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بسم الله الرحمن الرحيم

IN THE NAME OF ALLAH

THE MOST GRACIOUS, THE MOST MERCIFUL

2007 - 1428

جامعة الحدود الشمالية

NORTHERN BORDER UNIVERSITY

Kingdom of Saudi Arabia

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Predictors of Disaster Readiness Perceptions among Emergency Department Nurses in the Eastern Region of Saudi Arabia

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(**Received:** 7th March 2026; **Accepted:** 13th April 2026)

Abstract
Background: Nurses play a crucial role in disaster response within emergency departments; however, limited evidence exists regarding their knowledge and skills in performing this role effectively.

Aim: This study aimed to explore emergency nurses' perceptions of their role in disaster management across selected hospitals in the eastern region of Saudi Arabia.

Methods: A descriptive cross-sectional design was used, involving a convenience sample of 150 emergency nurses from seven private hospitals in the region. Data collection was conducted over one month (1–31 October 2025) using a validated short-form electronic questionnaire adopted from a previous study and analyzed using SPSS version 30.

Results: The primary roles identified during disaster management included patient assessment and care, triage, leadership, resuscitation, and psychological support. Nurses demonstrated a high perception of their essential role in disaster response, with confidence and adequate knowledge. Married nurses reported significantly higher disaster role perception scores than single nurses ($p < 0.01$).

Conclusions: Emergency nurses are fundamental to disaster response efforts and possess satisfactory knowledge of their roles in management in the eastern region of Saudi Arabia. Continuous education and targeted training programs are recommended to enhance preparedness and strengthen the effectiveness of emergency nursing practice in disaster situations.

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Keywords: Emergency Nurses; Nurses' Perception; Disaster Preparedness; Saudi Arabia.

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1. INTRODUCTION

Emergencies are situations in which normal regulatory requirements cannot be temporarily met, and immediate action is required due to a potential threat to public health (Sunshine et al., 2019). These emergencies usually result due to disasters, like natural disasters (Tornadoes and severe storms, hurricanes and tropical storms, floods, wildfires, earthquakes, and drought), Human-Caused Disasters, such as incidents of mass violence, wars, and nuclear missiles, or other incidents of mass trauma such as infectious disease outbreaks like COVID-19 outbreak (Jacobs - Wingo et al., 2019; Shi, 2019). The World Health Organization (WHO) defined a disaster as a sudden ecological event of such severity that it overwhelms local capacity and necessitates assistance from external sources (Makwana, 2019).

In the emergency department, nurses may confront a wide range of disasters, including natural events (such as floods, sandstorms, heat waves, and earthquakes), technological/ industrial incidents (chemical spills, explosions, fires, radiation leaks), and human-made crises (mass-casualty traffic accidents, building collapses, acts of violence, and terrorism) (Elkhouly et al., 2024). The healthcare environment nowadays is highly complex, and the nature of emergency nursing practice necessitates adequate orientation and practice in dealing with a wide array of patient conditions, supplies, equipment, procedures, policies, and processes (Rowe & Knox, 2023). Nurses working in emergencies should be able to quickly assess and analyze the patient's problems systematically and professionally and develop solutions that prioritize urgent intervention. Emergencies require advanced, specialized knowledge to be managed effectively, including proficiency with critical equipment and disaster supplies (Zhang et al., 2024). In disaster situations, nurses must be able to use and coordinate key resources such as airway and breathing equipment (oxygen delivery systems, bag–valve masks, suction devices), monitoring devices (cardiac monitors, pulse oximeters, blood pressure equipment), resuscitation and trauma supplies (defibrillators, IV access and fluids, dressings, splints), medications (emergency drugs, analgesics, sedatives), and personal protective equipment and isolation materials (Ghimire & Ghimire, 2025). Access to adequate logistical supplies, communication tools, and basic life-support materials is also essential to support safe, timely, and effective nursing interventions during disasters (Bekman & Benbenishty, 2025).

Nurses comprise the largest share of the healthcare workforce and would likely be the recipients of an emergency patient (Hassmiller & Wakefield, 2022). In such situations, the nurse's main role is to ensure rapid, safe, and coordinated care: performing triage and initial assessment, stabilizing and resuscitating critically ill or injured patients, administering medications and treatments, monitoring vital signs, and continuously reassessing priorities as new casualties arrive. Emergency nurses also play key roles in implementing the hospital disaster plan, communicating with the multidisciplinary team and families, maintaining infection-prevention and safety measures, and providing psychological support to patients, relatives, and colleagues throughout and after the event (Noh & Bae, 2025).

