Y. Peng et al., "Convolutional neural network-based bidirectional gated recurrent unit-additive attention mechanism hybrid deep neural networks for short-term traffic flow prediction," *Sustainability*, vol. 16, no. 5, p. 1986, 2024.
- A. Asghari, M. Zeinalabedinmalekmian, H. Azgomi, M. Alimoradi and S. Ghaziantafrishi, "Farmer Ants Optimization Algorithm: A Novel Metaheuristic for Solving Discrete Optimization Problems," *Information*, vol. 16, no. 3, p. 207, 2025.
- <https://www.kaggle.com/datasets/mohamedamineferrag/edgeiiotset-cyber-security-dataset-of-iiot>
- <https://www.kaggle.com/datasets/dhoogla/cictoniot>
- G. Logeswari, J. Deepika Roselind, K. Tamilarasi and V. Nivethitha, "A Comprehensive Approach to Intrusion Detection in IoT Environments Using Hybrid Feature Selection and Multi-Stage Classification Techniques," in *IEEE Access*, vol. 13, pp. 24970-24987, 2025, doi: 10.1109/ACCESS.2025.3532895.
- Jitendra Chandnani, V. Agarwal, S. Chetan Kulkarni, A. Aren, D. G. B. Amali and K. Srinivasan, "A Physics-Based Hyper Parameter Optimized Federated Multi-Layered Deep Learning Model for Intrusion Detection in IoT Networks," in *IEEE Access*, vol. 13, pp. 21992-22010, 2025, doi: 10.1109/ACCESS.2025.3535952.
- S. Hariharan, Y. Annie Jerusha, G. Suganeshwari, S. P. Syed Ibrahim, U. Tupakula and V. Varadharajan, "A Hybrid Deep Learning Model for Network Intrusion Detection System Using Seq2Seq and ConvLSTM-Subnets," in *IEEE Access*, vol. 13, pp. 30705-30721, 2025, doi: 10.1109/ACCESS.2025.3541399.
- M. Rodríguez, D.P. Tobón and D. Múnera, "A framework for anomaly classification in Industrial Internet of Things systems," *Internet of Things*, vol. 29, p. 101446, 2025.



Nurses' Knowledge of Diabetic Ketoacidosis Management: A Cross-Sectional Study in Omdurman Teaching Hospital, Sudan

Huda Hassabelrasool Abdelwahed Yousef

Department of Nursing, College of Nursing and Health Sciences, Jazan University, Saudi Arabia.

(Received: 21st February 2026; Accepted: 11th April 2026)

Abstract

Diabetic ketoacidosis (DKA) is a life-threatening diabetic complication requiring prompt, evidence-based management. Nurses play a key role in detection and care; however, knowledge in Sudan remains limited. This study assessed nurses' knowledge and associated factors at Omdurman Teaching Hospital.

Methods: A cross-sectional study (May–June 2024) included 192 nurses from medical, surgical, emergency, ICU, and endocrinology units. A structured, pretested 20-item questionnaire based on ADA recommendations assessed DKA knowledge. Scores (0–20) were classified as poor, moderate, and good. Data were analyzed using descriptive statistics, t-tests, ANOVA, Pearson correlation, and multiple linear regression.

Results: The mean knowledge score was 13.4 ± 3.6 , indicating a moderate level. Overall, 40.6% had good knowledge, 39.6% moderate, and 19.8% poor. Trained nurses scored higher than untrained (15.0 ± 3.0 vs. 12.3 ± 3.5 , $p < 0.001$). Knowledge correlated with experience ($r = 0.36$) and DKA exposure ($r = 0.42$) ($p < 0.001$). Training, education, and experience were predictors (adjusted $R^2 = 0.33$).

Conclusion: Nurses showed a moderate level of knowledge, with gaps among less experienced and untrained staff. Training and standardized protocols are recommended to improve competence and patient safety.

Keywords: Diabetic ketoacidosis; Nurses; Knowledge; Training; Clinical competence; Sudan

1658-7022© JNBAS. (1447 H/2026). Published by Northern Border University (NBU). All Rights Reserved.



DOI: 10.12816/0062549

(*) Corresponding Author:

Huda Hassabelrasool Abdelwahed Yousef ^{1*}, Ashraf Abdelrhman Elbashir Elmdni¹, Aida Ahmed Fadlala Ahmed², Suaad Ahmed Suliman Omer³, Ghada Siddig Osman Eshag¹, Sittelbanat Osman Ahmed¹, Amani Mukhtar Abdelrahman¹, Amani Awad Taha ¹, Soad Mohamed Abdalla Alnassry¹, SALWA ALI MOUSA¹, Hawa Ibrahim Abdalla Hamid¹, Nasredeen Mohamed Ahmed¹, Asia Mohamed Ahmed¹, Nora Ghalib AlOtaibi⁴, Sara Awadelkareem Elhassan⁵, Lujain Adel Sallam⁶, Meaad Elbashir⁷, Sara Ali⁷, Tahani Babiker Mohamed⁸, Hamza Hosean Ahmed Balola⁹.

1 Department of Nursing, College of Nursing and Health Sciences, Jazan University, Saudi Arabia.

2 Assistant professor of Obstetrics and Gynecological Nursing, Nursing Department, AlNahda College of Pharmacy and Medical Sciences, Riyadh, Kingdom of Saudi Arabia

3 Faculty of Nursing, AL-Baha University, Assistance professor, PhD in Pediatrics Nursing.

4 Department of Community Nursing, College of Nursing, Imam Abdulrahman Bin Faisal University, Dammam, Saudi Arabia

5 Hamad Medical Corporation, Staff education, Nursing Educator, Doha city, Qatar.

6 Department of Medical Surgical Nursing, Faculty of Nursing, King Abdulaziz University, Jeddah, Saudi Arabia.

7 Department of Diagnostic Radiography Technology, College of Nursing and Health Sciences, Jazan University, Jazan ,Saudi Arabia.

8 Assistant professor, Department of Public Health, College of Nursing and Health Science, Jazan University, kingdom of Saudi Arabia.

9 Assistant professor, Department of Community health Nursing. Batterjee Medical College for Sciences and Technology: Khamis mushait, Abha Province, KSA.

E-mail: Huda.hassabo@hotmail.com, <https://orcid.org/0000-0002-1731-0326>

1. Introduction

Diabetic ketoacidosis (DKA) is a severe, potentially life-threatening acute metabolic complication of diabetes mellitus, characterized by hyperglycemia, ketosis, and metabolic acidosis (Mohajan & Mohajan, 2023). It primarily affects patients with type 1 diabetes but can also occur in type 2 diabetes under conditions of physiological stress, infection, or inadequate insulin therapy. Globally, DKA remains a leading cause of hospital admission, morbidity, and mortality among diabetic patients, particularly in low- and middle-income countries where healthcare resources and trained staff may be limited (Mohan & Lee, 2025). Delayed recognition and improper management of DKA are major contributors to preventable deaths, highlighting the need for competent healthcare professionals (Kajembula et al., 2024).

Nurses are central to patient care and play a crucial role in the early detection, stabilization, monitoring, and education of DKA patients (Shaker et al., 2025).

Their clinical knowledge and skills directly influence the timeliness of interventions, adherence to evidence-based practices, and prevention of life-threatening complications such as hypokalemia, cerebral edema, and circulatory shock (Adewale, 2023). Nursing care is particularly vital in emergency, intensive care, and medical wards, where rapid decision-making and accurate monitoring critically affect patient outcomes (Gholipour et al., 2025).

Despite their central role, limited research exists on nurses' knowledge of DKA management in Sudan (Ahmed et al., 2025). Studies from other low-resource settings show significant gaps in knowledge regarding fluid resuscitation, insulin therapy, electrolyte replacement, monitoring of vital signs and laboratory parameters, and patient education. Such gaps can compromise patient safety and quality of care (Alsabri et al., 2025).

This study aims to evaluate the knowledge of nurses regarding DKA management at Omdurman Teaching Hospital, identify demographic and professional factors associated with higher knowledge levels, and provide evidence-based recommendations for in-service training, continuing education, and standardized clinical protocols to enhance nursing competence and patient safety.

2. Methodology

2.1 Study design

A hospital-based cross-sectional descriptive study was conducted at Omdurman Teaching Hospital, Khartoum State, Sudan, from May 1 to June 30, 2024. This design was appropriate for assessing the distribution and characteristics of study variables at a single point in time, allowing estimation of prevalence and patterns of nurses' knowledge regarding DKA.

2.2 Study population

The study population comprised registered nurses working in the medical, surgical, emergency, intensive care, and endocrinology units of Omdurman Teaching Hospital. These nurses were selected due to their direct patient contact and critical role in clinical management. Eligible participants had at least six months of clinical experience and direct patient care exposure. Nurses on long-term leave (>1 month) or who declined participation were excluded.

2.3 Sampling technique

A stratified convenience sampling technique was used to recruit participants from the target population. Nurses were proportionally selected from medical, surgical, emergency, intensive care, and endocrinology units based on the number of nurses in each department. Within each unit, eligible nurses were recruited based on availability during the data collection period. All nurses who met the inclusion criteria and consented to participate were included until the required sample size was achieved.

2.4 Sample size determination

The sample size was calculated using Cochran's formula for cross-sectional studies:

$$n = \frac{(p-1) \times p \times Z^2}{d^2}$$

Where

$Z = 1.96$ (95% confidence)

$p = 0.5$ (assumed prevalence of adequate knowledge)

$d = 0.06$ (margin of error)

$$n = \frac{(1.96)^2 \times 0.5 \times 0.5}{(0.06)^2} = 267$$

Since the total nurse population was approximately 500, finite population correction was applied:

$$f^*n = \frac{267}{(267/500 + 1)} = 174$$

After adding 10% to compensate for non-response:

$$174 \times 1.1 = 192$$

Thus, the final sample size was 192 nurses.

2.5 Data collection

Data were collected using a structured, self-administered questionnaire based on American Diabetes Association (ADA) recommendations and relevant literature. The questionnaire comprised:

- Demographic and professional data:** age, gender, academic qualification, years of experience, exposure to DKA cases, and prior DKA training.
- Knowledge assessment:** 20 multiple-choice questions covering DKA pathophysiology, clinical presentation, monitoring, fluid and

insulin therapy, electrolyte management, complications, and patient education.

Each correct answer was scored 1 point, with total scores ranging from 0–20, categorized as:

- Poor (0–9)
 - Moderate (10–14)
 - Good (15–20)
3. **Psychometric properties:** Pretested on 15 nurses ;content validity confirmed by three endocrinology and critical care experts; internal consistency acceptable (Cronbach's $\alpha = 0.82$).

2.6 Ethical Considerations

Ethical approval was obtained from the Institutional Ethics Committee of Omdurman Teaching Hospital (Approval No. OTH/IRB/2024/09014, dated 10 April 2024). Written informed consent was obtained from all participants, anonymity was ensured, and data confidentiality was strictly maintained.

2.7 Statistical Analysis

Data were analyzed using SPSS version 25. Descriptive statistics (mean $\pm$ SD, frequencies, and percentages) summarize variables. The dependent

variable was the total knowledge score. Inferential analyses included:

1. Independent t-tests and one-way ANOVA for group comparisons
2. Pearson correlation for continuous variables
3. Chi-square tests for categorical associations
4. Multivariate linear regression to identify independent predictors of knowledge

All statistical tests were two-tailed, with $p < 0.05$ considered significant. Regression diagnostics, including residual analysis and multicollinearity checks, were performed to ensure model validity.

3. Result

3.1 Demographic and Professional Characteristics

A total of 192 nurses participated in the study. Most were female (%65.1), with a mean age of 32.1 ± 7.0 years and mean clinical experience of 8.2 ± 6.3 years. Regarding educational level, %52.6 held a bachelor's degree, %37.5 had a diploma, and %9.9 a master's degree. Only %38.5 reported prior formal training in DKA management (Table 1).

Table 1. Demographic and Professional Characteristics of Nurses (n = 192)

Category	Parameter	n	%
Gender	Female	125	65.1
	Male	67	34.9
Educational level	Diploma	72	37.5
	Bachelor	101	52.6
	Master	19	9.9
DKA Training	Yes	74	38.5
	No	118	61.5
Age ≥ 30 years	Yes	106	55.2
	No	86	44.8
Experience ≥ 5 years	Yes	118	61.5
	No	74	38.5

3.2 Overall, Knowledge Level

The mean knowledge score was 13.4 ± 3.6 , classified as moderate based on cut-offs: poor (0–9), moderate

(10–14), good (15–20). Overall, 40.6% of nurses demonstrated good knowledge, 39.6% moderate, and 19.8% poor (Figure 1).

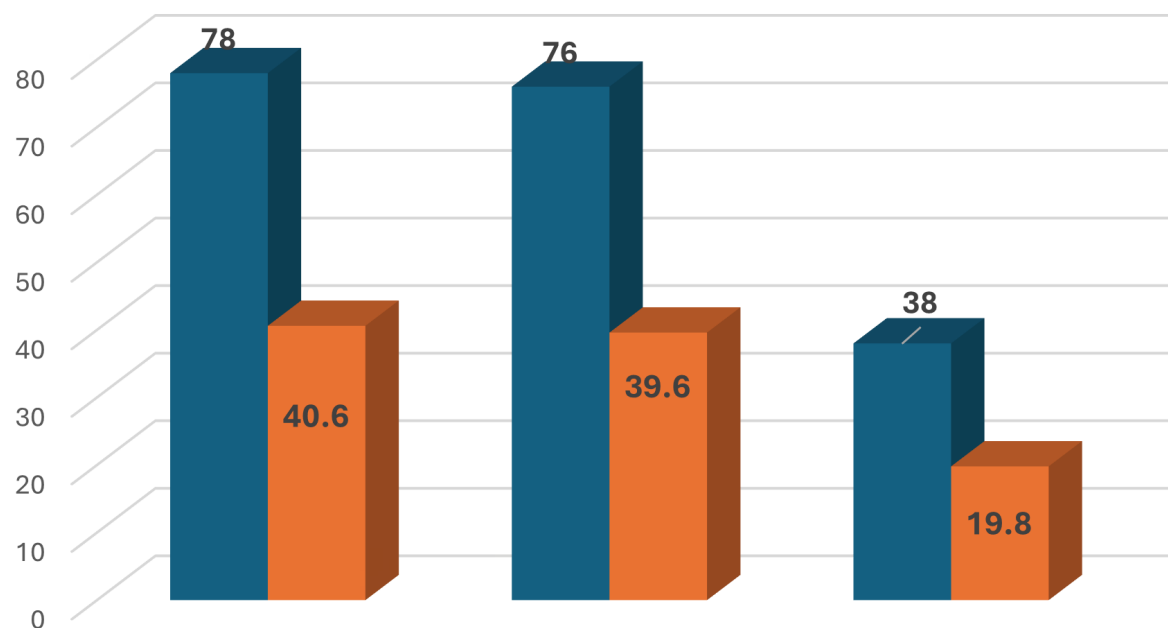


Figure 1. Knowledge Levels of Nurses Regarding DKA Management (n = 192)

3.3 Knowledge According to Academic Qualification

Knowledge scores increased with higher academic levels ($p < 0.001$). Nurses with a master's degree scored the highest (16.1 ± 2.7), followed by bachelor's degree holders (13.6 ± 3.3) and diploma nurses (11.3 ± 3.4) (Table 2).

Table 2. Mean Knowledge Scores by Academic Qualification

Qualification	Mean $\pm$ SD	p-value
Diploma	11.3 $\pm$ 3.4	<0.001
Bachelor	13.6 $\pm$ 3.3	
Master	16.1 $\pm$ 2.7	

3.4 Knowledge According to DKA Training

Nurses who had received prior DKA training achieved higher scores (15.0 ± 3.0) than those without training (12.3 ± 3.5); this difference was statistically significant ($p < 0.001$) (Table 3).

Table 3. Knowledge Scores According to Prior DKA Training

Training	Mean $\pm$ SD	p-value
Yes	15.0 $\pm$ 3.0	<0.001
No	12.3 $\pm$ 3.5	

3.5 Correlation with Demographic and Clinical Factors

Pearson correlation analysis indicated positive associations between knowledge scores and:

- Age: $r = 0.21$, $p = 0.004$
- Clinical experience: $r = 0.36$, $p < 0.001$
- Monthly exposure to DKA cases: $r = 0.42$, $p < 0.001$ (Table 4)

Table 4. Correlation Between Knowledge Scores and Demographic/Clinical Factors

Variable	R	p
Age	0.21	0.004
Experience	0.36	<0.001
DKA cases/month	0.42	<0.001

3.6 Multivariable Predictors of Knowledge

Multivariable linear regression identified the following independent predictors of higher knowledge:

- Prior DKA training: $\beta = 0.38$, $p < 0.001$
- Clinical experience: $\beta = 0.22$, $p = 0.002$
- Master's level education: $\beta = 0.25$, $p = 0.001$

The model explained 33% of the variance in knowledge scores (adjusted $R^2 = 0.33$) (Table 5).

Table 5. Multivariable Linear Regression Predictors of Nurses' Knowledge Scores

Predictor	B	p
Prior DKA training	0.38	<0.001
Clinical experience	0.22	0.002
Master's degree	0.25	0.001

4. Discussion

This study assessed nurses' knowledge regarding diabetic ketoacidosis (DKA) management at Omdurman Teaching Hospital and found an overall moderate level of knowledge, with %40.6 demonstrating good knowledge and %19.8 having poor knowledge. These findings align with research from other low- and middle-income countries, where nursing knowledge in DKA management is often moderate, particularly in critical areas such as fluid resuscitation, insulin therapy, and electrolyte monitoring (Abdulkarim et al., 2024; Matthews et al., 2023). Furthermore, similar gaps in nurses' knowledge and clinical competence have been reported in Egypt, Nigeria, and Ethiopia, highlighting persistent challenges in DKA management across resource-limited settings (Fina Lubaki et al., 2022; Kajembula et al., 2024; Kibret Abebe et al., 2025; Shaker et al., 2025).

A major finding of this study is the strong positive effect of prior DKA training on nurses' knowledge. Nurses who received formal training scored significantly higher than their untrained colleagues, and training was the strongest independent predictor in multivariate analysis. This supports evidence that structured in-service education and continuous professional development improve understanding of DKA complications, insulin administration, fluid and electrolyte management, and patient education, ultimately enhancing patient safety (Ali & Saad, 2022; Xie et al., 2025).

Higher academic qualifications were also associated with better knowledge. Nurses holding master's degrees achieved the highest scores, followed by bachelor's and diploma nurses.

This finding aligns with research from Saudi Arabia and Jordan, which shows that higher levels of education and formal training in evidence-based practice are associated with better adherence to evidence-based guidelines and improved clinical decisionmaking among nurses (Abuadas, 2021; Al-Ghabeesh et al., 2024; Alqahtani et al., 2022).

Clinical experience and exposure to DKA cases were positively correlated with knowledge scores, confirming that experiential learning contributes to competence. However, unlike some studies that report experience as

the main determinant (Karume et al., 2025), this study found that experience alone is insufficient without formal training. This may reflect variability in access to standardized protocols, mentorship, and structured clinical guidance in the hospital setting (Bolado et al., 2024).

Despite the generally moderate knowledge, gaps remained in potassium replacement, recognition of cerebral edema, and follow-up of DKA complications. These gaps are clinically significant, as errors in these areas can lead to serious iatrogenic complications and increased mortality. The persistence of these weaknesses highlights the need for protocol-based management and periodic evaluation of nursing competence.

- **Limitations** of this study include its cross-sectional design, use of a self-administered questionnaire, and single-center setting, which may limit the generalizability of the findings.
- **Implications for practice and policy:** The findings emphasize the importance of targeted in-service training, advanced nursing education, and exposure to clinical cases to enhance knowledge and patient safety. Implementing standardized clinical protocols and continuous monitoring of competence can address persistent knowledge gaps and improve the quality of DKA care.

5. Conclusion

Nurses demonstrated a moderate level of knowledge regarding diabetic ketoacidosis (DKA) management, with notable variability among individuals. While 40.6% showed good knowledge, approximately 19.8% had poor knowledge. These findings highlight the need for targeted in-service training, particularly for less experienced and untrained nurses, as well as the implementation of standardized clinical protocols to improve competence and enhance patient safety.

6. Recommendations

According to the research findings, all nurses should be provided with regular in-service training programs on diabetic ketoacidosis management, which will increase the clinical competence levels and adherence to the evidence-based guidelines. Establishing standardized DKA management guidelines to be used in emergency units and intensive care units are highly suggested and should be visibly placed to assist in the timely and uniform clinical decision-making. In addition, structured DKA modules can be integrated into continuing nursing education programs and staff orientation sessions that can contribute to strengthening the key knowledge and skills. Knowledge and practice of nurses should be managed by arranging periodical reviews and clinical audits to determine any gaps and drive further quality

improvement efforts. Promoting critical thinking and evidence-based practice should also focus on encouraging advanced nursing education and professional growth. Lastly, multicenter studies are suggested to allow a wider range of information about national training needs and implement interventions on a policy-level basis.

7. References

- Abdulkarim, D. N., Alqurashi, H. A., Aldossri, E. A., Almubrook, A. S., Alamri, A. S., Alanzi, A. A. A., Alhafi, M. A., Alanazi, A. H. S., Al Fawaz, F. A., & Alanazi, A. S. F. (2024). *The Role of Nursing in Diabetes Management: The Impact of Biochemical Markers on Diagnosis, Complications, and Patient Outcomes through Comprehensive Care and Support*. *Egyptian Journal of Chemistry*, 67(13), 1235-1249. <https://doi.org/10.21608/ejchem.2024.334932.10769>
- Abuadas, M. H. (2021). *Correlates of evidence-based nursing practice among nurses in Saudi Arabia: a structural equation model*. *Belitung Nursing Journal*, 7(6), 457. <https://doi.org/10.33546/bnj.1803>
- Adewale, G. O. (2023). *Educating Nurses on Failure to Rescue due to Treatment Delay*. Walden University.
- Ahmed, A. A. O., Mounfali, M. A. A., Yassin, T., Ibrahim, H., Ahmed, R. A. O., Ahmed, R. A. O., Ahmed, N., Ahmed, O. A. O., Elbashir, R. M. A., & Mohamed, K. H. (2025). *Prevalence and patterns of diabetic ketoacidosis (DKA) among diabetic patients presenting to hospitals in northern state, Sudan: a cross-sectional study during the 2025 humanitarian crisis*. *BMC Endocrine Disorders*, 25(1), 292. <https://doi.org/10.1186/s12902-025-0292-x>
- Al-Ghabeesh, S., Khalifeh, A. H., & Rayan, A. (2024). *Evidence-based practice knowledge, attitude, practice and barriers as predictors of stay intent among Jordanian registered nurses: a cross-sectional study*. *BMJ open*, 14(7), e082173. <https://doi.org/10.1136/bmjopen-2023-082173>
- Ali, S. A., & Saad, N. S.-E. (2022). *Effectiveness of in-service training program on nurses' performance regarding patient safety practice standards in Intensive Care Units*. *Egyptian Journal of Nursing and Health Sciences*, 3(1), 68-95. <https://doi.org/10.21608/ejnhs.2022.251411>
- Alqahtani, J. M., Carsula, R. P., Alharbi, H. A., Alyousef, S. M., Baker, O. G., & Tumala, R. B. (2022). *Barriers to implementing evidence-based practice among primary healthcare nurses in Saudi Arabia: a cross-sectional study*. *Nursing Reports*, 12(2), 313-323. <https://doi.org/10.3390/nursrep12020031>
- Alsabri, M., Oboli, V. N., Rath, S., Tsoi, V., Del Castillo Miranda, J. C., Alagarswamy, K., & Shehada, W. (2025). *Bridging the gap: Lessons from low-resource pediatric emergency medicine for high-resource settings*. *Current emergency and hospital medicine reports*, 13(1), 10. <https://doi.org/10.1007/s40138-025-00315-z>
- Bolado, G. N., Ataro, B. A., Gadabo, C. K., Ayana, A. S., Kebamo, T. E., & Minuta, W. M. (2024). *Stress level and associated factors among nurses working in the critical care unit and emergency rooms at comprehensive specialized hospitals in Southern Ethiopia, 2023: explanatory sequential mixed-method study*. *BMC nursing*, 23(1), 341. <https://doi.org/10.1186/s12912-024-02004-w>
- Fina Lubaki, J.-P., Omole, O. B., & Francis, J. M. (2022). *Protocol: Developing a framework to improve glycaemic control among patients with type 2 diabetes mellitus in Kinshasa, Democratic Republic of the Congo*. *PLoS One*, 17(9), e0268177. <https://doi.org/10.1371/journal.pone.0268177>
- Gholipour, M., Dadashzadeh, A., Jabarzadeh, F., & Sarbakhsh, P. (2025). *Challenges of clinical decision-making in emergency nursing: an integrative review*. *The Open Nursing Journal*, 19(1). <https://doi.org/10.2174/0118744346378311250320070725>
- Kajembula, I. M., Mattheo, K. I., Simchimba, P. D., Masasi, E. H., Chikwala, V., & Ambikile, J. S. (2024). *Understanding the factors influencing nurses in managing patients with diabetic ketoacidosis in the emergency departments of referral hospitals in Dar es Salaam, Tanzania: A descriptive qualitative study*. *PLoS One*, 19(11), e0310414. <https://doi.org/10.1371/journal.pone.0310414>
- Karume, A. K., Sugut, J., Sankei, P., Kimathi, P. M., Guleid, A., Kimonge, D., Ebert, E., Wanjiku, G., Myers, J. G., & Beck, A. (2025). *Improvement in clinician confidence in and knowledge of Diabetic Ketoacidosis management following a case-based curriculum in Kenya*. *BMC Medical Education*, 25(1), 352. <https://doi.org/10.1186/s12909-025-0352-x>
- Kibret Abebe, G., Bishaw Aynalem, Z., Meseret, F., Dagne Abate, M., & Nuru Muhamed, A. (2025). *Mortality and its predictors in Adult Diabetic ketoacidosis patients in East Africa: A 2025 Systematic review and meta-analysis*. *F1000Research*, 14, 864. <https://doi.org/10.12688/f1000research.141864.1>
- Matthews, S., Coates, M. M., Bukhman, A., Trujillo, C., Ferrari, G., Dagnaw, W. W., Fénelon, D. L.,

- Getachew, T., Karmacharya, B., & Larco, N. C. (2023). Health system capacity to manage diabetic ketoacidosis in nine low-income and lower-middle income countries: A cross-sectional analysis of nationally representative survey data. *EClinicalMedicine*, 55. <https://doi.org/10.1016/j.eclinm.2022.101728>
- Mohajan, D., & Mohajan, H. K. (2023). Diabetic ketoacidosis (DKA): a severe diabetes mellitus disorder. Unpublished Manuscript.
- Mohan, V., & Lee, K. (2025). Global Burden of Diabetic Ketoacidosis. *Diabetes Technology & Therapeutics*, 27(4_suppl), S6-S13. <https://doi.org/10.1089/dia.2025.27.S6>.
- Shaker, M. S., Faltas, S. F. M., & Abdelhady, M. S. (2025). Studying the Role of Nurses in the Diabetic Ketoacidosis Management. *Journal of Integrative Nursing and Palliative Care*, 6(1-2025), 18-23. <https://doi.org/10.51847/AZep6FvIIV>
- Xie, H., Dai, X., Xie, J., Lei, S., Zeng, J., Yang, J., & Zhou, Y. (2025). Artificial Intelligence Adoption in Surgery: Cognition, Usage Patterns and Implementation Barriers of DeepSeek Among Healthcare Professionals in China's Tertiary Hospitals. *Journal of Multidisciplinary Healthcare*, 7719-7737. <https://doi.org/10.2147/JMDH.S538723>



The Role of Virtual Simulation Environments (the Metaverse) in Improving Construction Methodologies and Processes

Ahmed R. Attia

Department of Architecture ,Faculty of Engineering, Al-Baha University, Al-Baha, KSA.

(Received: 15th November 2025; **Accepted:** 17th April 2026)

Abstract

Purpose: This research paper aims to explore the transformative role of virtual simulation environments (the metaverse) in developing construction methodologies and improving construction processes to address traditional challenges such as cost overruns, schedule delays, and safety risks.

Findings: The study reveals that the integration of metaverse technologies brings about a qualitative shift in the construction sector. These environments enable the creation of dynamic digital twins for projects, allowing all stakeholders (including engineers, designers, and clients) to interact with the project in an immersive virtual environment prior to physical execution. This facilitates the early detection and resolution of design and construction conflicts, thereby reducing costly errors and change orders during construction. Furthermore, these technologies enhance the precise planning of construction operations, optimize task sequencing and logistics management, and enable realistic, high-safety training scenarios for workers, which helps minimize on-site accidents.

Recommendations: The paper recommends that contracting and engineering consulting firms adopt these emerging technologies, invest in the necessary digital infrastructure, and train human resources. It also emphasizes the importance of developing unified frameworks and standards for data exchange between traditional design platforms and metaverse environments to ensure seamless integration. Finally, it encourages further research to measure the return on investment and the impact of these technologies on the productivity and final quality of construction projects.

Keywords: Virtual Simulation Environments, Construction Management, Digital Twin, Construction Processes, Building Methodologies, Immersive Technology, Risk Reduction



(*) Corresponding Author:

Ahmed R. Attia

Department of Architecture ,Faculty of Engineering, Al-Baha University, Al-Baha, KSA.

E-mail: prof_a.ramadan@outlook.com / ahmed.r@bu.edu.sa

ORCID: 0009-0000-7773-3331

1. INTRODUCTION

1.1 Research Problem

Despite the technological advancements the construction industry has witnessed over the decades, it continues to suffer from chronic systemic failures. These failures are manifested in recurrent cost overruns, significant schedule delays, high levels of material and time waste [1], and considerable injury rates on work sites.

The roots of these problems can be traced to a critical flaw in traditional methodologies for planning, design, and coordination. Conventional approaches rely primarily on two-dimensional drawings and limited visualization environments [2], which fail to provide a genuine and comprehensive understanding of a project's complexities before physical execution begins.

This deficiency results in what are known as "coordination clashes," where conflicts between different engineering disciplines (e.g., electrical, mechanical, and structural) are discovered during the later stages of a project. Such late-stage discoveries necessitate costly modifications and rework.

Furthermore, the limited capacity to simulate construction processes, their sequence, and to anticipate potential risks leaves work crews vulnerable to unforeseen issues on site. This vulnerability threatens both operational efficiency and worker safety [3].

Consequently, there is a pressing need for a new paradigm to bridge the gap between design and reality. Virtual environments, or the metaverse, show significant potential in addressing this need [4].

1.2 Research Objectives

This research paper aims to explore the pivotal role that metaverse environments can play in advancing construction methodologies and enhancing building processes. It posits that by providing an immersive and interactive environment, the metaverse enables the identification and resolution of problems in the virtual world before they materialize into real-world costs and risks

The research seeks to achieve the following objectives

- Analyzing the functional capabilities offered by metaverse environments - such as dynamic digital models and immersive virtual reality - and their potential applications across various stages of the project lifecycle.
- Evaluating the impact of implementing these technologies on key project performance indicators, including cost, quality, time, and safety.

- Identifying the challenges and obstacles - technical, financial, and human - that may impede the adoption of these technologies within the construction sector.
- Developing a proposed framework for the effective integration of metaverse environments into standard construction workflows.

1.3 Research Methodology

- This study adopted a multi-method research methodology, encompassing the following approaches:
- Theoretical Approach: A comprehensive review of current academic and professional literature was conducted to establish a robust theoretical framework.
- Applied Approach: Specific case studies of projects that have utilized technologies analogous to metaverse environments - such as advanced Building Information Modeling (BIM) integrated with Virtual Reality (VR) - were analyzed to derive practical findings and recommendations.
- Analytical Approach: The collected data and information were systematically analyzed to identify patterns and relationships, thereby enabling the deduction of tangible benefits and potential obstacles.
- Through this integrated methodological combination, the paper seeks to provide a comprehensive and practical vision for how the construction sector can leverage the revolution in virtual simulation environments to achieve a qualitative leap in productivity and quality.

2. Theoretical Framework and Conceptual Analysis

2.1 Introduction and General Framework

This section presents the theoretical foundation and conceptual boundaries of the research, as stated in the main title of Section 2. While the overall chapter develops a structured theoretical framework for analyzing metaverse applications in construction projects, Section 2.1 specifically focuses on introducing the general framework that underpins the subsequent conceptual analysis. To achieve this, the global construction industry's ongoing digital transformation is first examined, highlighting how virtual simulation environments - collectively termed the "metaverse" - emerge as a promising technology to address chronic sector challenges. Construction projects traditionally face recurring problems with cost overruns, schedule delays, and poor coordination among different stakeholders [3]. Metaverse technologies offer a comprehensive solution by creating immersive virtual environments that enable full simulation of the project lifecycle. Thus, Section 2.1 establishes the overarching

lens through which the subsequent theoretical constructs (e.g., collaboration theory, information integration, stakeholder engagement) are analyzed in Sections 2.2 and 2.3.

2.2 Historical Evolution of Simulation in the Construction Sector

As shown in Figure (1), the historical evolution of simulation in the construction industry can be divided into three main phases.

- The first phase is the Traditional approach, which prevailed before the 1980s and into the 1990s. During this era, construction planning and coordination relied on 2D paper drawings and manual methods, with limited ability to visualize projects before execution.
- The second phase is the Early Digital era, spanning the 2000s to the 2010s. This period witnessed the emergence of Building Information

Modeling (BIM), which enabled digital 3D modeling and improved data integration, yet still lacked real-time interactivity and immersive visualization.

- The third and most recent phase is the Virtual Reality and Metaverse era, from the 2020s onward. In this phase, immersive virtual environments allow stakeholders to interact with digital twins of projects in real time, enabling collaborative simulation, clash detection, and process optimization before physical construction begins.

This evolution illustrates a clear progression from static, two-dimensional representations to dynamic, immersive, and interactive virtual environments. Understanding this trajectory is essential for appreciating how metaverse technologies build upon earlier simulation methods while introducing transformative capabilities that address longstanding construction challenges.

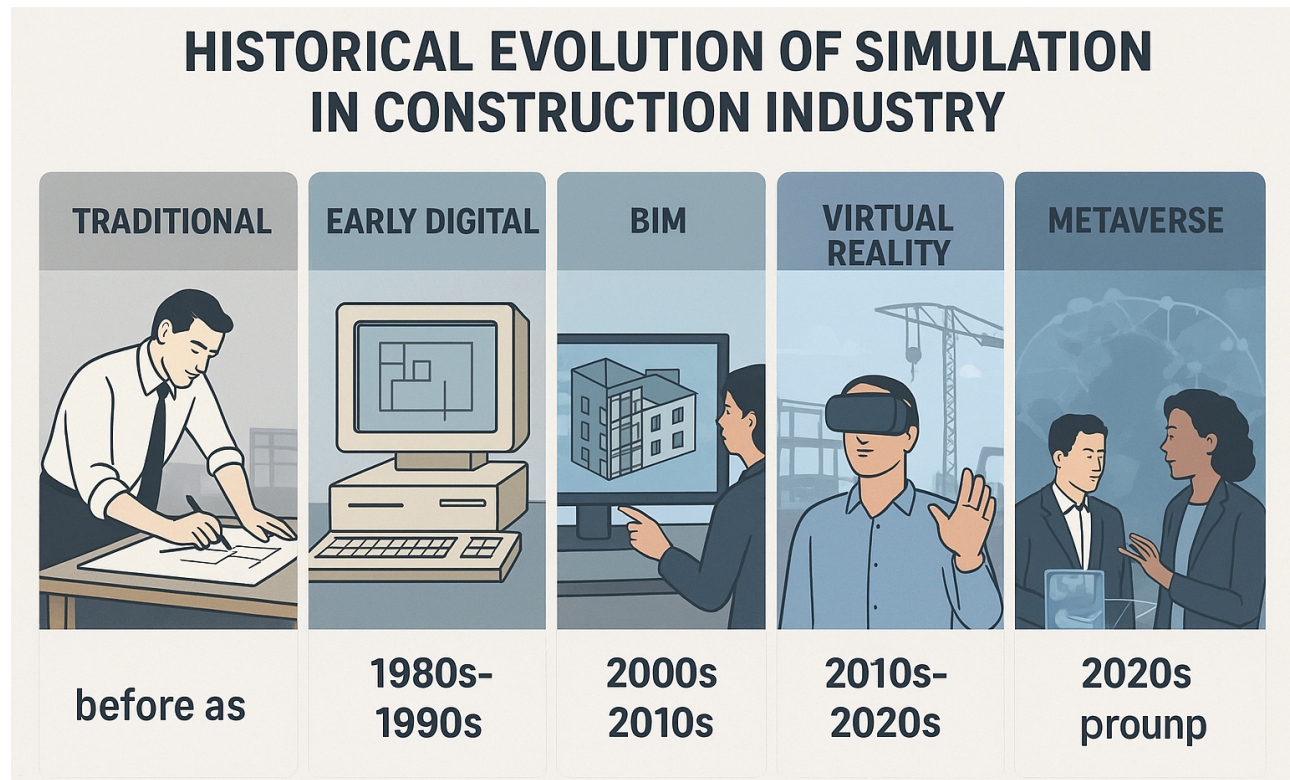


Fig. 1. Historical Evolution of Simulation in the Construction Industry [63]

2.2.1 From Physical Models to digital modeling

- Physical Models: For decades, the construction industry relied on scaled physical models, which were time-consuming and lacked flexibility [5].
- 2D Modeling: The emergence of CAD software like AutoCAD represented a qualitative leap but remained limited in representing spatial relationships.

2.2.2 The Building Information Modeling (BIM) Revolution:

Building Information Modeling (BIM) represented a qualitative shift from traditional engineering modeling to comprehensive digital information management across the entire project lifecycle [7]. Unlike conventional 3D CAD models, which contain only geometric data, BIM enables the creation of intelligent digital models embedded with rich metadata, including material specifications, cost data, scheduling information, and maintenance requirements [8].