Education curriculum should play a central role in developing core actions to improve interventions in emergencies, including training nurses and health workers for emergencies, improving emergency response in health facilities, and maintaining inventories for medical equipment and supplies for emergency interventions, mass casualties, and disaster management (Alrabie et al., 2025; Hamdi & Al Thobaity, 2023; Lin et al., 2024). However, schools of nursing offer little information on disaster response, and there is no standardized, evidence-based, multidisciplinary training for emergency response (AlOtaibi et al., 2024; White et al., 2025). Research has assessed the development of nursing competencies in students before and after internship programs (Hindriyastuti et al., 2019), and other studies have examined the level of competence demonstrated by nursing professionals in emergencies (Manero-Solanas et al., 2024). Across this literature, several factors consistently influence nurses' disaster-related roles, competencies, and knowledge, including the amount and quality of formal disaster education, participation in drills and simulations, prior experience with real disaster events, organizational support and clear role descriptions, availability of resources and equipment, and individual characteristics such as years of experience, specialty training, and self-efficacy. These factors collectively shape how confidently and effectively nurses perform their roles during disasters (da Conceição Gatinho Pires et al., 2026; Feng et al., 2025).

Saudi hospitals lack structured transition programs to develop these competencies in newly graduated nurses. Consequently, limited practical disaster training during undergraduate education means many graduates are not fully prepared to respond effectively to emergencies and disasters. In the absence of targeted emergency response interventions in clinical practice, nurses may experience role confusion and default to traditional bedside care during catastrophic events, rather than undertaking specialized responsibilities such as promoting recovery and critically evaluating the situation (Alzahrani & Kyratsis, 2017).

This research aimed explore emergency nurses' perceptions of their role in disaster management across selected hospitals in the eastern region of Saudi Arabia.

1.1 Theoretical framework

The theoretical framework for this study integrates a social–behavioral perspective with a mid-range nursing theory. Disaster readiness perceptions are conceptualized as nurses' cognitive appraisal of their own competencies—knowledge, expertise, and clinical judgment—in relation to the demands of emergency and disaster settings. Within this view, readiness reflects not only what nurses know, but also how confident they feel in mobilizing that knowledge under time pressure and uncertainty.

First, the theory of human behavior in the social environment (Sharma & Gupta, 2026) provides a broad lens to understand how both individual attributes and contextual factors shape nurses' disaster-related behaviors and perceptions. In emergency departments, nurses' responses are embedded in social norms, team dynamics, institutional policies, and the wider sociocultural and organizational environment, including the specific disaster risks and mass gathering context in Saudi Arabia. This theory supports examining individual variables (e.g., training, experience, prior disaster exposure) alongside contextual influences when exploring predictors of perceived readiness.

Second, the mid-range nursing theory of wisdom-in-action (Glück & Brienza, 2025; Matney et al., 2020) is adopted as the primary guiding framework. Wisdom-in-action describes how nurses integrate knowledge, experiential learning, and clinical judgment to make timely, appropriate decisions in complex and uncertain situations. In disasters and other high-acuity emergencies, there is limited time for extensive assessment; nurses must rapidly interpret clinical cues, rely on established cognitive schemas, and implement interventions with precision and confidence. From this perspective, disaster readiness perceptions represent nurses' self-evaluation of their capacity to enact wisdom-in-action when confronted with unpredictable, high-pressure events.

In line with these frameworks, the study focuses on disaster-related competencies—such as prior disaster education, clinical experience, perceived knowledge, and confidence—as key predictors of perceived disaster readiness among emergency department nurses. The social–behavioral perspective emphasizes attention to the contextual characteristics of the Eastern Region of Saudi Arabia (e.g., mass gatherings, organizational preparedness). At the same time, wisdom-in-action highlights the central role of knowledge integration and decision-making under uncertainty. Together, these theories provide a coherent basis for selecting study variables and interpreting how individual and contextual factors shape nurses' perceptions of disaster readiness.