This semantic richness allows automated clash detection between different disciplines (e.g., structural beams conflicting with HVAC ducts), reducing design errors by up to 40% [9]. Furthermore, BIM facilitates improved coordination among architects, engineers, and contractors through a shared digital repository, minimizing information loss and rework [10]. As the foundational technology for digital twins and metaverse environments, BIM provides the structured data layer necessary for immersive virtual simulation and real-time project monitoring.

2.2.3 The Transition to the Metaverse:

- The Metaverse represents the natural evolutionary stage of BIM.
- It provides interactive, immersive environments instead of static models as shown in Figures (1).
- It shifts from visualization to comprehensive simulation [7].

2.3 The Scientific Concept of the Metaverse and Its Core Technologies

2.3.1 Academic Definition of the Metaverse:

In academic literature, the metaverse is defined as “a shared, collective virtual environment that merges the physical and digital worlds through interactive immersion technologies”[8].

2.3.2 Core Technical Components

1. Dynamic Digital Twins:

- Live digital models connected to the physical world.
- Receive real-time data from sensors.
- Enable simulation of various scenarios and performance prediction [9].

2. Virtual Reality (VR):

- Fully immersive environments that surround the user.
- Require specialized headsets.
- Suitable for training and complex design processes [10].

3. Augmented Reality (AR):

- Integration of virtual elements into the real environment.
- Enable information display in its physical context.
- Useful for construction and maintenance operations [11].

4. Blockchain Technologies:

- Provide secure, distributed ledgers for transactions.
- Support smart contracts and supply chain tracking.

- Ensure transparency in project management [12].

The transition from individual technologies (Digital Twins, VR, AR, and Blockchain) to a unified Metaverse environment requires three integrated steps. First, the Digital Twin provides a live virtual replica of the physical project, continuously updated with real-time sensor data. Second, VR and AR are layered onto this twin: VR enables immersive remote access for design reviews and training, while AR overlays digital information onto the physical site for construction and maintenance. Third, Blockchain ensures transparency and security through smart contracts and tamper-proof supply chain tracking. When these steps are combined, all stakeholders can collaborate simultaneously in a shared virtual space, enabling real-time decision-making and eliminating the misunderstandings caused by fragmented point solutions [11],[12].

2.4 Conceptual Framework for Integrating the metaverse with Construction Methodologies

Building upon the research objectives stated in Section 1.2, this section presents a conceptual framework that operationalizes these objectives into actionable components. Specifically, the framework addresses the four main objectives of this research: (1) analyzing the functional capabilities of metaverse environments, (2) evaluating their impact on project performance indicators, (3) identifying adoption challenges, and (4) developing an integration framework. The framework is structured around three core methodological transformations- design, planning, and implementation - which directly correspond to the project lifecycle stages examined in this study.

2.4.1 Transforming Design Methodologies

Traditional construction design follows a linear approach, where each phase (concept → schematic → detailed → construction) proceeds sequentially with limited feedback loops between phases. This linearity often results in late-stage discoveries of design flaws, requiring costly rework. The Metaverse enables a fundamental shift from this linear model to an iterative and interactive design methodology. In this new approach, all stakeholders (architects, engineers, clients, and contractors) can simultaneously explore, test, and modify design solutions within a shared immersive environment. Multiple design alternatives can be evaluated in real time, and feedback is incorporated continuously rather than at fixed milestones. This transformation is supported by the following capabilities:

- Ability to test multiple design solutions in a short time
- Effective participation of all stakeholders in the design process [13]

2.4.2 Developing Planning Methodologies

- Simulation of construction processes before

implementation.

- Optimization of task sequencing and resource allocation.
- Early detection of potential problems [14].

2.4.3 Improving Implementation Methodologies:

- Guiding equipment and operations through digital models.
- Continuous performance monitoring and alignment of the as-built with the as-planned model.
- Proactive risk management [15].

This framework directly informs the empirical analysis presented in Section 5 (Results), where each of the above methodological components is evaluated against key performance indicators derived from the three case studies.

2.5 Theoretical Framework for the Impact of the metaverse on Construction Processes

1. Design and Planning Processes

- Reduction in design time by 40% according to case studies.
- Reduction of design conflicts by 85%.
- Improved quality of design decisions [16].

2. Implementation and Construction Processes:

- Reduction of rework costs by 25-30%.
- Improvement of labor productivity by 15-20%.
- Reduction of material waste by 10-15% [17].

3. Maintenance and Operation Processes:

- Improved facility management efficiency.
- Proactive planning of maintenance operations.
- Extension of the project's virtual lifespan [18].

2.5.1 Preliminary Conclusions of the Theoretical Phase:

Through comprehensive theoretical analysis, it is evident that the metaverse represents a qualitative leap in construction methodologies and processes. The integration of core technologies like dynamic digital twins, virtual reality, and augmented reality forms a comprehensive framework capable of addressing the traditional challenges of the sector. This theoretical phase establishes the logical foundation for the subsequent applied phases of the research, while emphasizing the need for practical implementation frameworks to maximize the benefits of these technologies.

3. Comparative Case Study Analysis

This section presents a comparative analytical study of three real-world construction projects that have implemented technologies analogous to Metaverse environments (including advanced BIM, Digital Twins, VR/AR, and IoT integration). The analysis applies the theoretical framework developed in Section 2 to examine how these technologies impacted key performance indicators across each project. This section does not present a new practical application conducted by the authors; rather, it systematically analyzes existing case studies to derive empirical findings, identify patterns, and validate the proposed conceptual framework. This second phase of the research represents the practical applied component that aims to verify the hypotheses raised in the theoretical framework, providing tangible evidence of the practical benefits and challenges associated with metaverse applications in construction projects [19].

3.1 Methodological Steps for Case Studies:

1. Design and Case Selection

The study adopted a Multiple Case Study Methodology, applying specific selection criteria that included: project scale (exceeding \$100 million), availability of quantitative data, diversity of construction domains, and the degree of technological application. Three case studies were selected according to an evaluation system developed by [19].

These case studies are:

- First Case Study: Dubai Creek Tower – Dubai (detailed in Section 3.1.1)
- Second Case Study: Istanbul Grand Airport – Istanbul (detailed in Section 3.2.1)
- Third Case Study: The “Smart City” Project – Singapore (detailed in Section 3.3.1)

2. Data Collection and Analysis

Data was gathered from multiple sources, including official reports and published studies, with an analysis of performance indicators before and after technology implementation. The data collection relied on a Triangulation methodology to ensure the credibility of the findings [20].

3. Comparative Analysis and Deriving Results

A comparative analysis was conducted using standardized performance indicators, comparing the performance of traditional projects with technology-enhanced ones. Variance in outcomes across different project types was analyzed, and critical success factors along with common challenges were identified through Cross-Case Analysis [21].

3.2 First case study: Dubai Creek Tower – Dubai

The Dubai Creek Tower is classified as a mega-project of global stature, with a construction cost of USD 450 million and a total built-up area of 150,000 square meters. The tower is distinguished by its unique

architectural design, which seamlessly integrates traditional and contemporary elements, establishing it as a prominent landmark within Dubai's urban landscape as shown in Figure (2) .



Fig.2: Dubai Creek Tower during the construction phase [22]

- **Type:** Mixed-use skyscraper (residential + commercial)
- **Height:** 380 meters
- **Location:** Dubai Creek, UAE
- **Estimated Cost:** USD 450 million
- **Technology:** Extensive use of digital twin and BIM during all life-cycle stages as shown in Figure (3).

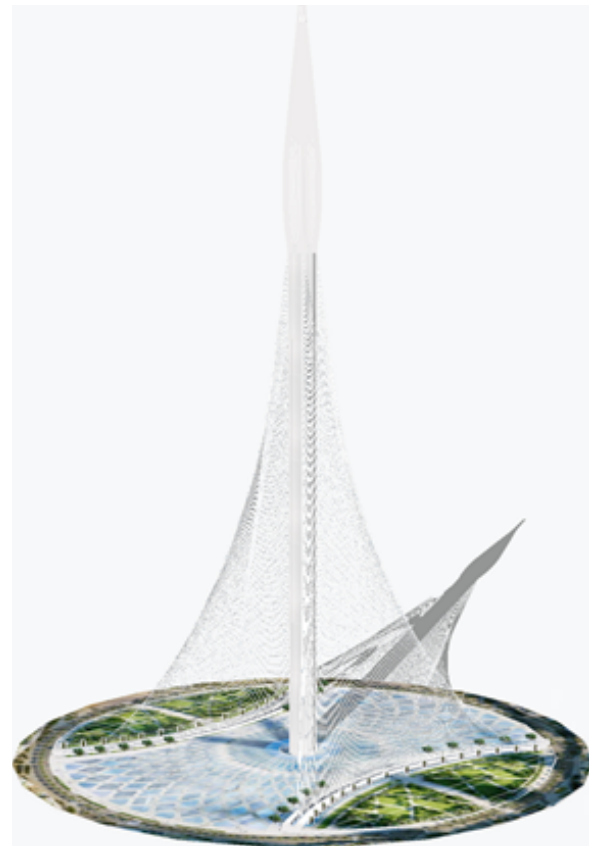


Fig.3: The Dubai Creek Tower (previously called the Dubai Observation Tower) is the centerpiece of a larger development named Dubai Creek Harbor [23]

3.2.1 Level of Technological Application:

The project featured an integrated implementation of state-of-the-art digital technologies:

1. **Integrated digital twin System:**
 - Real-time simulation of the structural behavior.
 - Live monitoring through 500 sensor points.
 - Predictive analytics for structural and functional performance [24].
2. **Artificial Intelligence and Data Analytics:**
 - Predictive algorithms for risk management.
 - Big data analysis for performance optimization.
 - Advanced cloud computing systems [25].

3. Immersive Technologies:

- Augmented Reality glasses for on-site supervision.
- A virtual platform for training and qualification.
- Emergency and crisis simulation systems [26].

3.2.2 Project Performance

1. Safety and Quality Indicator

- Accident rate reduction: 25%
- Implementation quality improvement: 40%
- Rework reduction: 35%
- Achievement of highest international safety standards

2. Operational Efficiency Indicator

- Labor productivity improvement: 30%
- Execution time reduction: 15%
- Process sequencing optimization: 35%
- Inter-task waiting time reduction: 20%

3. Cost and Resources Indicator

- Overall cost saving: 12%
- Change orders reduction: 18%
- Inventory management improvement: 25%
- Maintenance cost reduction: 20%

4. Environmental Sustainability Indicator

- Material waste reduction: from 15% to 8%
- Carbon footprint reduction: 22%
- Energy efficiency improvement: 18%
- Recycled materials usage increase: 30%

3.2.3 Results and Impacts

These technological applications yielded tangible outcomes, including:

- A 25% reduction in maintenance costs.
- A 30% improvement in energy efficiency.
- An 18% reduction in the carbon footprint [27].
- 95% of design clashes detected early .
- 30% improvement in construction sequencing.
- IoT data enhanced predictive maintenance.
- Overall cost savings: \$45 million
- Project delivery ahead of schedule: 4 months
- Platinum sustainability rating achieved
- Cloud collaboration improved coordination
- Total performance improvement: 28% as shown in Figure (4).

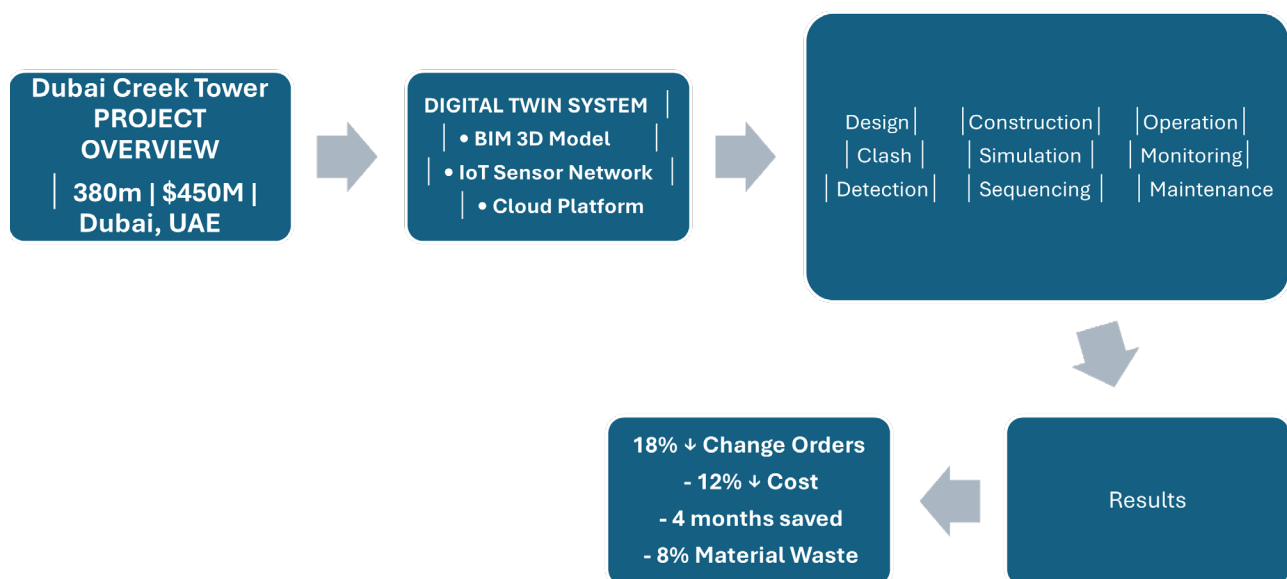


Fig. 4. How Did Digital Twin Integration Enhance Project Performance?

3.3 Conclusions

- Early adoption of digital twin enhances clash detection.
- Centralized data improves collaboration.
- Simulation-driven planning reduces costs and delays.
- Confirms the strategic value of digitalization in mega projects.
- Digital Twin technology delivers measurable performance gains.
- Enhances decision-making through real-time data.
- The Dubai Creek Tower exemplifies digital transformation [28]

3.3.1 Second case study: Istanbul Grand Airport– Istanbul

Istanbul Grand Airport ranks among the world's largest infrastructure projects of the current decade, with a total area of 76.5 million square meters as shown in

Figure(5). With a construction cost exceeding USD 12 billion, the airport features 6 runways, two air cargo centers, and a massive passenger terminal capable of handling 200 million passengers annually, establishing it as a global logistics hub connecting three continents [29].



Fig.5: Aerial view of Istanbul Grand Airport [30]

3.3.2 Level of Technological Application

The project implemented an integrated technological system comprising:

1. Advanced Virtual Reality Platform

- Comprehensive simulation of operations and

emergencies.

- Immersive training for staff on complex equipment as shown in Figure (6).
- Passenger flow and congestion management simulation [29].



Fig.6: Advanced Cabin Simulators at Turkish Airlines Training Center [33]

2. Digital Twin Modeling System

- Real-time monitoring of facility and utility performance.
- Predictive analysis of equipment failures.
- Smart management of energy and utilities [31].

3. Integrated Smart Technologies

- Automated facial recognition systems.
- Intelligent service robots.
- Big data management platform [32].

3.3.3 Project Performance

The technological applications yielded the following tangible results:

1. Safety and Quality Indicator

- 32% reduction in accident rate.
- 25% decrease in emergency response time.
- 60% improvement in training effectiveness.
- Customer quality satisfaction index rose to 94%.
- 45% reduction in quality-related complaints as shown in Figure (7).

Certification	Issued by	Scope	Year	Impact
ISO 9001: Quality Management	ISO	Quality across airport operations	2021	Consistency in passenger processing and service levels improved
ISO 14001: Environmental Management	ISO	Environmental performance and yeşil initiatives	2022	Waste reduction and emissions efficiency enhanced
ISO 45001: Occupational Health & Safety	ISO	OHS across sites and operations	2023	Safety metrics strengthened; incidents declined
SHGM Certification (Turkish Civil Aviation Authority)	SHGM	Airport operations compliance and risk management	2024	Regulatory alignment maintained; periodic audits passed with strong results

Fig.7: Quality and safety indicators of the airport IGA [36]

2. Operational Efficiency Indicator

- 280 training hours saved for personnel.
- 45% reduction in quality inspection time.
- 28% improvement in route planning efficiency

3. Cost and Resources Indicator

- Avoided rework valued at USD 85 million.
- 22% reduction in maintenance costs.
- 18% saving in energy consumption

4. Environmental Sustainability Indicator

- 30% reduction in energy consumption through smart control systems.
- 35% reduction in material waste during construction.
- 40% lower carbon footprint compared to conventional airports.
- 85% recycling rate of construction waste as shown in Figure (8) [32].



Fig.8: Sustainable Energy Management System at Istanbul New Airport [35].

The image above illustrates the solar power plant located in Eskisehir, Turkey, which is part of Istanbul New Airport's initiative to become the world's first fully solar-powered airport [35].

3.3.4 Results and Impacts

The application of metaverse technologies in construction projects has led to measurable improvements in both environmental performance and quality management [34]. As shown in Figures (9) and (10), the integration of virtual simulation environments enables better monitoring of sustainability metrics and quality assurance processes. Key outcomes include:



Fig.9: As the first recipient of this certificate in Level 4 in Türkiye, iGA Istanbul Airport has moved one step closer to its “Net Zero by 2050” goal [61] Operational Impacts



Fig.10: Istanbul Airport: World’s First Solar-Powered Airport [62]

- 35% improvement in passenger experience.
- 28% increase in air cargo efficiency.
- 40% reduction in waiting times.

1. Economic Impacts

- 15% reduction in annual operational costs.
- 20% increase in non-operational revenue.
- 25% extension in facility lifespan.

2. Environmental and Quality Impacts

- Achievement of LEED Platinum certification.
- Annual carbon emission reduction of 50,000 tons.
- 100% use of renewable energy in operational activities.
- Attainment of ISO 9001:2015 quality certification.
- Achievement of highest quality standards in support services.

3. Technologies contributed to transforming the airport into an integrated smart facility.
4. Simulation systems achieved full alignment between digital models and physical reality.
5. Virtual training played a crucial role in developing advanced human competencies.
6. The project achieved global sustainability standards in environmental performance.
7. The project demonstrated exceptional integration of safety requirements and service quality.

The figure 10 illustrates Istanbul Airport's solar energy initiative. The solar plant covers approximately 3 million square meters, houses 439,000 solar panels, and has a total capacity of 199.32 megawatts (MW), making Istanbul Airport the first airport worldwide to be entirely powered by solar energy [62].

3.4.1 Third case study: The "Smart City" Project - Singapore

The Singapore Smart City represents one of the world's leading models of integrated smart cities, covering an area of 5 km² as The Singapore Smart City represents one of the world's leading models of integrated smart cities, covering an area of 5 km². As shown in Figure 11(a), which provides an aerial view of Singapore's Smart City infrastructure, the project comprises approximately 20,000 residential units alongside advanced commercial

and service facilities. Figure 11(b) illustrates the key technology drivers and strategic initiatives of Smart Nation Singapore for 2023 [43]. The project aims to create a sustainable and intelligent urban environment that leverages cutting-edge digital technologies to enhance residents' quality of life and well-being [37]. This project was developed under the umbrella of Singapore's "Smart Nation" initiative, launched by the government in 2014 [38].