1.2 Significance of the study

Despite the central role of frontline nurses in hospital emergency departments (EDs) during disaster response, studies found that nurses still have limited knowledge of the skills and expertise required to perform emergency clinical roles effectively in disaster management (Murphy et al., 2021). Little is known about their perception and understanding of their role during disaster management to perform this important clinical role effectively. In particular, there is a paucity of Saudi studies that directly measure emergency nursesâ•Ž disaster preparedness (AlDulijand et al., 2023; Alzahrani & Kyratsis, 2017; Banaser et al., 2020), especially in the eastern region of Saudi Arabia. The Eastern Region of Saudi Arabia represents a critical setting for advancing emergency care research due to its unique demographic and geographical characteristics. This region is expected to host a substantial number of visitors during the FIFA World Cup 2034, significantly increasing population density and placing considerable demands on emergency healthcare services. In addition, the region is known for its diverse recreational activities and large-scale events, which regularly attract both domestic and international visitors to relatively confined areas. Such conditions heighten the risk of mass gatherings, injuries, and public health emergencies, thereby underscoring the urgent need for context-specific research to enhance preparedness, optimize emergency response systems, and ensure the safety and well-being of both residents and visitors. Therefore, the current study was imperative to assess nurses' perceptions of their roles during disaster management, especially given the dramatic circumstances in countries surrounding Saudi Arabia, which certainly increase the likelihood of future disasters requiring emergency management, God forbid.

1.3 Aim of the study

This study aimed to explore emergency nurses' perceptions of their role in disaster management across selected hospitals in the eastern region of Saudi Arabia.

Thus, the following are the objectives of this research:

1. To assess the sociodemographic characteristics of the participant emergency nurses.
2. To explore nurses' perception of their roles during disaster management at the Emergency Departments of Eastern Region Hospitals.
3. To identify the predictors of nurses' perception of their role during disaster management based on various sociodemographic characteristics.

1.4 Research question:

What are nurses' perceptions of their roles in disaster management within the emergency departments of hospitals in the Eastern Region of Saudi Arabia?

Which sociodemographic factors predict nurses' perceptions of their roles in disaster management?

2. METHODOLOGY

- **Research design:** A descriptive, cross-sectional design was used for the current study.
- **Research Setting:** The emergency departments of selected private hospitals in the eastern region served as the setting for the current study, including Almana General Hospitals (AGH Dammam, AGH Aziziah, AGH Dammam, AGH Khobar, AGH Jubail, and AGH Hofuf) and Dar Afia Hospital. In addition to the convenience for the researcher, the hospitals were chosen for their large emergency departments, large staff, modern facilities, and staff cooperation.

2.1 Sample selection

A non-probability convenience sampling approach was used in this study. All accessible nurses with more than 6 months of experience in the emergency departments of the selected hospitals, regardless of nationality or gender, were invited to participate and constituted the study sample. The estimated total number of nurses working in the emergency departments of the seven hospitals was 200, of whom 182 met the eligibility criteria. The sample size was calculated using OpenEpi (Version 3) for a finite population of 200 nurses, assuming a 50% expected proportion, a 95% confidence level, 5% precision, and a design effect of 1, yielding a minimum required sample of 132 nurses. Multiple reminders and support from nurse managers were used to enhance participation and reduce non-response bias. Ultimately, 150 nurses completed the survey, yielding a response rate of 82.4%, exceeding the minimum required sample size and adequate to achieve the targeted statistical power.

2.2 Instruments

The study used a short-form, self-administered questionnaire adopted from a previous study conducted in Makkah, Saudi Arabia (Alzahrani & Kyratsis, 2017). The tool consisted of two parts: the first covered sociodemographic variables, and the second assessed nurses' perceptions of the emergency nurse's role in disaster management using 12 statements rated on a five-point Likert scale (from strongly agree to strongly disagree).

The original English questionnaire was used without modification. It was piloted with 20 emergency nurses from the same setting before large-scale distribution to ensure clarity of language and the absence of errors. As no substantial modifications were required, the pilot data were included in the final analysis. The tool had previously demonstrated validity and internal consistency in a Saudi Arabian study (Alzahrani & Kyratsis, 2017). In the current study, test–retest reliability was assessed using the pilot sample, and the questionnaire showed acceptable reliability (Cronbach's alpha = 0.87).

2.3 Data Collection Procedure

Data collection was conducted by distributing an electronic Microsoft Forms questionnaire to a convenience sample of nurses over one month (1–31 October 2025) via email, WhatsApp, and other online platforms. Data collection commenced after obtaining ethical approval to conduct the study. The questionnaire began with a cover letter that introduced the researcher, outlined the aim of the study, described the procedures, potential benefits, and possible inconveniences associated with participation, and clearly explained that participation was voluntary, anonymous, and confidential. The cover letter also emphasized participants' autonomy, including their right to decline without any consequences.

Before accessing the main questionnaire, participants were explicitly asked whether they were willing to take part in the study. They were required to indicate their agreement electronically before proceeding, and this was considered informed consent. Registration using the participant's email address was required within Microsoft Forms solely to prevent duplicate responses; however, email addresses were not stored or linked to the dataset, and no personally identifying information was collected, thereby ensuring that all responses remained fully anonymous.

2.4 Ethical issues

Before conducting this research, approval was secured from the Institutional Review Board (IRB) of Mohammed Al-Mana College for Medical Sciences (IRB No. SR/RP/103) and Dar Afia Hospital (ethics approval No. DA-077/022/140) on May 12, 2025. In dealing with respondents, informed consent was obtained after the purpose and scope of the study were extensively explained on the survey cover page. Participants' acceptance without coercion to participate in the current study and to fill out the electronic questionnaire was considered informed consent. All respondents participated voluntarily in the study without coercion and were free to withdraw without any consequences. Respondents were not exposed to any harmful procedures or deceptions. Study participants were sufficiently protected from misuse of their data by the use of anonymous questionnaires.

2.5 Data analysis

Retrieved data from Microsoft Forms were then revised, coded, and analyzed using the Statistical Package for Social Sciences (SPSS), version 30 (IBM Corp, 2024). Data were presented using descriptive statistics, such as the mean and standard deviation, or number and percentage. The mean and standard deviation were used for continuous variables, whereas numbers and percentages were used for categorical variables. Additionally, regression analysis was conducted to identify significant independent predictors of the nurses' perception of the disaster management role, and P values were considered significant at 0.05 or lower.

3. RESULTS

Table 1 presents the sociodemographic characteristics of the 150 participating emergency nurses. The majority of participants were aged between 25 and <30 years (34.0%), followed by those aged 30 to <35 years (27.3%). Most respondents were Saudi nationals (72.7%) and females (61.3%). Regarding marital status, more than half were married (65.3%).

In terms of job title, nurse specialists accounted for the largest proportion (61.3%), followed by nursing technicians (15.3%), in-charge nurses (9.3%), head nurses (6.7%), and nursing supervisors (7.3%). The majority of participants had 5-9 years of experience (42.0%), followed by those with 6 months to <5 years (28.7%). Regarding educational attainment, most held a Bachelor of Nursing degree (67.3%), with fewer holding a nursing diploma (24.7%) or a postgraduate qualification (8.0%).

Table 1: Sociodemographic characteristics of the participants (N=150)

Sociodemographic data		n (%)
Age	<25 years	9 (6.1%)
	25 to <30 years	51 (34.0%)
	30 to <35 years	41 (27.3%)
	35 to <40 years	28 (18.7%)
	40 to <45 years	14 (9.3%)
	45 years or more	7 (4.6%)
	Total	150 (100.0%)
Nationality	Saudi	109 (72.7%)
	Non-Saudi	41 (27.3%)
	Total	150 (100.0%)
Gender	Male	58 (38.7%)
	Female	92 (61.3%)
	Total	150 (100.0%)
Marital status	Single	52 (34.7%)
	Married	98 (65.3%)
	Total	150 (100.0%)
Job title	Nursing Technician	23 (15.3%)
	Nurse Specialist	92 (61.3%)
	In-charge nurse	14 (9.3%)
	Head Nurse/Assistant	10 (6.7%)
	Nursing supervisor	11 (7.3%)
	Total	150 (100.0%)
Years of experience	6 months - < 5 years	43 (28.7%)
	5-9 years	63 (42.0%)
	10-14 years	35 (23.3%)
	15-19 years	5 (3.3%)
	20 years or more	4 (2.7%)
	Total	150 (100.0%)
Educational level	Nursing Diploma	37 (24.7%)
	Bachelor of Nursing	101 (67.3%)
	Postgraduate education	12 (8.0%)
	Total	150 (100.0%)

Figure 1 showed that most participants reported that their likely role in disaster management would be general patient assessment and care (41.3%), followed by triage (21.3%) and leadership (20.7%). Resuscitation was selected by 14.0% of respondents, while only a small proportion indicated psychological care as their likely role (2.7%). Each participant selected a single role, and the categories were mutually exclusive.