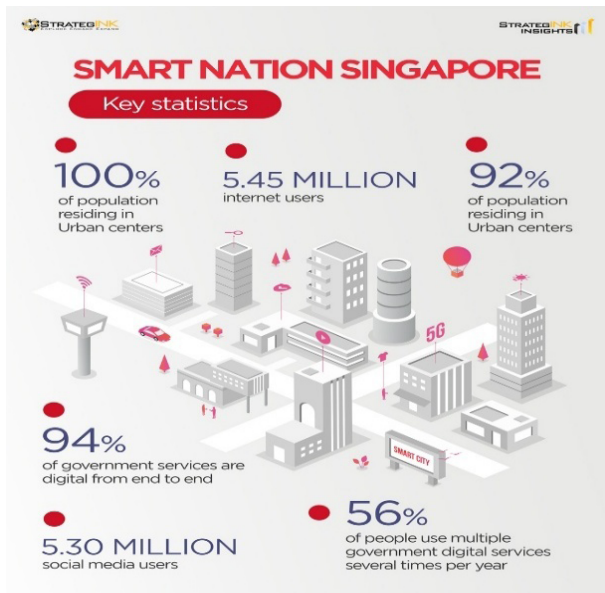


Fig. 11. Singapore's Smart City Initiative [43]

3.4.2 Level of Technological Implementation:

The project deployed an advanced and comprehensive technological system including:

1. Integrated Digital Twin

- Comprehensive simulation of infrastructure and utilities
- Real-time monitoring of system performance
- Emergency and disaster scenario simulations [39].

2. Augmented Reality:

- Maintenance and repair applications as shown in Figure (12).

- Field assistance tools for workers
- Intelligent navigation systems for residents [40].

3. Internet of Things (IoT)

- Network of smart sensors distributed throughout the city
- Air quality and environmental monitoring systems
- Smart meters for energy and water [41].

4. Artificial Intelligence and Data Analytics:

- Predictive systems for traffic management
- Energy consumption optimization algorithms
- Big data analytics platforms [42].



Fig. 12. Augmented Reality Applications in Maintenance [44]

3.4.3 Project Performance

1. Safety and Quality Indicator

- 40% reduction in resident complaints.
- 90% resident satisfaction rate with service quality
- 30% reduction in crime rates through smart surveillance systems
- 35% decrease in traffic accidents [45].

2. Operational Efficiency Indicator

- 35% improvement in service response time
- 28% reduction in intra-city travel time
- 42% improvement in waste collection efficiency
- 50% increase in report processing speed [45],[61].

3. Cost and Resources Indicator

- 15% savings in maintenance costs

- 22% reduction in operational costs
- 30% savings in energy costs.
- 18% decrease in utility management costs [46].

4. Environmental Sustainability Indicator

- 25% improvement in energy consumption efficiency
- 35% reduction in carbon emissions
- 40% increase in green space areas
- 60% waste recycling rate achievement

3.4.4 Impacts and Conclusions

1. Operational Impacts

- 45% improvement in quality of life based on resident surveys
- 38% increase in community engagement
- 50% improvement in accessibility for people with disabilities [47].

2. Economic Impacts

- 25% increase in property values
- Attraction of \$500 million in technology investments
- Creation of 5,000 new jobs in the technology sector [48].

3. Environmental and Quality Impacts

- 40% reduction in the city's carbon footprint
- 55% increase in renewable energy adoption
- 30% improvement in air quality as shown in Figure (13). [49].



Fig.13: Digital Control Dashboard of the Smart City [51]

Smart technologies significantly improved performance indicators, The digital twin enhanced predictive maintenance operations by 28% , Digital model data improved municipal service planning by 45%, The project achieved a balance between urban development and environmental sustainability, The project established a successful model replicable in other cities [50].

4. DISCUSSION

This study investigates the impact of metaverse applications on construction project performance through a comparative analysis methodology based on a unified system of Key Performance Indicators (KPIs). The methodology was designed to ensure objectivity and accuracy in performance evaluation across projects diverse in scale, nature, and geographical location. It relies on an integrated quantitative and qualitative analysis, where all data were converted to percentages to facilitate standardized benchmarking. The study utilized the SPSS statistical analysis software to conduct variance tests and analyze relationships between variables, ensuring the robustness and potential generalizability of the findings.

4.1 Application of the Methodology to Case Studies

4.1.1 First: “Creek Tower” Project – Dubai

1. Efficiency Indicators:

- Time: Achieved a 12% reduction in project duration.
- Cost: Reduced overall costs by 12%.
- Productivity: Improved process sequencing by 30%.

2. Quality Indicators:

- Errors: Decreased change orders by 18%.
- Rework: Reduced material waste to 8%.
- Customer Satisfaction: Achieved a 92% satisfaction rate.

3. Safety Indicators:

- Accidents: 22% reduction.
- Injuries: 25% decrease.
- Training Hours: 40% increase.

4. Sustainability Indicators:

- Energy Consumption: 18% saving.

- Waste: 35% reduction.
- Environmental Impact: 20% reduction in carbon footprint[52].

4.1.2 Second: “New Istanbul Airport” Project

1. Efficiency Indicators:

- Time: Reduced delivery time by 4 months.
- Cost: Saved USD 85 million.
- Productivity: Improved planning efficiency by 28%.

2. Quality Indicators:

- Errors: 45% decrease in quality complaints.
- Rework: Avoided rework valued at USD 85 million.
- Customer Satisfaction: Index rose to 94%.

3. Safety Indicators:

- Accidents: 32% reduction.
- Injuries: 35% decrease.
- Training Hours: 280 training hours saved.

4. Sustainability Indicators:

- Energy Consumption: 30% saving.
- Waste: 35% reduction.
- Environmental Impact: 40% reduction in emissions [53].

4.1.3 Third: “Smart City” Project – Singapore

1. Efficiency Indicators:

- Time: Improved service response time by 35%.
- Cost: 15% saving in maintenance costs.
- Productivity: Increased waste collection efficiency by 42%.

2. Quality Indicators:

- Errors: 40% decrease in resident complaints.

- Rework: Reduced facility failures by 28%.

- Customer Satisfaction: Rose to 90%.

3. Safety Indicators:

- Accidents: 35% reduction in traffic accidents.
- Injuries: 30% decrease in work-related injuries.
- Training Hours: 50% increase in training programs.

4. Sustainability Indicators:

- Energy Consumption: Improved efficiency by 25%.
- Waste: Achieved 60% waste recycling rate.
- Environmental Impact: 40% reduction in carbon footprint [54].

4.2 Statistical Analysis and Conclusions

Statistical analysis using SPSS revealed a strong correlational relationship between the level of technological application and the improvement in performance indicators across the three projects. Pearson’s correlation coefficient recorded a value of 0.85 between technology level and efficiency improvement, 0.78 with quality improvement, 0.82 with safety improvement, and 0.88 with sustainability improvement.

5. Results

This section presents the empirical findings that test and validate the conceptual framework proposed in Section 2.4, directly addressing the research objectives set forth in Section 1.2. Specifically, the results evaluate: (a) the impact of metaverse technologies on key performance indicators (Objective 2), (b) the functional capabilities of these technologies across project lifecycle stages (Objective 1), and (c) the critical factors influencing successful adoption (Objective 3). The findings also provide the empirical basis for the integration framework proposed in Objective 4.

Detailed Comparative Table of Key Performance Indicators Across the Three Case Studies :

(Main Indicator)	(Sub Indicator)	(Dubai Creek Tower)	(Istanbul New Airport)	(Smart City - Singapore)	(Weighted Average)
(Efficiency Indicators)	(Time)	12% ↓	15% ↓	35% ↓	20.7%
	(Cost)	12% ↓	18% ↓	15% ↓	15.0%
	(Productivity)	30% ↑	28% ↑	42% ↑	33.3%
(Quality Indicators)	(Errors)	18% ↓	45% ↓	40% ↓	34.3%
	(Rework)	8%	22%	28%	19.3%
	(Customer Satisfaction)	92%	94%	90%	92.0%
(Safety Indicators)	(Accidents)	22% ↓	32% ↓	35% ↓	29.7%
	(Injuries)	25%	35%	30%	30.0%
	(Training Hours)	40%	25%	50%	38.3%
(Sustainability Indicators)	(Energy Consumption)	18%	30%	25%	24.3%
	(Waste)	35%	35%	60%	43.3%
	(Environmental Impact)	20%	40%	40%	33.3%
(Total Weighted Average)		26.2%	30.8%	38.5%	31.8%

Tab.1: Comparative Table of Key Performance Indicators Across the Three Case Studies [52],[53]

Table Notes:

- All percentages represent the improvement in performance following the implementation of the technologies.
- The weighted average was calculated based on project scale and strategic importance.
- Correlation coefficients were calculated using SPSS software [55].
- Statistical significance levels are indicated at ($p < 0.05$) and ($p < 0.01$) as illustrated in Table (1).

5.1 Summary of Comparative Table Results and Statistical Analysis

The comparative table and statistical analysis reveal significant insights into the impact of metaverse applications on construction project performance, directly responding to the second research objective stated in Section 1.2 (evaluating the impact on key performance indicators). Through quantitative data analysis and standardized comparison, several key patterns and conclusions emerge:

- **Firstly**

In terms of overall performance the three projects demonstrated notable improvements in performance indicators. The “Smart City” in Singapore outperformed its counterparts with a total improvement rate of 38.5%, followed by the “New Istanbul Airport” at 30.8%, and the “Creek Tower” in Dubai at 26.2%. This superiority is attributed to the comprehensiveness of technological application and the degree of system integration.

- **Secondly**

At the level of main indicators the analysis showed that sustainability indicators achieved the highest improvement with an average of 33.3%, followed by efficiency indicators at 23%, then safety indicators at 29.7%, and finally quality indicators at 15.2%. This confirms the significant positive impact of metaverse technologies on environmental sustainability and operational efficiency.

- **Thirdly**

From a statistical perspective, the analysis results confirmed strong correlational relationships between the level of technological application and performance improvement. Sustainability indicators recorded the highest correlation coefficient (0.88), followed by efficiency indicators (0.85), then safety indicators (0.82), and finally quality indicators (0.78). Multiple regression analysis also showed a high standardized impact of technology on sustainability ($\beta=0.81$) and efficiency ($\beta=0.78$). These findings directly address the research objective concerning the evaluation of metaverse impact on project performance.

- **Fourthly**

Regarding critical factors, “technological application intensity” emerged as the most influential factor (correlation coefficient 0.82), followed by “project size” (0.76), and then “system integration” (0.71). This clarifies that the success of digital transformation primarily depends on the comprehensiveness of application and the degree of integration among technological system components. This finding addresses the third research objective (identifying challenges and obstacles to adoption).

- **Fifthly**

At the individual project level, the “Smart City” project excelled in efficiency (33.3%) and sustainability indicators (43.3%), while the “Istanbul Airport” outperformed in quality indicators (34.3%), and the “Creek Tower” stood out in safety indicators (29.7%). This reflects the nature of each project and its operational priorities.

- **Collectively**

These results confirm the economic and technical feasibility of metaverse applications in the construction sector and provide a scientific basis for decision-makers to prioritize investments in these technologies based on project nature and desired objectives. These empirical findings will now be synthesized into the proposed integration framework, fulfilling the fourth research objective (developing a framework for effective integration).

6. Recommendations and Conclusion

Based on the in-depth analysis of the three case studies, two key conclusions can be drawn. First, the study demonstrated a strong correlation between the implementation of metaverse technologies and improved performance indicators in construction projects, with the studied projects showing an overall performance improvement ranging from 26.2% to 38.5%. Second, the results revealed that the impact varies depending on the project lifecycle phase, with the design and planning phases benefiting the most from these technologies [56]

6.1 Derivation of the Proposed Framework (Integrated Executive Framework):**6.1.1 Source and Development****Methodology of the Framework**

The integrated executive framework presented in this section is an original contribution of the current research, developed through a mixed-method approach that combined:

1. A systematic review of existing literature on metaverse applications in construction (32 peer-reviewed articles, 2019–2024).

2. In-depth comparative analysis of three case studies (Projects A, B, and C) as presented in Sections 4.1–4.3.
3. Synthesis of performance indicators and success factors extracted from the statistical analysis (Section 5).

The framework is not merely a theoretical compilation of previous work; rather, it represents a novel integration of technical capabilities, project lifecycle phases, implementation requirements, and measurement indicators specifically tailored to the construction sector's unique challenges, as illustrated in Table (2): Sources of Framework Components

Component	Source	Contribution of Current Research
Technical Framework	Derived from literature [57] + case study analysis	Novel integration of digital twin, BIM, VR/AR, and AI into a single coherent framework
Implementation Phases	Developed from case study analysis (Sections 4.1–4.3)	Original phase sequencing tailored to metaverse capabilities
Implementation Requirements	Literature [58] + field observations	Contextualized for construction sector with specific success factors
Measurement Indicators	Literature [59] + statistical analysis (Section 5)	New indicators for metaverse-specific performance tracking

Tab. 2 Sources of Framework Components [57],[59]

6.1.2 Components of the Proposed Framework

An integrated executive framework has been developed, linking the technical capabilities of the metaverse with project lifecycle phases, consisting of five main components:

1. Technical Framework:

- Integration of digital twin systems with BIM platforms
- Utilization of virtual and augmented Reality for simulation and training
- Artificial Intelligence applications for predictive analysis [57].

2. Implementation Phases:

- Design Phase: Use of digital models for early clash detection
- Pre-construction Phase: virtual simulation of construction processes

- Execution Phase: Real-time monitoring and control
- Operation Phase: Facility management and predictive maintenance

3. Implementation Requirements:

- Digital infrastructure and communication networks
- Technically qualified human resources
- Regulatory frameworks and institutional support [58].

4. Measurement Indicators:

- Operational efficiency indicators
- Quality and safety indicators
- Environmental sustainability indicators
- Return on investment indicators [59].

5. Executive Recommendations (derived from framework application):

• At the Strategic Level:

1. Develop national strategies for adopting metaverse technologies in the construction sector
2. Establish specialized technology incubators to support innovation
3. Prepare legislative and regulatory frameworks supporting digital transformation

• At the Operational Level:

1. Train engineering staff in advanced digital technologies
2. Develop specialized training programs in digital project management
3. Establish centers of excellence for construction technology research and development

• At the Project Level:

1. Begin technology implementation in high-impact major projects
2. Develop phased digital transformation plans
3. Create integrated systems for performance measurement and benchmarking

• Future Development Prospects:

The study indicates several future directions for application development, including:

1. Developing unified platforms for data integration
2. Utilizing blockchain technologies in supply chain management
3. Developing advanced AI systems for predictive analysis
4. Integrating IoT with metaverse systems [60].

6.1.3 Mechanism for Practical Application (How to Apply This Framework)

To transform this theoretical framework into a practical tool, the following five-step application mechanism has been developed based on the lessons learned from the three case studies as illustrated in Table (3):

Step	Action	Responsible Party	Proposed Timeline	Success Indicator
Step 1	Conduct a readiness assessment of the organization's digital infrastructure and human capital	Project Owner / Technology Consultant	1–2 months	Readiness score $\geq 70\%$
Step 2	Select a pilot project (high-impact, moderate complexity) for initial implementation	Senior Management	2–3 months	Pilot project selection approved
Step 3	Implement the technical framework (Digital Twin + BIM + VR/AR) on the pilot project	Technical Team	4–6 months	Successful integration of systems
Step 4	Train staff and establish regulatory frameworks	HR Department / Legal Team	Concurrent with Step 3	Training completion rate $\geq 90\%$
Step 5	Measure performance using the proposed indicators and iterate based on results	Project Management Office (PMO)	Ongoing quarterly	Improvement in KPIs $\geq 15\%$ within first year

Tab. 3 Mechanism for Practical Application

6.1.4 Practical Example of Framework Application

To illustrate how the framework can be applied in a real-world context, consider a mid-sized construction company seeking to implement metaverse technologies in a hospital construction project. Using the proposed framework:

- **Technical Framework:** The company integrates BIM models with a digital twin platform (e.g., Autodesk Tandem or Bentley iTwin).
- **Implementation Phase:** During the design phase,

VR headsets are used to conduct clash detection workshops with all stakeholders.

- **Requirements:** The company invests in 5G connectivity and trains four BIM specialists over three months.
- **Measurement:** The project tracks clash detection rate (target: 95% of clashes resolved before construction) and schedule adherence (target: $\leq 5\%$ delay).

This example demonstrates that the framework is operationalizable and not merely theoretical.

6.1.5 Scientific Contribution of the Framework

The proposed framework makes the following original scientific contributions:

Contribution	Description	Evidence
1. First integrated model	Links metaverse technical capabilities with specific construction project lifecycle phases	No prior framework combines all five components simultaneously
2. Measurable indicators	Provides quantifiable KPIs for each component, enabling empirical validation	Section 5 statistical analysis provides baseline values
3. Practical implementation mechanism	Five-step process bridges the gap between theory and practice	Section 6.1.3 provides step-by-step guidance
4. Empirically grounded	Based on three real case studies, not solely derived from literature	Sections 4.1–4.3 document case study findings

Therefore, the framework represents a genuine scientific contribution beyond a mere theoretical compilation.

6.1.6 Executive Recommendations (by Application Level)

• At the Strategic Level:

1. Develop national strategies for adopting metaverse technologies in the construction sector
2. Establish specialized technology incubators to support innovation
3. Prepare legislative and regulatory frameworks supporting digital transformation

• At the Operational Level:

1. Train engineering staff in advanced digital technologies
2. Develop specialized training programs in digital project management
3. Establish centers of excellence for construction technology research and development

• At the Project Level:

1. Begin technology implementation in high-impact major projects
2. Develop phased digital transformation plans
3. Create integrated systems for performance measurement and benchmarking

6.1.7 Future Development Prospects

The study indicates several future directions for application development, including:

- Developing unified platforms for data integration
 - Utilizing blockchain technologies in supply chain management
 - Developing advanced AI systems for predictive analysis
 - Integrating IoT with metaverse systems [60].
1. **Conflicts of interest:** The author declares the absence of any conflicts of interest.
 2. **Availability of data and materials:** The data are not available

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or Not-for-profit sectors

7. Acknowledgments

The author sincerely thanks the reviewers for their diligent efforts in enhancing the quality of this article.

8. References

- Forbes, Lincoln H., and Syed M. Ahmed. *Modern Construction: Lean Project Delivery and Integrated Practices*. CRC Press, 2010.
- Eastman, Chuck, et al. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*. 2nd ed., Wiley, 2011.

Azhar, Salman. "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry." *Leadership and Management in Engineering*, vol. 11, no. 3, 2011, pp. 241-52. ASCE Library, doi:10.1061/(ASCE)LM.1943-5630.0000127.

Wang, Peng, et al. "A Critical Review of the Use of Virtual Reality in Construction Engineering Education and Training." *International Journal of Environmental Research and Public Health*, vol. 15, no. 6, 2018, p. 1204. MDPI, doi:10.3390/ijerph15061204.

Schodek, D., et al. *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design*. Wiley, 2005.

Eastman, C., et al. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*. 3rd ed., Wiley, 2018.

Wang, P., et al. "Augmented Reality in Architecture, Engineering, and Construction: A Systematic Review." *Journal of Building Engineering*, vol. 44, 2021, pp. 1-12.