Figure 1: participants' most likely role in disaster management (N=150)

Table 2 showed that nurses generally held positive perceptions of emergency nurses' roles in disaster management, with the highest agreement for being key players in disasters (mean 3.75 ± 1.29) and for being confident and knowledgeable in responding effectively (3.60 ± 1.37). Moderate agreement was reported for roles related to general assessment and caring, timely response, communication, triage, resuscitation, surveillance, prevention, leadership, and psychological care, with mean scores ranging approximately from 3.05 to 3.40. Overall, 51.2% of respondents (agree and strongly agree) expressed favorable perceptions across items, with an overall mean perception score of 3.29 ± 1.26, indicating a generally positive but not strongly unequivocal perception of emergency nurses' disaster roles.

Table 2: Perception of the roles of Emergency nurses during disaster management

Items	Strongly disagree	Disagree	Neither	Agree	Strongly agree	Mean ± SD
	n (%)	n (%)	n (%)	n (%)	n (%)	
1. Emergency nurses are confident and knowledgeable in effectively responding to a disaster.	16 (10.7%)	24 (16.0%)	14 (9.3%)	46 (30.7%)	50 (33.3%)	3.60 ± 1.37
2. Emergency nurses are key players in a disaster.	13 (8.7%)	16 (10.7%)	21 (14.0%)	46 (30.7%)	54 (36.0%)	3.75 ± 1.29
3. The main role of emergency nurses during disasters is to provide general assessment and care for patients.	14 (9.3%)	30 (20.0%)	20 (13.3%)	54 (36.0%)	32 (21.3%)	3.40 ± 1.28
4. Emergency nurses are able to provide timely responses to emergency situations.	14 (9.3%)	23 (15.3%)	34 (22.7%)	51 (34.0%)	28 (18.7%)	3.37 ± 1.22
5. The main role of emergency nurses during disasters is to provide resuscitation.	15 (10.0%)	39 (26.0%)	25 (16.7%)	51 (34.0%)	20 (13.3%)	3.15 ± 1.23

Items	Strongly disagree	Disagree	Neither	Agree	Strongly agree	Mean ± SD
	n (%)	n (%)	n (%)	n (%)	n (%)	
6. The main role of emergency nurses during disasters is to provide triage and initial consultation.	21 (14.0%)	24 (16.0%)	35 (23.3%)	49 (32.7%)	21 (14.0%)	3.17 ± 1.26
7. During disasters, emergency nurses are responsible for providing direct clinical care and treatment to affected patients.	15 (10.0%)	44 (29.3%)	26 (17.3%)	48 (32.0%)	17 (11.3%)	3.05 ± 1.21
8. Emergency nurses can effectively communicate with patients, families and other clinicians to provide therapies during emergency situations.	11 (7.3%)	33 (22.0%)	25 (16.7%)	50 (33.3%)	31 (20.7%)	3.38 ± 1.24
9. During disasters, emergency nurses are responsible for surveillance.	16 (10.7%)	30 (20.0%)	37 (24.7%)	49 (32.7%)	18 (12.0%)	3.15 ± 1.19
10. During disasters, emergency nurses are responsible for prevention.	19 (12.7%)	37 (24.7%)	27 (18.0%)	44 (29.3%)	23 (15.3%)	3.10 ± 1.29
11. The main role of emergency nurses during disasters is to act as team leaders.	13 (8.7%)	39 (26.0%)	26 (17.3%)	49 (32.7%)	23 (15.3%)	3.20 ± 1.23
12. The main role of emergency nurses during disasters is to provide psychological care.	22 (14.7%)	29 (19.3%)	32 (21.3%)	41 (27.3%)	26 (17.3%)	3.13 ± 1.32
Overall perception score (mean of items)						3.29 ± 1.26

Figure 2 revealed that nurses generally had a positive perception of all listed emergency roles during disaster management, with mean scores clustered in the mid to upper range of the scale.