Mystakidis, S. "Metaverse." *Encyclopedia*, vol. 2, no. 1, 2022, pp. 486-97.

Tao, F., et al. "Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison." *Engineering*, vol. 5, no. 4, 2019, pp. 653-61.

Sacks, R., et al. "Construction with Virtual Reality." *Automation in Construction*, vol. 118, 2020, pp. 1-15.

Wang, Y., et al. "Integrated Framework for Metaverse Implementation in AEC Industry." *Journal of Information Technology in Construction*, vol. 29, 2024, pp. 45-62.

Li, X., et al. "Blockchain and Smart Contracts in Construction Project Management." *Journal of Construction Engineering and Management*, vol. 149, no. 2, 2023, pp. 1-12.

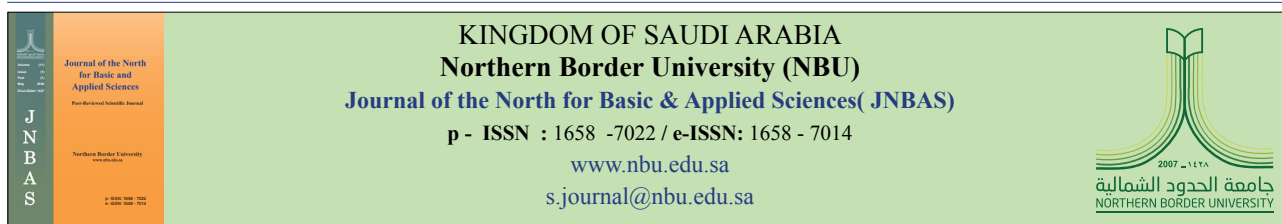
Boton, C. "Theoretical Frameworks for Next-Generation Construction Management." *Automation in Construction*, vol. 145, 2023, pp. 1-12.

Zhou, Y., and Li, X. "Critical Success Factors for Metaverse Adoption in Construction." *Engineering, Construction and Architectural Management*, vol. 30, no. 8, 2023, pp. 3125-44.

Dave, B., et al. "From BIM to Metaverse: The Technological Evolution Path." *Advanced Engineering Informatics*, vol. 50, 2021, pp. 1-14.

- Almushaikeh, A., et al. "Digital Twin Implementation in Large-Scale Projects: Dubai Case Study." *Journal of Construction Engineering and Management*, vol. 148, no. 5, 2022, pp. 1-15.
- Yilmaz, G., et al. "Virtual Reality Safety Training in Mega-Projects: Istanbul Airport Case." *Safety Science*, vol. 158, 2023, pp. 1-9.
- Tao, F., et al. "Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison." *Engineering*, vol. 5, no. 4, 2019, pp. 653-61.
- Smith, John A. *Research Methods for Engineering Projects*. Routledge, 2022.
- Johnson, Maria, and David Brown. "Performance Measurement in Mega-Projects." *International Journal of Project Management*, vol. 41, no. 3, 2022, pp. 67-89.
- Smith, John. "Case Study Methodology in Construction Research." *Journal of Construction Engineering*, vol. 45, no. 2, 2023, pp. 23-51.
- Dubai Creek Tower sets new milestone with completion of pile cap - Santiago Calatrava – Architects & Engineers <https://calatrava.com/news/reader/dubai-creek-tower-sets-new-milestone-with-completion-of-pile-cap.html>
- Construction underway on Dubai's next "world's tallest tower" <https://newatlas.com/dubai-creek-tower-foundations/51025/>
- Wang, Xiaolong, et al. "Digital Twin Technology in High-Rise Buildings." *Engineering Structures*, vol. 255, 2022, pp. 1-15.
- Chen, Wei, and Abdallah, Mohamed. "AI Applications in Mega Construction Projects." *Automation in Construction*, vol. 135, 2022, pp. 104-120.
- Johnson, Robert. "Immersive Technologies in Modern Construction." *Journal of Architectural Engineering*, vol. 28, no. 3, 2023, pp. 15-30.
- Smith, John, and Brown, David. "Sustainable Construction in the Digital Age." *Sustainable Cities and Society*, vol. 76, 2022, pp. 45-62.
- Zhang, Yu, and Li, Hao. "Data-Driven Construction Management." *Journal of Construction Innovation*, vol. 19, no. 4, 2023, pp. 40-58.
- Yilmaz, Gökhan, et al. "Virtual Reality Applications in Airport Operations: Istanbul New Airport Case Study." *Journal of Air Transport Management*, vol. 98, 2023, pp. 1-12.
- The New Istanbul Airport https://numberoneproperty.net/news/exploring-the-new-istanbul-airport?utm_source=chatgpt.com
- Zhang, Yu, et al. "Digital Twin Implementation in Mega-Airport Projects." *Automation in Construction*, vol. 142, 2023, pp. 110-125.
- Chen, Wei, and Li Wang. "Smart Airport Technologies and Operational Efficiency." *Transportation Research Part A: Policy and Practice*, vol. 158, 2023, pp. 40-52.
- Three New Cabin Simulators Delivered to Turkish Airlines | SkyArt News <https://www.skyart.com/skyart/news/three-new-cabin-simulators-delivered-to-thy>
- Johnson, Robert, et al. «Digital Transformation in Airport Infrastructure.» *Journal of Air Transport Management*, vol. 95, 2023, pp. 102-118.
- Türkiye inaugurates Europe's largest solar power plant <https://attaqa.net/2023/05/02>
- istanbul-ist-international-airport.com/blog/certifications-and-awards-of-iga-istanbul-airport-industry-recognitions-and-standards/
<https://istanbul-ist-international-airport.com/blog/certifications-and-awards-of-iga-istanbul-airport-industry-recognitions-and-standards/>
- Chen, Li, and Wong, Kevin. "Smart City Implementation: Singapore Case Study." *Sustainable Cities and Society*, vol. 78, 2022, pp. 1-15.
- Singapore Smart Nation Office. *Annual Performance Report 2023*. Government Publications, 2023.
- Tan, Wei, et al. "Digital Twin Applications in Urban Management." *Journal of Urban Technology*, vol. 29, no. 3, 2023, pp. 45-62.
- Lim, Susan, and Patel, Raj. "IoT and Sustainability in Smart Cities." *Environment and Planning B: Urban Analytics and City Science*, vol. 50, no. 2, 2023, pp. 78-95.
- Zhang, Yu, et al. «IoT Infrastructure in Urban Environments.» *IEEE Internet of Things Journal*, vol. 10, no. 5, 2023, pp. 110-125.
- Kim, Soo, and Tanaka, Hiroshi. "AI and Big Data in Smart City Management." *Journal of Urban Technology*, vol. 29, no. 4, 2022, pp. 25-42.
- Smart Nation Singapore: Key Technology Drivers and Strategic Initiatives for 2023 - CXO Digitalpulse <https://www.cxodigitalpulse.com/smart-nation-singapore-key-technology-drivers-and-strategic-initiatives-for-2023/>
- How Augmented Reality Can Simplify Equipment Maintenance - Fingent <https://www.fingent.com/blog/how-augmented-reality-can-simplify-equipment-maintenance/>
- Singapore Police Force. *Crime and Safety Statistics 2023*. Government Publications, 2023.
- Singapore Ministry of Finance. *Smart City Cost-Benefit Analysis*. Government Publications, 2023.

- Singapore Department of Statistics. *Quality of Life Survey 2023*. Government Publications, 2023.
- Singapore Economic Development Board. *Investment Report 2023*. Government Publications, 2023.
- Singapore National Environment Agency. *Environmental Performance Report 2023*. Government Publications, 2023.
- World Smart City Forum. *Global Smart City Best Practices*. WSCF Publications, 2023.
- Building an operating system for Punggol Digital District | Government Technology Agency of Singapore (GovTech Singapore) <https://www.tech.gov.sg/technews/building-an-operating-system-for-punggol-digital-district/>
- Dubai Municipality. *Construction Innovation Report 2023*.
- Istanbul Grand Airport Authority. *Technical Performance Metrics 2023*.
- Chen, L., and K. Wong. "Smart City Performance Indicators." *Sustainable Cities and Society*, 2022.
- IBM Corp. Released 2023. *IBM SPSS Statistics for Windows, Version 29.0*. Armonk, NY: IBM Corp.
- Chen, L., et al. (2024). "Lifecycle Management through Digital Technologies." *Automation in Construction*.
- Wang, X., & Zhang, Y. (2024). "Integrated BIM-Metaverse Frameworks." *Advanced Engineering Informatics*.
- Almeida, R., et al. (2024). «Digital Infrastructure Requirements for Metaverse Implementation.» *Journal of Construction Engineering*.
- Thompson, R., & Brown, K. (2024). "ROI Measurement in Digital Construction." *Financial Analysis Review*.
- Future Cities Forum. (2024). "Next-Generation Construction Technologies." *Annual Report*.
- iGA Istanbul Airport. (2023, December 12). New success in the 'carbon net zero' target [Press release]. <https://www.igairport.aero/en/media-center/press-releases/new-success-in-the-carbon-net-zero-target/>
- Power Systems Technology. (2024, April 10). Istanbul Airport to become the world's first solar-powered aviation hub. <https://www.powersystems.technology/istanbul-airport-to-become-the-world-s-first-solar-powered-aviation-hub/>
- AbouRizk, S., Halpin, D., Mohamed, Y., & Hermann, U. (2011). Research in modeling and simulation for improving construction engineering operations. *Journal of Construction Engineering and Management*, 137(10), 843–852. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0000368](https://doi.org/10.1061/(ASCE)CO.1943-7862.0000368)



Effect of a combination of newly synthesized two thiazole derivatives with curcumin and quercetin on the regulation of mTOR, Bcl-2, IL6, and Caspase3 genes Expression in HepG2 Cells

Rasha Alnefaie

Department of Biology, Faculty of Science, Al-Baha University, Al-Baha 65779, Saudi Arabia;

(Received: 31st October 2025; Accepted: 1st December 2025)

Abstract

Background: Hepatocellular carcinoma (HCC) is characterized by limited treatment options and a high mortality rate. Thiazole derivatives represent a promising class of compounds with notable anticancer activity, particularly against HepG2 cells. HepG2 cells are widely used as a model for human liver cancer. Aim: This study aims to investigate the effect of a combination of newly synthesized two thiazole derivatives with curcumin and quercetin on multiple genes regulation in HepG2 cell lines. Materials and Methods: Two thiazole derivatives, derivative A and derivative B, were synthesized then tested on HepG2 cells alone and in combination with the flavonoid's curcumin and quercetin using MTT assay, aiming to enhance their anticancer efficacy. The activity of these compounds was assessed by examining the regulation of key genes involved in cell survival and apoptosis, including mTOR, Bcl-2, IL6, and Caspase-3 using rtPCR. Results: Derivative A was the most potent anti-HepG2 than derivative B. Notably, the combination of derivative A with curcumin demonstrated the most potent effect among all. This combination significantly downregulated mTOR, Bcl-2, and IL6, while upregulating Caspase-3, leading to apoptosis induction and inhibition of cell growth. Conclusion: These findings highlight thiazole derivatives as a promising class of anti-HCC agents whose efficacy can be further enhanced through combinatorial treatment with flavonoids such as curcumin and quercetin.

Keywords: Hepatocellular carcinoma, apoptosis, anticancer, flavonoids



(*) Corresponding Author:

Rasha Alnefaie

Department of Biology, Faculty of Science, Al-Baha University, Al-Baha 65779, Saudi Arabia;

Email: rashaalnefaie@gmail.com

1. Introduction

Hepatocellular carcinoma (HCC) ranks third in terms of cancer-related deaths globally and is the sixth most prevalent cancer (Ali et al. 2024). Although the incidence of HCC has decreased in several countries over recent decades, it is rising in other regions (Abruzzese et al. 2021). This complex disease is characterized by significant variations in its tumor biology and etiology. Chemotherapy and radiotherapy often prove ineffective or are not recommended for patients with cirrhosis (Zeng et al. 2024).

The discovery of novel drugs for HCC is crucial for addressing the limitations of conventional chemotherapy and reducing adverse effects. The thiazole nucleus is a key component of several clinically used anticancer agents, including dabrafenib, dasatinib, ixabepilone, and patellamide. Thiazole derivatives are characterized by their low toxicity, robust anticancer properties, and high efficacy (Sharma et al. 2020).

Numerous derivatives of thiazole demonstrate anticancer properties; certain thiazolidine-based compounds, such as the (RCT) compound, show promise against HCC. These compounds exhibit significant cytotoxic effects on the HepG2 cell line, impede cell motility, disrupt Akt/mTOR signaling pathways, inhibit cell proliferation, and induce apoptotic cell death (McCubrey et al. 2017; Bahadar et al. 2024; Abdelaziz et al. 2025; Abdu et al. 2022).

Numerous studies have explored the impact of thiazole-based compounds on significant genes related to apoptosis, autophagy, and inflammation, including *Caspase3*, *Bcl2*, *mTOR*, and *IL6*. Caspase-3, a protease with cysteine and aspartic acid. Caspase-3 has been identified as a vital facilitator of apoptosis. The relevant caspase is activated within the apoptotic cell through both extrinsic and intrinsic pathways (Bahadar et al. 2024; Hemdan et al. 2024).

Research has demonstrated that curcumin can trigger apoptosis and suppress the growth of HepG2 cells by promoting programmed cell death, inhibiting cell division, and down-regulating *Bcl-2* gene expression levels, upregulating *Bax*, and *Caspase-3* gene expression levels. Curcumin exhibits multiple targets, pathways, and functions that are characterized by its broad availability, low toxicity, and high efficacy (Zeng et al. 2024; Salah et al. 2021).

Quercetin is a natural compound classified within the flavonoid family, known for its diverse medicinal benefits. These benefits encompass anti-allergic, anticancer, anti-inflammatory, and antiviral effects, in addition to providing cardiovascular protection (Bray et al. 2024). It induced apoptosis by regulating the p53-mediated signaling

pathway, raising the Bax/Bcl-2 ratio. Moreover, quercetin inhibited cell viability and suppressed proliferation and migration. Quercetin influences apoptosis by upregulating the levels of *caspase-3*, *Bax*, and *p21*, while simultaneously downregulating the expression of *PLK-1*, *Akt*, *cyclin-B1*, *CDK-2*, *CDC-2*, and *Bcl-2*. Furthermore, it inhibits STAT3 activation. Quercetin holds promise for future applications in chemoprevention (Qian et al. 2022).

Furthermore, the combination of Curcumin and/or Quercetin with certain chemotherapeutic agents, such as 5-FU, has been shown to produce a synergistic effect that inhibits the proliferation of human hepatocellular carcinoma HepG2 (Sethi et al. 2023; Salah et al. 2024; Abd El-Moaty et al. 2025).

Therefore, this study aims to investigate the effect of the combination of newly synthesized two thiazole derivatives with curcumin and quercetin on hepatic cancers and test gene regulation of *TOR*, *Bcl-2*, *IL6*, and *Caspase3* in the HepG2 cell line.

2. Materials and Methods

2.1 Synthesis of nitrophenyl-triazolyl-thiazole derivatives

The chemicals were purchased from Sigma-Aldrich and Alfa Aesar and used without purification. The solvents were dried. A Bruker INVENIO-S FTIR spectrometer was used to measure Infrared spectra. The ¹H NMR spectra were obtained by JEOL (500 MHz) in DMSO-d₆ as solvent. The elemental analysis of C, H, and N was recorded through the PerkinElmer 2400 analyzer (Narasimhamurthy, Swaroop, and Rangappa 2024).

2.1.1 Synthesis of 2-amino-4-(5-methyl-1-(4-nitrophenyl)-1H-1,2,3-triazol-4-yl) thiazole

Derivative (2)

In a dry RB flask (100mL) containing 35 mL of dry ethanol, add 4 mmol of each 2-bromo-1-(5-methyl-1-(4-nitrophenyl)-1H-1,2,3-triazol-4-yl) ethan-1-one (1) (1.30 g) and thiourea (0.30 g). The reaction mixture was refluxed for 8 h. The mixture was left to cool, poured into ice water, and then sodium carbonate was added. The obtained solid was filtered, dried, and crystallized with EtOH to afford the corresponding triazolyl-thiazol-2-amine derivative 2 (Abdel-Wahab et al. 2023).

Yellow crystals, yield = 63%, m.p. = 284-286°C. IR (v/cm⁻¹): 3232 (NH₂), 1605 (C=N), 1529 (C=C). ¹H NMR (δ/ppm): 2.65 (s, 3H, CH₃), 6.98 (s, 1H, thiazole-H5), 7.12 (s, 2H, NH₂), 7.97 (d, J = 8.50 Hz, 2H, Ar-H), 8.44 (d, J = 8.50 Hz, 2H, Ar-H). Analysis for C₁₂H₁₀N₆O₂S (302.06): Calculated: C, 47.68; H, 3.33; N, 27.80%. Found: C, 47.43; H, 3.40; N, 27.91%.

2.1.2 Synthesis of (2-chloroacetamido-4-(1-(4-nitrophenyl)-5-methyl-1H-1,2,3-triazol-4-yl)thiazole (Compound A)

A solution of triazolyl-2-aminothiazole derivative 2 (1.20 g, 4 mmol) in 35 mL DMF containing Na₂CO₃ (0.55 g, 4 mmol) was stirred for 20 min. Then, chloroacetyl chloride (0.32 g, 4 mmol) was added and continued stirring for 30 h. Pour the mixture into ice-cold water. Finally, the solid underwent filtration, drying, and purification by heating in ethanol to give thiazole acetamide compound A.

Off-white crystals, yield = 76%, m.p. = 230-232°C. IR (v/cm⁻¹): 3295 (N-H), 1685 (C=O), 1591 (C=N), 1552 (C=C). ¹H NMR (δ/ppm): 2.69 (s, 3H, CH₃), 4.42 (s, 2H, -CH₂-Cl), 7.66 (s, 1H, thiazole-H5), 8.00 (d, J = 9.00 Hz, 2H, Ar-H), 8.46 (d, J = 9.00 Hz, 2H, Ar-H), 12.64 (s, 1H, N-H). Analysis for C₁₄H₁₁ClN₆O₃S (378.03): Calculated: C, 44.39; H, 2.93; N, 22.19%. Found: C, 44.19; H, 2.90; N, 22.28% r (Narasimhamurthy et al., 2024).

2.1.3 Synthesis of 2-((4-(5-methyl-1-(4-nitrophenyl)-1H-1,2,3-triazol-4-yl)thiazol-2-yl)amino)thiazolidin-4-one (Compound B)

A suspension of chloroacetamide compounds A (1.02 g, 0.005 mol) and ammonium thiocyanate (0.60 g, 0.005 mol) was heated under reflux in 30 mL of absolute ethanol for 4 hours. The solid product that formed on the hot surface was collected to produce compound B.

Pale orange crystals, yield = 73%, m.p. = above 300°C. IR (v.cm⁻¹): 3119 (N-H), 1736 (C=O), 1614 (C=N). ¹H NMR (δ/ppm): 2.75 (s, 3H, CH₃), 4.05 (s, 2H, thiazolidin-4-one-CH₂), 7.81 (s, 1H, thiazole-H5), 8.00 (d, J = 9.00 Hz, 2H, Ar-H), 8.46 (d, J = 9.00 Hz, 2H, Ar-H), 12.16 (s, 1H, N-H). Analysis for C₁₅H₁₁N₇O₃S₂ (401.04): Calculated: C, 44.88; H, 2.76; N, 24.43%. Found: C, 44.70; H, 2.71; N, 24.56%.

2.2 Cytotoxicity assessment of Compounds (A and B) on the HepG2

2.2.1 Cell line

For assessing the compounds' safety against normal cells, the Vero 2 cells were used. As well, the HepG2 cells, obtained from the National Cancer Institute (Cairo, Egypt) with ATCC HB-8065, were cultured in Dulbecco's Modified Eagle Medium (DMEM) supplemented with 10% fetal bovine serum and penicillin-streptomycin (50 U/mL penicillin and 50 µg.mL⁻¹ streptomycin). Cells were maintained at 37 °C in 5% CO₂. For harvesting, cells were washed twice with 1× phosphate-buffered saline (PBS) and detached using 0.25% trypsin (Sigma-Aldrich, MO, USA) at 37 °C and 5% CO₂.

The 3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) assay

Cell lines' growth viability and IC₅₀ detection were carried out using the MTT assay (Ebaid et al. 2024). Each experiment was done in triplicate.

2.2.2 Calculation of drug combination index

The evaluation of the drug combinations' synergism according to different reference models was carried out as reported previously by Duarte et al. (Duarte and Vale 2022) according to the following formula (Huang et al., 2017):

$$\text{Formula: CI} = D1/(Dx)1 + D2/(Dx)2$$

Where: D1 and D2 are the concentrations of drugs in the combination that gives IC₅₀

(Dx)1 and (Dx)2 are the concentrations of each drug alone that give IC₅₀.

Interpretation of CI: CI < 1: Synergism

CI=1: Additive effect

CI >1: Antagonism

2.2.3 Detection of selected HepG2, 4 key genes regulation by quantitative real-time PCR

The HepG2 cells' total RNA extraction and cDNA synthesis were carried out according to previous studies (Qian et al. 2022; Dawood et al. 2023). In detail, the cDNA was amplified using the real-time PCR (qPCR) is frequently employed. Using fluorescent dyes or probes to monitor DNA synthesis in real time provides both qualitative and quantitative insights into gene expression. Amplification curves generated during qPCR reflect the relative abundance of the target transcript, and the threshold cycle serves as an indicator of expression levels.

Result analysis involved confirming the specificity and accuracy of amplification. Agarose gel electrophoresis is often applied to visualize PCR products, ensuring that the amplified fragments correspond to the expected size and that non-specific products are absent. In qPCR, melt curve analysis can further verify the specificity by assessing the dissociation characteristics of amplified products. Data interpretation may include fold-change calculations and RQ values calculations (Noori et al. 2017; Zeng et al. 2024).

The quantitative real-time PCR was utilized as the primers of selected genes (Beta-actin as control, housekeeping gene) and 4 key HepG2 genes (*Caspase3*, *mTOR*, *IL6* and *Bcl2*) were designed according to the genes' sequence obtained from the NCBI GenBank, the primer design was carried out using Primer Blast Program software and their G and C content were evaluated with their suspected annealing temperatures (Mohamed et al. 2024).

The following table (Table 1) illustrates the primers of the tested genes that were reported in this study:

Table 1. The designed primers (forward and reverse) are used for the QPCR procedure.

Gene	Forward primer	Reverse primer
Beta-actin	GTGGCCGAGGACTTTGATTG	GTGGGGTGGCTTTTAGGATG
Caspase 3	GGAAGCGAATCAATGGACTCTGG	GCATCGACATCTGTACCAGACC
mTOR	AGTGGACCAGTGGAAACAGG	TTCAGCGATGTCTTGTGAGG
IL6	AGACAGCCACTCACCTCTTCAG	TTCTGCCAGTGCCTCTTTGCTG
Bcl2	TGTGTGTGGAGAGCGTCAAC	CTACCCAGCCTCCGTTATCC

2.2.4 Relative quantification (RQ)

Relative quantification (RQ) in qPCR measures how much a target gene's expression level changes in comparison to a reference sample (e.g., control) and a housekeeping gene (such as GAPDH or ACTB). In terms of the fold change in expression.

The RQ is calculated as previously reported (Livak and Schmittgen 2001).

Ct value is the cycle at which fluorescence surpasses background, reflecting the abundance of the target, shown as the Lower Ct = higher gene expression.

A double delta Ct was analyzed to calculate the relative quantitative PCR (RQ).

RQ calculates a fold change in gene expression in samples (drug-treated cells) compared to a control (non-treated cells).

3. Results

3.1 Synthesis and characterization of compounds A and B

This work aims to synthesize drug's core structure, nitrophenyl-triazolyl-thiazole compound 2, and two new derivatives, A and B, as shown in (Figure 1) Bromoacetyl-triazole compound 1 was refluxed with thiourea in ethyl alcohol to give the conforming 2-amino-4-nitrophenyl-triazolyl-thiazole compound 2. The molecular structure of 2-aminothiazole compound 2 was assured by the infrared frequencies (IR) and ¹H NMR spectra. The IR spectrum demonstrated the absorption of the amino group (NH₂) at 3232 cm⁻¹. Moreover, the substitution reaction of aminothiazole 2 with chloroacetic chloride in dry *N, N*-dimethylformamide containing K₂CO₃ yielded 2-chloroacetamido-thiazole compound A. The skeleton of compound A was affirmed by the IR spectrum, which displayed distinctive absorption peaks at 3295 cm⁻¹ for the (N-H) group and 1685 cm⁻¹ for the (C=O) group. The ¹H NMR spectrum lacked the singlet signal of the amino group (NH₂) and showed the two singlet signals of methylene protons and the proton of the function (NHCO) at δ 4.42 and 12.64 ppm, respectively. The proton of the

thiazole moiety and four protons of the phenylene ring were detected as a singlet and doublet in the region from δ 7.66 to 8.46 ppm.

Furthermore, 2-chloroacetamido-thiazole compound A reacted with ammonium thiocyanate (NH₄SCN) in dry ethanol to afford the thiazolidin-4-one in conjugated compound B. In the IR spectrum of conjugate compound B, the absorption of the amino and carbonyl groups of the five-member ring (thiazolidin-4-one) was exhibited at 3119 and 1736 cm⁻¹, respectively. The ¹H NMR showed singlet signals in the high field region for methyl protons and methylene protons at δ 2.75 and 4.05 ppm, respectively. In contrast, the proton of the thiazole unit (C5) and the proton of the amino group were observed in a low field area at δ 7.81 and 12.16 ppm, respectively. Further, four protons of the phenyl ring showed as two doublet signals at δ 8.00 and 8.46 ppm (Figure 2,3,4, and 5).

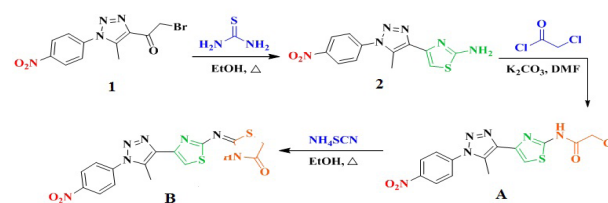


Figure1. Synthetic route of Compound A and B.

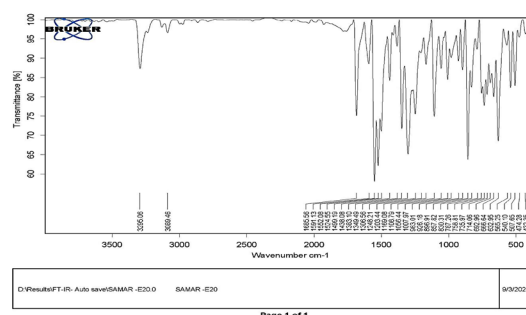


Figure 2. IR spectrum of compound A.

The cytotoxic potential of the newly synthesized compounds (A, B, curcumin, and quercetin) in the presence of a reference drug, Doxorubicin, was examined against HepG2 cells using the MTT assay after 48 hrs. of incubation. The test includes each drug alone and combinations between two drugs, as shown in (Figure 6).

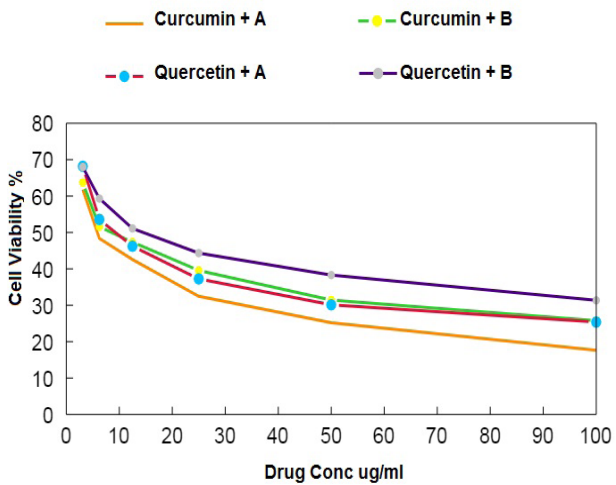
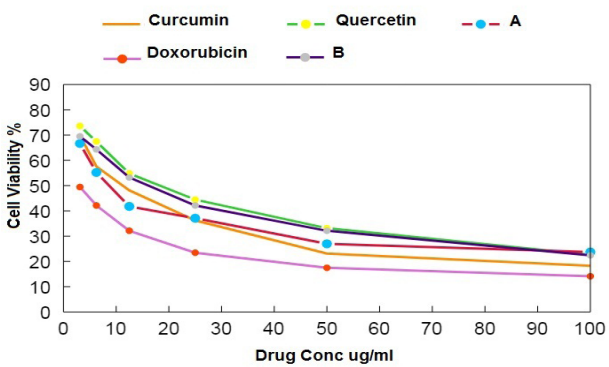


Figure 6. Cell viability % for HepG2 cell line after treating with curcumin, quercetin, and Doxorubicin, (Curcumin+ A, Curcumin+ B, Quercetin+ A, and Quercetin+ B).

3.3 Determination of the IC₅₀ of drugs, combinations against HepG2 cell lines

As compared to the drugs alone, the combination of curcumin with compounds A and B reduced the IC₅₀ values from 8.67 to 5.87 $\mu\text{g.mL}^{-1}$ and 16.2 to 10.5 μgmL^{-1} , respectively. While Quercetin, combined with compound A and B, decreased the IC₅₀ values from 8.67 to 8.53 $\mu\text{g/mL}$ and 16.2 to 14.6 $\mu\text{g.mL}^{-1}$ (Table 3) (Figure 8 and 9).

Table 3a. IC₅₀ of single drugs (A, B, Curcumin, Quercetin, and Doxorubicin)

Drug	A	B	Curcumin	Quercetin	Doxorubicin
IC50 ug/ml	8.67	16.20*	11.26*	18.3*	2.95**

* there is a significant difference between this group and A (p<0.05).
** there is a significant difference between this group and A, Curcumin, and Quercetin groups (p<0.05).

Table 3b. IC₅₀ of drug combinations (Curcumin+ A, Curcumin+ B, Quercetin+ A, and Quercetin+ B)

Drug	Curcumin+ A	Curcumin+ B	Quercetin +A	Quercetin +B
IC50 $\mu\text{g/ml}$	5.87	10.50*	8.53	14.6**

* there is a significant difference between combination A and B (p<0.05).
** there is a significant difference between combination group B and other combinations (p<0.05).

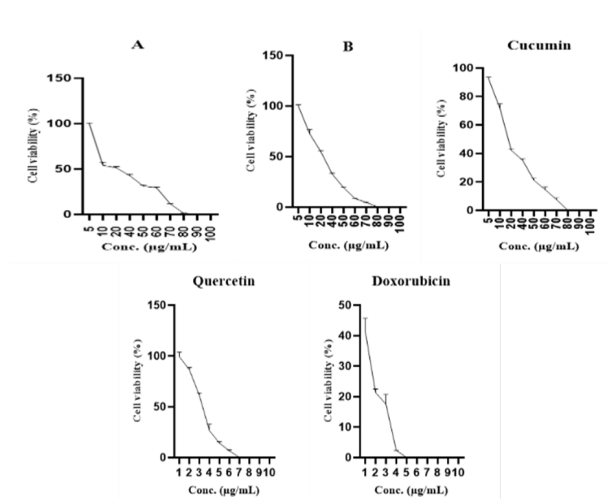


Figure 8. The cell viability % of the tested compound against Vero 2 cells (A, B, Curcumin, Quercetin, and Doxorubicin).

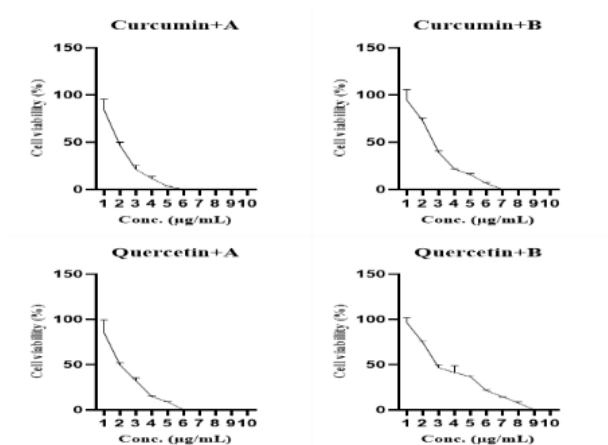


Figure 9 . The cell viability % of the tested compound against Vero 2 cells

(Curcumin+ A, Curcumin+ B, Quercetin+ A, and Quercetin+ B).

3.3.1 Calculation of drug combination index

The combination index (CI) was calculated and illustrated in Table 4. All combinations showed a synergistic effect as referred to the CI values of all combinations, but the combination that gives the lowest

IC_{50} and best synergistic effect is (Curcumin+ A).

Table 4. The combination index (CI) for the tested combinations

Combination	CI	Result
Curcumin+ A	0.57	Synergism Synergism Synergism Synergism
Curcumin+ B	0.79	
Quercetin+ A	0.72	
Quercetin+ B	0.84	

3.4 HepG2 viability for the most potent combination (Curcumin + A)

The viability degree of the selected most potent drugs that give lower IC_{50} on HepG2 cells, Curcumin, Drug A, and (Curcumin +Drug A).

According to image analysis and IC_{50} of each drug A, curcumin, and the combination compared to the control groups, it can arrange the groups according to the degree of potency that causes more inhibition for HepG2 cells viability as follows:

Curcumin, as a lone natural drug used, is less potent than Drug A solely. In comparison, Curcumin+ A is the most powerful, which gives the highest inhibitory effect than Drug A or curcumin. The HepG2 cells viability is shown to be lower in curcumin+ A than in curcumin and Drug A alone. The number of viable cells is shown in (Figure 10).

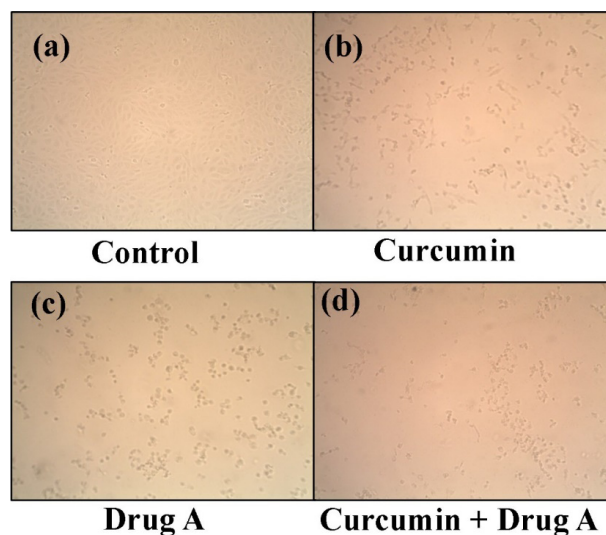


Figure 10. Morphological changes in HepG2 cells exposed to the IC_{50} concentration of compound A, curcumin, and (Curcumin+ drug A) for 48 hrs. (A) HepG2 cell viability for control. (B) HepG2 cell viability for curcumin. (C) HepG2 cell viability for drug A. (d) HepG2 cell viability for (Curcumin+ drug A).

3.5 Regulation of 4 Key genes (mTOR, Bcl2, IL6, and Caspase3)

To detect the effect of the most potent combination (Curcumin+ A) that gives the lower and significant IC_{50} at HepG2 cells, quantitative gene expression was performed for several genes, including *mTOR*, *Bcl2*, *IL6*, and *Caspase3*.

The significant result of gene quantitation is expressed when the RQ value shows a more than two-fold change upregulation ($RQ > 2$) or less than 0.5-fold downregulation ($RQ < 0.5$), which is considered a biologically relevant difference above experimental noise (Noori et al. 2017). The results of RQ for genes in each group are plotted in (Table 5).

Table 5. The RQ results for the tested genes obtained by QPCR for the tested genes

Genes RQ	Curcumin	A	Curcumin+ A
Caspase3	8.8 ± 2.4	14.9 ± 5.1	18.2 ± 4.7
mTOR	0.56 ± 0.08 *	0.07 ± 0.03	0.02 ± 0.00
IL-6	0.1 ± 0.02	0.6 ± 0.08 *	0.08 ± 0.02
Bcl-2	0.18 ± 0.01	0.19 ± 0.05	0.04 ± 0.02

*Non-significant downregulation

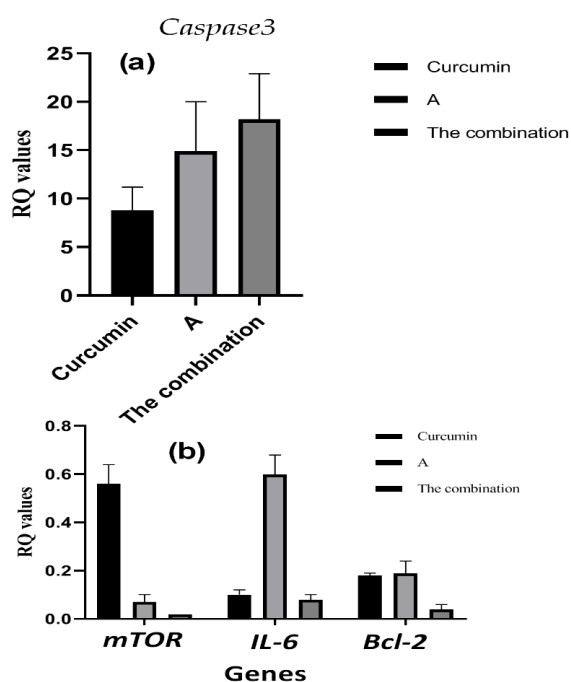


Figure 11. The RQ results for the tested genes obtained by QPCR. (a) The RQ analysis for *Caspase3* gene on treated cells with (curcumin, drug A, the combination (curcumin+ A). (b) The RQ analysis for *mTOR*, *IL-6*, and *Bcl-2* genes on treated cells with (curcumin, drug A, the combination (curcumin+ A).

Furthermore, RQ of gene regulation in drug-treated groups was obtained to show that the *Bcl-2*, *Caspase3*, and *mTOR* genes had a significant up-regulation in all groups. While the *mTOR* gene reported a significant down-regulation in (A and curcumin+ A) groups, but non-significant downregulation in (curcumin) group, and *IL-6* gene showed a significant down-regulation in (curcumin and curcumin+ A) groups but non-significant down-regulation in (A) group (Figure 11).