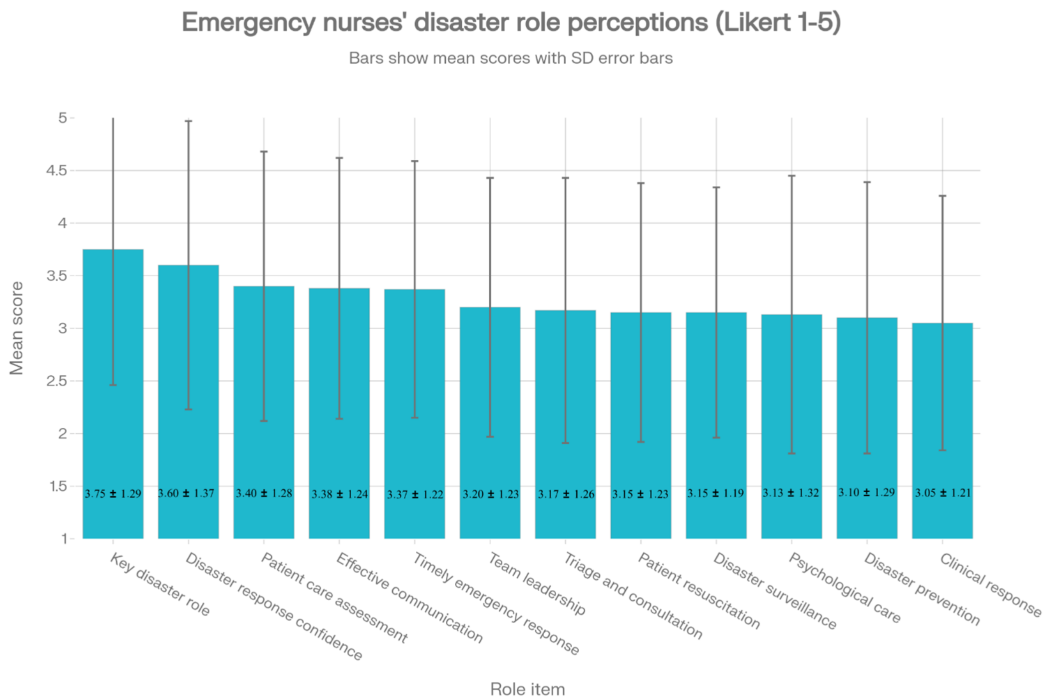

Figure 2. Perception of the roles of Emergency nurses during disaster management

Table 3 shows that, among the examined variables, only marital status significantly predicted nurses' perception of disaster management (B = 0.512, p = 0.008, CI = 95%), with married nurses reporting higher perception scores than single nurses (3.50 ± 0.95 vs. 2.88 ± 1.01). The regression coefficients for age, nationality, gender, job title, years of experience, and educational level were not statistically significant, indicating that these factors did not meaningfully influence perception scores in this model.

Table 3. Multiple linear regression for the predictors of nurses' perception of disaster management

ANOVA Model		**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**	
1	Regression	17.277	7	2.468	2.581	.016b	
	Residual	135.781	142	0.956			
	Total	153.058	149				
Multiple Linear Regression Model		Mean ± SD B	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
			Std. Error	Beta			
(Constant)			1.764	0.489		3.608	0
Age	<25 years	2.78 ±1.07	0.02	0.080	0.026	0.254	0.800
	25 to <30 years	3.16 ±1.02					
	30 to <35 years	3.40 ±1.02					
	35 to <40 years	3.39 ±1.06					
	40 to <45 years	3.50 ±0.69					
	45 and more	3.10 ±1.33					
Nationality	Saudi	3.16 ±1.03	0.326	0.230	0.144	1.416	0.159
	Non-Saudi	3.62 ±0.90					
Gender	Male	3.17 ±1.08	-0.044	0.208	-0.021	-0.213	0.831
	Female	3.36 ±0.97					
Marital status	Single	2.88 ±1.01	0.512	0.190	0.241	2.699	0.008*
	Married	3.50 ±0.95					
Job title	Nursing Technician	3.01 ±0.78	0.068	0.086	0.070	0.796	0.427
	Nurse Specialist	3.38 ±1.06					
	In-charge nurse	2.86 ±0.97					
	Head nurse	3.17 ±1.05					
	Nursing supervisor	3.76 ±0.88					
years of experience	6 months - less than 5 years	3.11 ±1.03	-0.007	0.106	-0.006	-0.063	0.950
	5-9 years	3.54 ±1.05					
	10-14 years	3.03 ±0.89					
	15-19 years	2.93 ±0.40					
	20 years or more	4.00 ±1.02					
Educational level	Nursing Diploma	3.08 ±0.98	0.070	0.185	0.038	0.379	0.705
	Bachelor of Nursing	3.31 ±1.04					
	Postgraduate education	3.73 ±0.75					

- Dependent Variable: Mean of Total Scores
- Predictors: (Constant), Educational level, Age, Gender, Job title, Marital status, years of experience, Nationality
- Significant at < 0.05

Marital status was the only sociodemographic variable that significantly predicted nurses' perception scores ($p < 0.05$); all other predictors in the model were not statistically significant.