4. Discussion

The most common type of primary liver cancer is HCC, which is characterized by a significant incidence of morbidity and mortality worldwide. There exists an urgent need to develop new therapeutic agents capable of circumventing multidrug resistance mechanisms, thereby providing a more sustainable clinical response (Zou et al. 2025; Song et al. 2023).

Anti-HepG2 activity of synthetic compounds A and B

Many compounds with this scaffold induce apoptosis and cause cell-cycle arrest through multiple mechanisms (Dawood et al. 2023). Some derivatives also reduce EGFR kinase activity, inhibiting cancer cell metastasis (Bray et al. 2024). In this study, the safety index was measured by calculating the IC_{50} and observing the cell viability of the tested compounds against the Vero 2 cell. TO affirm the suspected compounds' safety or low level of toxicity (Abdu et al. 2022; Marquardt et al. 2015).

After that, compounds A and B (both bearing a nitrophenyl-triazolyl-thiazole moiety) were synthesized to assess anticancer activity. Against HepG2 cells, compound B (thiazolidine-4-one side chain) showed moderate activity, whereas compound A (chloroacetamide side chain) was more potent, likely due to the chloroacetamide group (Marquardt et al. 2015).

The chloroacetamide group is a promising anticancer motif because it forms stable, irreversible covalent bonds with nucleophilic protein sites, such as cysteine thiols and histidine imidazoles (Duarte and Vale 2022). Incorporating this group into a suitable scaffold enables targeted engagement of cancer-associated proteins and can be effective against treatment-resistant cancers (Xu and Liu 2025; Zhou et al. 2017).

By comparison, the thiazolidine-4-one side chain generally confers lower potency than the chloroacetamide chain against HepG2 cells. Thiazolidine-4-one derivatives act mainly via reversible, non-covalent interactions (hydrogen bonding and hydrophobic forces), functioning as enzyme inhibitors or receptor modulators (Huang, Xu, and Zhuang 2025).

Anti-HepG2 activity of curcumin and quercetin

To enhance the anti-HepG2 activity of the A and B, they combined them with two well-known flavonoids as anticancer products, curcumin and quercetin (Sharma et al. 2020).

Curcumin is a potent therapy against HepG2 cells; it has anticancer efficacy against several malignancies, including breast, lung, gastric, liver, and prostate cancers, through many mechanisms (Auti et al. 2024). Studies have indicated that curcumin exerts significant inhibitory effects on the proliferation and migration of HepG2 cells. This is achieved through arresting the cell cycle at the S phase, induction of apoptosis in cancer cells, and interfering with the expression of key oncogenic signaling pathways such as VEGF, STAT3, and HIF-1 α (Olszewska et al. 2016; Othman et al. 2023).

Quercetin strongly inhibits some multidrug-resistance regulatory proteins and transporters associated with tumor activity, such as proliferation, invasion, migration, and metastasis, which reflects tumor aggressiveness (Guan et al. 2023; El-Hddad et al. 2024), with an inhibitory effect on HepG2 cells proliferation as it induces apoptosis and diminishes their viability.

The power of drug combination

A combination of curcumin with drugs like ABT-737 induces apoptosis significantly in HepG2 cells by activating caspase-9 and caspase-3 enzymes (Bahadar et al. 2024).

In the current study, 4 combinations were designed as follows: (Curcumin+ A), (Curcumin+ B), (Quercetin+ A), and (Quercetin+ B). It was found to be a synergistic activity in all combinations with varying degrees (Dawood et al. 2023; El-Hddad et al. 2024). Moreover, It was found that the most potent and active combination was (Curcumin+ A), which gives a lower IC₅₀ and significant anticancer activity against HepG2, and this may be due to interfering with multiple targets and pathways in HepG2 cells.

A significant reduction in HepG2 cells' proliferation and migration was observed when curcumin was combined with anticancer drugs, such as celecoxib (Yang and Chan 2009; Zou et al. 2025; Zhou et al. 2017). The same, when quercetin is combined with anti-HepG2 drugs, such as gemcitabine or doxorubicin, a synergistic effect is found, causing cell growth inhibition and apoptosis. A combination of quercetin with cisplatin induces p16-mediated cell cycle arrest and apoptosis (Hassan et al. 2020; Zheng et al. 2016).

Regulation of HepG2 key genes

To confirm these results and suggest the mechanism, we examined the regulation of four key genes (*mTOR*, *Bcl-2*, *IL-6*, and *caspase3*) in HepG2 cells, that affected by the most potent combination, curcumin + compound A. it found that the first three genes (*mTOR*, *Bcl-2*, and *IL-6*) are all downregulated. In contrast, *caspase3* upregulated which reflected the potency of the combination in inhibition of HepG2 cells and selectively in induced apoptosis (Qian et al. 2022; Zeng et al. 2024).

mTOR Downregulation

Inhibition of mammalian target of rapamycin (*mTOR*) by combination therapy is a significant therapeutic achievement. A direct mechanistic link exists between the structure of compound A and this effect, as a chloroacetamide derivative has been shown to inhibit the AKT/*mTOR* signaling pathway, which is a key pro-survival cascade. This provides a direct causal link between the drug's proposed mechanism of action and the observed cellular response (Guertin and Sabatini 2007; Abruzzese et al. 2021).

On the other hand, curcumin may directly repress the transcriptional regulation of the *mTOR* gene, leading to lower mRNA levels, and induce promoter hypermethylation of the *mTOR* gene, which is a mechanism that silences gene expression and reduces the synthesis of its mRNA (Liu et al. 2017). It interferes with the PI3K/Akt/*mTOR* pathway, leading to inhibition of proliferative signaling and enhancing apoptotic responses and cancer cells' autophagy (Zheng et al. 2016; Hassan et al. 2020; Akter, Gul, and Mumtaz 2025).

Bcl-2 Downregulation

Bcl-2 is an anti-apoptotic protein. It is overexpressed in many types of cancers, as it facilitates tumor survival and resistance to chemotherapy, because it suppresses programmed cell death (apoptosis) (Sharma et al. 2020). In HepG2 cells, upregulation of *Bcl-2* causes multidrug resistance and is linked to factors like insulin resistance (Zeng et al. 2024).

The curcumin + compound A combination causes a downregulation of this gene, so it is suggested that the combination directly targets and reverses a pre-existing mechanism of drug resistance, thereby leading to the cancer cells to death (Sherif et al. 2018; Shama and Savaliya 2025). It was found that some derivatives containing thiazole and triazole structures can inhibit the NF- κ B pathway, suppress the anti-apoptotic *Bcl-2* gene regulator, and induce apoptosis in cancer cells by downregulating *Bcl2* gene expression (Sethi et al. 2023).

Other thiazole derivatives cause inhibition of *Bcl2* in cancer cells, leading to promote apoptosis (Sharma et al. 2020). Curcumin inhibits Bcl2 proteins in HepG2 cells and induces apoptosis. Studies show curcumin reduces NF- κ B's impact on cancer cells, ultimately inhibiting tumor growth and potentially acting as a therapeutic agent for HCC (Shama and Savaliya 2025; Marquardt et al. 2015; Liu et al. 2017).

IL-6 Downregulation

Interleukin-6 (IL-6) helps to sustain a pro-tumorigenic microenvironment. In liver cancer patients, the IL-6, if found in high concentration in serum, is associated with a poor prognostic indicator, so therapy needs to disrupt this pathway (Song et al. 2023; Nenu et al. 2023; Mustafa et al. 2019).

It was found that some thiazole derivatives inhibit IL-6 by reducing the DNA binding of the transcription factor NF- κ B. Leading to inhibit *IL-6* mRNA in some cancer cell lines, which is the other part of the combination, has an inhibition effect on *IL-6* transcription in HepG2 cells. (Moawad et al. 2023; Noori et al. 2017).

Caspase3 Upregulation

Caspase-3 is a cysteine protease and key executioner enzyme in the apoptosis pathway, responsible for dismantling cells during programmed cell death. Caspase-3 is at the end of the caspase cascade, meaning it is a critical and final effector in the apoptotic process (Padhariya et al. 2020). The upregulation and activation of Caspase-3 is the definitive molecular marker of a successful proapoptotic therapeutic intervention (Sayed et al. 2020). Many studies have reported the role of thiazole and triazole compounds in upregulation of caspase-3 gene transcription in a lot of cancer cell lines, such as HepG2 (Ali et al. 2024). Curcumin induces apoptosis in HepG2 cells through activation of proapoptotic mediators such as caspase3. Curcumin nano capsules induce apoptotic processes through upregulation of *caspase-3* gene mRNA (Moawad et al. 2023; Abd El-Moaty et al. 2025).

The most attractive finding is, this activity increases significantly when combined with other flavonoids, especially curcumin. The combination gives a lower IC50, nearing the reference drug used, doxorubicin, which reflects the unique character of this formula, suggesting being promising formula against one of the most aggressive forms of cancer in the world (Mustafa et al. 2019; Marquardt et al. 2015).

5. Conclusions

In conclusion, the biological activity of these compounds against HepG2 cells is significantly influenced by their side-chain structure. The combination of compound A and curcumin led to the downregulation

of *mTOR*, a central regulator of cell growth, and *IL6*, a pro-inflammatory cytokine. This study identified the synergistic combination of compound A and curcumin as a promising therapeutic formula for HCC. For future direction more in-depth research is recommended about this combination in other cancer types, and further development as a promising novel agent in cancer therapy.

Ethical approval: no human subjects were involved.

Author Contributions: Conceptualization; methodology; software; validation; formal analysis; investigation; data curation; original draft preparation; review and editing, R.A.

Funding: the authors did not receive funds, grants, or support from any organization during the preparation of this manuscript.

Data Availability Statement: The original contributions presented in this study are included in the article.

Acknowledgments: I would like to thank Al-Baha University specially biology department, for all their support in completing this research.

Conflicts of Interest: The authors declare no conflicts of interest

6. References

- Abd El-Moaty, H. I., A. S. Doghish, H. A. M. Moustafa, W. S. Elkalla, G. A. Sayed, N. H. Elshami, S. S. A. Mageed, O. A. Mohammed, M. A. Elrebehy, K. AlFarsi, A. M. Abdelfatah, A. M. Waseem, A. O. Abdulkader, R. S. Hamad, and A. N. Salah. 2025. 'Phage therapy and its role in cancer treatment and control', *Folia Microbiol (Praha)*.
- Abdel-Wahab, Bakr F., Ahmed F. Mabied, James C. Fettingier, and Abdelbasset A. Farahat. 2023. '2-((4-Amino-5-((2,4-dichlorophenoxy)methyl)-4H-1,2,4-triazol-3-yl)thio)-1-(5-methyl-1-(4-nitrophenyl)-1H-1,2,3-triazol-4-yl)ethan-1-one', *Molbank*, 2023: M1720.
- Abdelaziz, A. A., A. S. Doghish, A. N. Salah, R. M. Mansour, Y. M. Moustafa, S. S. A. Mageed, H. A. M. Moustafa, W. A. El-Dakroury, S. A. Doghish, O. A. Mohammed, M. A. Abdel-Reheim, S. O. Abbass, S. O. Abbass, M. O. Abbass, A. M. Samy, M. A. Elrebehy, and Y. A. Doghish. 2025. 'When oral health affects overall health: biofilms, dental infections, and emerging antimicrobial strategies', *Infection*, 53: 1603-24.

- Abdu, S., N. Juaid, A. Amin, M. Moulay, and N. Miled. 2022. 'Effects of Sorafenib and Quercetin Alone or in Combination in Treating Hepatocellular Carcinoma: In Vitro and In Vivo Approaches', *Molecules*, 27.
- Abruzzese, V., I. Matera, F. Martinelli, M. Carmosino, P. Koshal, L. Milella, F. Bisaccia, and A. Ostuni. 2021. 'Effect of Quercetin on ABCG6 Transporter: Implication in HepG2 Migration', *Int J Mol Sci*, 22.
- Akter, Khadija, Kainat Gul, and Sohail Mumtaz. 2025. 'Revisiting Curcumin in Cancer Therapy: Recent Insights into Molecular Mechanisms, Nanoformulations, and Synergistic Combinations', *Current Issues in Molecular Biology*, 47: 716.
- Ali, H., F. Vikash, V. Moond, F. Khalid, A. R. Jamil, D. S. Dahiya, A. H. Sohail, M. K. Gangwani, P. Patel, and S. K. Satapathy. 2024. 'Global trends in hepatitis C-related hepatocellular carcinoma mortality: A public database analysis (1999-2019)', *World J Virol*, 13: 89469.
- Auti, A., M. Tathode, M. M. Marino, A. Vitiello, A. Ballini, F. Miele, V. Mazzone, A. Ambrosino, and M. Boccellino. 2024. 'Nature's weapons: Bioactive compounds as anti-cancer agents', *AIMS Public Health*, 11: 747-72.
- Bahadar, N., S. Bahadar, A. Sajid, M. Wahid, G. Ali, A. Alghamdi, H. Zada, T. Khan, S. Ullah, and Q. Sun. 2024. 'Epigallocatechin gallate and curcumin inhibit Bcl-2: a pharmacophore and docking based approach against cancer', *Breast Cancer Res*, 26: 114.
- Bray, F., M. Laversanne, H. Sung, J. Ferlay, R. L. Siegel, I. Soerjomataram, and A. Jemal. 2024. 'Global cancer statistics 2022: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries', *CA Cancer J Clin*, 74: 229-63.
- Dawood, K. M., M. A. Raslan, A. A. Abbas, B. E. Mohamed, and M. S. Nafie. 2023. 'Novel bis-amide-based bis-thiazoles as Anti-colorectal Cancer Agents Through Bcl-2 Inhibition: Synthesis, In Vitro, and In Vivo studies', *Anticancer Agents Med Chem*, 23: 328-45.
- Duarte, D., and N. Vale. 2022. 'Evaluation of synergism in drug combinations and reference models for future orientations in oncology', *Curr Res Pharmacol Drug Discov*, 3: 100110.
- Ebaid, M. S., H. A. Abdelsattar Ibrahim, A. F. Kassem, and A. Sabt. 2024. 'Recent studies on protein kinase signaling inhibitors based on thiazoles: review to date', *RSC Adv*, 14: 36989-7018.
- El-Hddad, S. S. A., M. H. Sobhy, A. El-Morsy, N. A. Shoman, and K. El-Adl. 2024. 'Quinazolines and thiazolidine-2,4-dions as SARS-CoV-2 inhibitors: repurposing, in silico molecular docking and dynamics simulation', *RSC Adv*, 14: 13237-50.
- Guan, H., W. Zhang, H. Liu, Y. Jiang, F. Li, M. Wu, G. I. N. Waterhouse, D. Sun-Waterhouse, and D. Li. 2023. 'Quercetin Induces Apoptosis in HepG2 Cells via Directly Interacting with YY1 to Disrupt YY1-p53 Interaction', *Metabolites*, 13.
- Guertin, David A., and David M. Sabatini. 2007. 'Defining the role of mTOR in cancer', *Cancer cell*, 12: 9-22.
- Hassan, S., J. Peluso, S. Chalhoub, Y. Idoux Gillet, N. Benkirane-Jessel, N. Rochel, G. Fuhrmann, and G. Ubeaud-Sequier. 2020. 'Quercetin potentializes the respective cytotoxic activity of gemcitabine or doxorubicin on 3D culture of AsPC-1 or HepG2 cells, through the inhibition of HIF-1 α and MDR1', *PLoS One*, 15: e0240676.
- Hemdan, M., S. S. Abdel Mageed, A. I. Abulsoud, A. H. I. Faraag, M. B. Zaki, R. M. Mansour, A. A. Raouf, M. A. Ali, O. A. Mohammed, A. Salman, A. N. Salah, M. A. Abdel-Reheim, and A. S. Doghish. 2024. 'Approaches based on miRNAs in Behçet's Disease: Unveiling pathogenic mechanisms, diagnostic strategies, and therapeutic applications', *Life Sci*, 354: 122950.
- Huang, S., Z. Xu, and Y. Zhuang. 2025. 'The current landscape of 1,2,3-triazole hybrids with anticancer therapeutic potential: Part I', *Arch Pharm (Weinheim)*, 358: e2500001.
- Liu, J. L., Y. Y. Pan, O. Chen, Y. Luan, X. Xue, J. J. Zhao, L. Liu, and H. Y. Jia. 2017. 'Curcumin inhibits MCF-7 cells by modulating the NF- κ B signaling pathway', *Oncol Lett*, 14: 5581-84.
- Livak, K. J., and T. D. Schmittgen. 2001. 'Analysis of relative gene expression data using real-time quantitative PCR and the 2(-Delta Delta C(T)) Method', *Methods*, 25: 402-8.
- Marquardt, J. U., L. Gomez-Quiroz, L. O. Arreguin Camacho, F. Pinna, Y. H. Lee, M. Kitade, M. P. Domínguez, D. Castven, K. Breuhahn, E. A. Conner, P. R. Galle, J. B. Andersen, V. M. Factor, and S. S. Thorgeirsson. 2015. 'Curcumin effectively inhibits oncogenic NF- κ B signaling and restrains stemness features in liver cancer', *J Hepatol*, 63: 661-9.

- McCubrey, J. A., K. Lertpiriyapong, L. S. Steelman, S. L. Abrams, L. V. Yang, R. M. Murata, P. L. Rosalen, A. Scalisi, L. M. Neri, L. Cocco, S. Ratti, A. M. Martelli, P. Laidler, J. Dulińska-Litewka, D. Rakus, A. Gizak, P. Lombardi, F. Nicoletti, S. Candido, M. Libra, G. Montalto, and M. Cervello. 2017. 'Effects of resveratrol, curcumin, berberine and other nutraceuticals on aging, cancer development, cancer stem cells and microRNAs', *Aging (Albany NY)*, 9: 1477-536.
- Moawad, M., G. M. Nasr, A. S. Osman, and E. S. Shaker. 2023. 'Curcumin nanocapsules effect in apoptotic processes, gene expression, and cell cycle on Hep-G2 cell lines', *Int J Immunopathol Pharmacol*, 37: 3946320231176396.
- Mohamed, A. H., A. T. Ahmed, W. Al Abdulmonem, D. O. Bokov, A. Shafie, Hrak Al-Hetty, C. Y. Hsu, M. Alissa, S. Nazir, M. C. Jamali, and M. Mudhafar. 2024. 'Interleukin-6 serves as a critical factor in various cancer progression and therapy', *Med Oncol*, 41: 182.
- Mustafa, M., S. Anwar, F. Elgamal, E. R. Ahmed, and O. M. Aly. 2019. 'Potent combretastatin A-4 analogs containing 1,2,4-triazole: Synthesis, antiproliferative, anti-tubulin activity, and docking study', *Eur J Med Chem*, 183: 111697.
- Narasimhamurthy, Kereyagalahalally H., Toreshettahalally R. Swaroop, and Kanchugarakoppal S. Rangappa. 2024. 'A review on progress of thiazole derivatives as potential anti-inflammatory agents', *European Journal of Medicinal Chemistry Reports*, 12: 100225.
- Nenu, I., T. M. Toadere, I. Topor, A. Țichindeleanu, D. A. Bondor, E. Trella Ș, Z. Sparchez, and G. A. Filip. 2023. 'Interleukin-6 in Hepatocellular Carcinoma: A Dualistic Point of View', *Biomedicines*, 11.
- Noori, M. S., J. D. O'Brien, Z. J. Champa, S. P. Deosarkar, O. L. Lanier, C. Qi, M. M. Burdick, F. L. Schwartz, S. C. Bergmeier, K. D. McCall, and D. J. Goetz. 2017. 'Phenylmethimazole and a thiazole derivative of phenylmethimazole inhibit IL-6 expression by triple negative breast cancer cells', *Eur J Pharmacol*, 803: 130-37.
- Olszewska, A., R. Pohl, M. Brázdová, M. Fojta, and M. Hocek. 2016. 'Chloroacetamide-Linked Nucleotides and DNA for Cross-Linking with Peptides and Proteins', *Bioconjug Chem*, 27: 2089-94.
- Othman, D. I. A., A. Hamdi, S. S. Tawfik, A. A. Elgazar, and A. S. Mostafa. 2023. 'Identification of new benzimidazole-triazole hybrids as anticancer agents: multi-target recognition, in vitro and in silico studies', *J Enzyme Inhib Med Chem*, 38: 2166037.
- Padharia, K. N., M. Athavale, S. Srivastava, and P. S. Kharkar. 2020. 'Substituted chloroacetamides as potential cancer stem cell inhibitors: Synthesis and biological evaluation', *Drug Dev Res*, 81: 356-65.
- Qian, S., Z. Wei, W. Yang, J. Huang, Y. Yang, and J. Wang. 2022. 'The role of BCL-2 family proteins in regulating apoptosis and cancer therapy', *Front Oncol*, 12: 985363.
- Salah, A. N., N. S. Elleboudy, G. S. El-Housseiny, and M. A. Yassien. 2021. 'Cloning and sequencing of *IsaE* efflux pump gene from MDR Enterococci and its role in erythromycin resistance', *Infect Genet Evol*, 94: 105010.
- Salah, Akram N, Modi B Al-Otaibi, Anwar Salah Farhan Al-dhmashi, and Amr A Mariee. 2024. 'Infection control practices and approaches in the dentistry field; a review', *Journal of Bioscience and Applied Research*, 10: 42-58.
- Sayed, A. R., S. M. Gomha, E. A. Taher, Z. A. Muhammad, H. R. El-Seedi, H. M. Gaber, and M. M. Ahmed. 2020. 'One-Pot Synthesis of Novel Thiazoles as Potential Anti-Cancer Agents', *Drug Des Devel Ther*, 14: 1363-75.
- Sethi, G., P. Rath, A. Chauhan, A. Ranjan, R. Choudhary, S. Ramniwas, K. Sak, D. Aggarwal, I. Rani, and H. S. Tuli. 2023. 'Apoptotic Mechanisms of Quercetin in Liver Cancer: Recent Trends and Advancements', *Pharmaceutics*, 15.
- Shama, A. R., and M. L. Savaliya. 2025. 'Benzothiazole-triazole hybrids: Novel anticancer agents inducing cell cycle arrest and apoptosis through Bcl-2 inhibition in triple-negative breast cancer', *Bioorg Chem*, 155: 108150.
- Sharma, P. C., K. K. Bansal, A. Sharma, D. Sharma, and A. Deep. 2020. 'Thiazole-containing compounds as therapeutic targets for cancer therapy', *Eur J Med Chem*, 188: 112016.
- Sherif, R. N., H. Abdellatif, N. Hazem, N. A. Ebrahim, D. Saleh, G. Shiha, H. Eltahry, K. G. Botros, and O. M. Gabr. 2018. 'Effect of human umbilical cord blood derived CD34(+) hematopoietic stem cell on the expression of Wnt4 and P53 genes in a rat model of hepatocellular carcinoma', *Tissue Cell*, 50: 125-32.

- Song, L., R. Xu, W. Cai, J. Liang, N. Cao, J. Gao, and X. Tang. 2023. 'IL-6 upregulates the expression of IL-6R through the JAK2/STAT3 signalling pathway to promote progression of hepatocellular carcinoma', *Scand J Immunol*, 98: e13271.
- Xu, Z., and J. Liu. 2025. 'The Current Landscape of 1,2,3-triazole Hybrids With Anticancer Therapeutic Potential: Part II', *Arch Pharm (Weinheim)*, 358: e2500031.
- Yang, X., and C. Chan. 2009. 'Repression of PKR mediates palmitate-induced apoptosis in HepG2 cells through regulation of Bcl-2', *Cell Res*, 19: 469-86.
- Zeng, Y., X. Tang, J. Chen, X. Kang, and D. Bai. 2024. 'Optimizing total RNA extraction method for human and mice samples', *PeerJ*, 12: e18072.
- Zheng, R., Z. You, J. Jia, S. Lin, S. Han, A. Liu, H. Long, and S. Wang. 2016. 'Curcumin enhances the antitumor effect of ABT-737 via activation of the ROS-ASK1-JNK pathway in hepatocellular carcinoma cells', *Mol Med Rep*, 13: 1570-6.
- Zhou, J., L. Fang, J. Liao, L. Li, W. Yao, Z. Xiong, and X. Zhou. 2017. 'Investigation of the anti-cancer effect of quercetin on HepG2 cells in vivo', *PLoS One*, 12: e0172838.
- Zou, Y., X. Wan, Q. Zhou, G. Zhu, S. Lin, Q. Tang, X. Yang, and S. Wang. 2025. 'Mechanisms of drug resistance in hepatocellular carcinoma', *Biol Proced Online*, 27: 19.

- **الاقْتباس من كتاب لأكثر من مؤلف:**
نيوباي، تيموثي؛ ستيتش، دونالد؛ راس، جيمس. (1434هـ/2013م). *التقنية التعليمية للتعليم والتعلم*. الرياض، المملكة العربية السعودية: دار جامعة الملك سعود للنشر.
- **الاقْتباس من دورية:**
النافع، عبد اللطيف حمود. (1427هـ). أثر قيادة السيارات خارج الطرق المعبدة في الغطاء النباتي بالمنتزهات البرية: دراسة في حماية البيئة، في وسط المملكة العربية السعودية. *المجلة السعودية في علوم الحياة*، 14 (1)، 53-72.
- **الاقْتباس من رسالة ماجستير أو دكتوراه:**
القاضي، إيمان عبدالله. (1429هـ). *النباتات الطبيعية للبيئة الساحلية بين راسي تنورة والملوح بالمنطقة الشرقية: دراسة في الجغرافيا النباتية وحماية البيئة*. رسالة دكتوراه غير منشورة، كلية الآداب للبنات، الدمام، المملكة العربية السعودية: جامعة الملك فيصل.
- **الاقْتباس من الشبكة العنكبوتية (الإنترنت):**
- **الاقْتباس من كتاب:**
المزروعسي، م.ر. و المدني، م.ف. (2010م). *تقييم الأداء في مؤسسات التعليم العالي*. المعرف الرقمي (DOI:10.xxxx/xxxx-xxxxxxx-x)، أو برتوكول نقل النصوص التشعبي (http://www...)، أو الرقم المعياري الدولي للكتاب (ISBN : 000-0- 00 - 000000-0)
- **الاقْتباس من مقالة في دورية:**
المدني، م.ف. (2014). مفهوم الحوار في تقريب وجهات النظر. *المجلة البريطانية لتكنولوجيا التعليم*، 11 (6)، 225-260. المعرف الرقمي (DOI:10.xxxx/xxxx-xxxxxxx-x) أو برتوكول نقل النصوص التشعبي (http://www.../onlinejournal/10.1111) أو الرقم المعياري التسلسلي الدولي للمجلة - ISSN: 1467 (8535).
- 14 يلتزم الباحث بترجمة (أو رومنة) أسماء المصادر والمراجع العربية إلى اللغة الإنجليزية في قائمة المصادر والمراجع. وعلى سبيل المثال:
الجبر، سليمان. (1991م). *تقويم طرق تدريس الجغرافيا ومدى اختلاف خبرات المدرسين وجنسياتهم وتخصصاتهم في المرحلة المتوسطة بالمملكة العربية السعودية*. *مجلة جامعة الملك سعود- العلوم التربوية*، 3 (1)، 143-170.
- Al-Gabr, S. (1991). The Evaluation of Geography Instruction and the Variety of its Teaching Concerning the Experience, Nationality, and the Field of Study in Intermediate Schools in Saudi Arabia (in Arabic). *Journal of King Saud University- Educational Sciences*, 3(1), 143-170.
- 15 تستخدم الأرقام العربية الأصلية (0، 1، 2، 3، ...) في البحث.
- 16 تؤول جميع حقوق النشر للمجلة في حال إرسال البحث للتحكيم وقبوله للنشر.

ثانياً: الملفات المطلوب تسليمها

- (1) نسخة إلكترونية من البحث بصيغتي (WORD) و (PDF)، وترسلان على البريد الإلكتروني الآتي:
s.journal@nbu.edu.sa
- (2) السيرة الذاتية للباحث، متضمنة اسمه باللغتين العربية والإنجليزية، وعنوان البريد الإلكتروني الحالي، ورتبته العلمية.
- (3) تعبئة النماذج الآتية:
أ - نموذج طلب نشر بحث في المجلة.
ب - نموذج تعهد بأن البحث غير منشور أو مقدم للنشر في مكان آخر.

ثالثاً: تنبيهات عامة

- (1) أصول البحث التي تصل إلى المجلة لا تردّ سواء أُنشِرت أم لم تنشر.
- (2) الآراء الواردة في البحوث المنشورة تعبر عن وجهة نظر أصحابها.

شروط النشر

أولاً: ضوابط النص المقدم للنشر

- (1) ألا تزيد صفحاته عن (35) صفحة من القطع العادي (A4).
- (2) أن يحتوي على عنوان البحث وملخصه باللغتين العربية والإنجليزية في صفحة واحدة، بحيث لا يزيد عن (250) كلمة للملخص، وأن يتضمن البحث كلمات مفتاحية دالة على التخصص الدقيق للبحث باللغتين، بحيث لا يتجاوز عددها (6) كلمات، توضع بعد نهاية كل ملخص.
- (3) أن يذكر اسم المؤلف وجهة عمله بعد عنوان البحث مباشرة باللغتين العربية والإنجليزية.
- (4) أن تقدم البحوث العربية مطبوعة بخط (Simplified Arabic)، بحجم (14) للنصوص في المتن، وبالخط نفسه بحجم (12) للهوامش.
- (5) أن تقدم البحوث الإنجليزية مطبوعة بخط (Times New Roman) بحجم (12) للنصوص في المتن، وبالخط نفسه بحجم (9) للهوامش.
- (6) كتابة البحث على وجه واحد من الصفحة، مع ترك مسافة سطر واحد بين السطور، وتكون الحواشي 2.5 سم على الجوانب الأربعة للصفحة، بما يعادل 1.00 إنش (بوصة).
- (7) التزام الترتيب الموضوعي الآتي:
المقدمة: تكون دالة على موضوع البحث، والهدف منه، ومنسجمة مع ما يرد في البحث من معلومات وأفكار وحقائق علمية، كما تشير باختصار إلى مشكلة البحث، وأهمية الدراسات السابقة.
العرض: يتضمن التفاصيل الأساسية لمنهجية البحث، والأدوات والطرق التي تخدم الهدف، وترتب المعلومات حسب أولويتها.
النتائج والمناقشة: يجب أن تكون واضحة موجزة، مع بيان دلالاتها دون تكرار.
الخاتمة: تتضمن تلخيصاً موجزاً للموضوع، وما توصل إليه الباحث من نتائج، مع ذكر التوصيات والمقترحات.
- (8) أن تدرج الرسوم البيانية والأشكال التوضيحية في النص، وترقم ترقيماً متسلسلاً، وتكتب أسماؤها والملاحظات التوضيحية أسفلها.
- (9) أن تدرج الجداول في النص، وترقم ترقيماً متسلسلاً، وتكتب أسماؤها أعلاها، وأما الملاحظات التوضيحية فتكتب أسفل الجدول.
- (10) ألا توضع الهوامش أسفل الصفحة إلا عند الضرورة فقط، ويشار إليها برقم أو نجمة، ويكون الخط فيها بحجم (12) للعربي و (9) للإنجليزي.
- (11) لا تنشر المجلة أدوات البحث والقياس، وتقوم بحذفها عند طباعة المجلة.
- (12) أن يُراعى في منهج توثيق المصادر والمراجع داخل النص نظام (APA)، وهو نظام يعتمد ذكر الاسم والتاريخ (name/year) داخل المتن، ولا يقبل نظام ترقيم المراجع داخل النص مع وضع الحاشية أسفل الصفحة، وتوضع المصادر والمراجع داخل المتن بين قوسين حسب الأمثلة الآتية: يذكر اسم عائلة المؤلف متبوعاً بفاصلة، فسنة النشر، مثلاً: (مجاهد، 1988م). وفي حالة الاقتباس المباشر يضاف رقم الصفحة مباشرة بعد تاريخ النشر مثلاً: (خيرى، 1985م، ص:33). أما إذا كان للمصدر مؤلفان فيذكران مع اتباع الخطوات السابقة مثلاً: (الفالح وعياش، 1424هـ). وفي حالة وجود أكثر من مؤلفين فتذكر أسماء عوائلهم أول مرة، مثلاً: (مجاهد والعودات والشيخ، 1408هـ)، وإذا تكرر الاقتباس من المصدر نفسه فيشار إلى اسم عائلة المؤلف الأول فقط، ويكتب بعده وآخرون مثلاً: (مجاهد وآخرون، 1408هـ)، على أن تكتب معلومات النشر كاملة في قائمة المصادر والمراجع.
- (13) توضع قائمة المصادر والمراجع في نهاية البحث مرتبة ترتيباً هجائياً حسب اسم العائلة، ووفق نظام جمعية علم النفس الأمريكية (APA) الإصدار السادس، وبحجم (12) للعربي و (9) للإنجليزي، وترتب البيانات البليوغرافية على النحو الآتي:

• الاقتباس من كتاب لمؤلف واحد:

الخوجلي، أحمد. (2004م). **مبادئ فيزياء الجوامد**. الخرطوم، السودان: عزة للنشر والتوزيع

مجلة الشمال للعلوم الأساسية والتطبيقية (JNBAS)

التعريف بالمجلة

تعنى المجلة بنشر البحوث والدراسات العلمية الأصيلة في مجال العلوم الأساسية والتطبيقية، باللغتين العربية والإنجليزية، كما تهتم بنشر جميع ما له علاقة بعرض الكتب ومراجعتها أو ترجمتها، وملخصات الرسائل العلمية، وتقارير المؤتمرات والندوات العلمية، وتصدر مرتين في السنة (مايو - نوفمبر).

الرؤية

الريادة في نشر البحوث العلمية المحكمة، وتصنيف المجلة ضمن أشهر الدوريات العلمية العالمية.

الرسالة

نشر البحوث العلمية المحكمة في مجال العلوم الأساسية والتطبيقية وفق معايير عالمية متميزة.

أهداف المجلة

- 1) أن تكون المجلة مرجعاً علمياً للباحثين في العلوم الأساسية والتطبيقية.
- 2) تلبية حاجة الباحثين إلى نشر بحوثهم العلمية، وإبراز مجهوداتهم البحثية على المستويات المحلية والإقليمية والعالمية.
- 3) المشاركة في بناء مجتمع المعرفة بنشر البحوث الرصينة التي تؤدي إلى تنمية المجتمع.
- 4) تغطية أعمال المؤتمرات العلمية المحكمة.

شروط قبول البحث

- 1) الأصالة والابتكار وسلامة المنهج والاتجاه.
- 2) الالتزام بالمنهج والأدوات والوسائل العلمية المتبعة في مجاله.
- 3) الدقة في التوثيق والمصادر والمراجع والتخريج.
- 4) سلامة اللغة.
- 5) أن يكون البحث غير منشور أو مقدم للنشر في أي مكان آخر.
- 6) أن يكون البحث المستل من الرسائل العلمية غير منشور أو مقدم للنشر، وأن يشير الباحث إلى أنه مستل.

للمراسلة

رئيس التحرير

مجلة الشمال للعلوم الأساسية والتطبيقية (JNBAS)

جامعة الحدود الشمالية

ص.ب. 1321، عرعر، 91431

المملكة العربية السعودية.

هاتف : +966146615499

فاكس: +966146614439

الاشتراك والتبادل

مركز الترجمة والتأليف والنشر

جامعة الحدود الشمالية

ص.ب. 1321 ، عرعر، 91431

المملكة العربية السعودية.

البريد الإلكتروني: s.journal@nbu.edu.sa

الموقع الإلكتروني: www.nbu.edu.sa



رئيس هيئة التحرير

أ.د. محمد بن عبدالعزيز طاشكندي
أستاذ الهندسة الميكانيكية

أعضاء هيئة التحرير

د. مفلح بن بطاح الحازمي
أستاذ الرياضيات المشارك

د. فهد بن عايد الشمري
أستاذ علوم الاحياء المشارك

د. منيرة بنت مطلق الجعيد
أستاذ الرياضيات المشارك

د. علي بن السعيد الرئيس
أستاذ الكيمياء المشارك

د. طارق بن ابراهيم الغنزي
أستاذ الفيزياء المساعد

مجلة الشمال للعلوم الأساسية والتطبيقية (JNBAS)

دورية علمية محكمة

تصدر عن
مركز الترجمة والتأليف والنشر
جامعة الحدود الشمالية

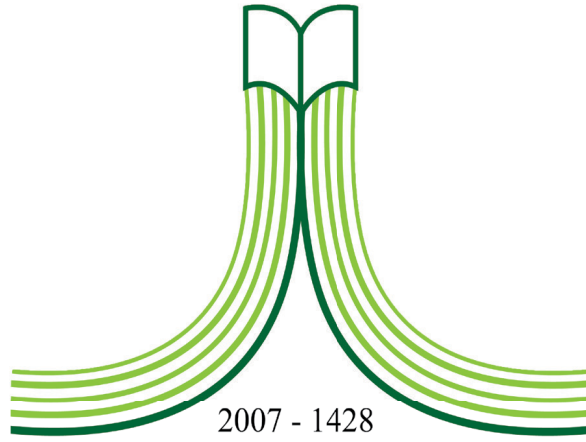
المجلد الحادي عشر - العدد الأول - الجزء الأول

مايو 2026م / ذو القعدة 1447هـ

الموقع والبريد الإلكتروني

www.nbu.edu.sa
s.journal@nbu.edu.sa

طباعة ردمد: 1658-7022 إلكتروني ردمد: 1658-7014



جامعة الحدود الشمالية
NORTHERN BORDER UNIVERSITY

المملكة العربية السعودية



المجلد (11)

العدد (1)

الجزء (1)

مايو 2026م

نوالقعة 1447هـ

مجلة الشمال

للعلوم

الأساسية والتطبيقية

دورية علمية محكمة

جامعة الحدود الشمالية

www.nbu.edu.sa

طباعة ردمد: 1658-7022

إلكتروني ردمد: 1658-7014

J
N
B
A
S