4. DISCUSSION

The importance of this study lies in its focus on exploring emergency nurses' perceptions of their roles in disaster management and identifying the key predictors of these perceptions in Saudi Arabia.

Perceived Roles of Emergency Nurses in Disaster Management

The majority of nurses reported assuming general patient assessment and care, followed by triage, leadership roles, and resuscitation; the least-reported emergency nurse role was psychological care for disaster victims.

A similar study was conducted to assess emergency nurses' disaster preparedness during mass gatherings at Mecca hospitals, based on their perceptions. The study similarly showed that emergency nurses perceived their dominant role as providing general assessment and patient care (38%), followed by triage (26%) and resuscitation (21%). In contrast, the respondents gave lower priority to their leadership role during disaster management (Alzahrani & Kyratsis, 2017). Most respondents agreed that nurses are responsible for frontline triage, patient communication, administering first aid, and conducting assessments, with over half supporting each role (Olofinbiyi et al., 2020).

Nurses in the emergency and intensive care units of the provincial hospital in Indonesia demonstrated a generally good understanding of disaster emergency preparedness information, particularly in triage and basic first aid, detection of biological agents, and communication and connectivity, but showed comparatively lower understanding in epidemiology and clinical decision making, indicating specific knowledge gaps that need to be addressed to optimize disaster response (Husna et al., 2022).

A study in Palestine found that emergency nurses in the Gaza Strip had a high role perception during disasters (81.5%) and strong disaster management knowledge (78%), reflecting confidence, participation in emergency plans, and updated experience (Saidam & Eljedi, 2020). On the contrary, a systematic review analyzed 62 studies across five major databases to assess critical care nurses' preparedness for disasters and found that nurses are generally underprepared for disastrous situations. These apparently conflicting findings may be partly explained by methodological and contextual differences. The Palestinian study was a single-country, cross-sectional survey focusing on self-reported role perceptions and knowledge among emergency nurses working in a setting of recurrent armed conflict and mass-casualty events, which may heighten perceived readiness through repeated exposure and frequent involvement in disaster response. By contrast, the systematic review pooled studies from diverse countries, healthcare systems, and clinical settings, many of which experience less frequent large-scale disasters, variable access to formal disaster training, and differing preparedness standards, which can lower average preparedness scores when combined. Our findings align more closely with the broader systematic evidence of under-preparedness, yet the Palestinian study highlights how repeated disaster exposure and strong role identity can lead to higher perceived readiness, underscoring the importance of considering both objective preparedness and contextual factors when interpreting nurses' disaster-related competencies.

Four main themes of disaster competence emerged: clinical critical care skills, operational readiness and coordination, public responsibility in disaster preparedness, and personal or intrinsic capacities for effective disaster response (van Esch et al., 2026).

There is potential to improve disaster readiness, national surge capacity, and community resilience, according to a United States study on the role of nurses as leaders in disaster planning and response. Nurses make up most of the healthcare workforce. The group of national institutions created a vision for the future of professional disaster nursing while also identifying potential and current impediments. The page summarizes a wide range of recommendations for nursing practice, education, legislation, and research, as well as implementation difficulties (King, 2022).

The literature agrees that nurses play a vital role in disaster response. Still, some studies, such as Köhler et al. (2026), highlight the lack of a clear mandate defining their specific responsibilities. The literature on nurses' roles in disaster management highlights three interrelated domains: their roles during emergency response, their knowledge and preparedness, and their lived experiences during disasters. Roles during response encompass hospital and public expectations, general and specialized nursing functions, assigned medical tasks (including during pandemics), role conflict, and willingness to respond. Knowledge-related themes include understanding what constitutes a catastrophe, core disaster competencies, the adequacy of undergraduate and continuing education, and participation in drills and training. Experiences during disasters involve the work environment, the nature of care provided, emotional responses, stressors, willingness to assist, lessons learned, and overall impact. Consistent with these themes, recent qualitative work with first-responder nurses in the Turkish earthquakes shows that nurses face major practical and psychosocial challenges, such as ineffective crisis management, poor communication, resource shortages, and emotional burden, alongside positive experiences like professional satisfaction and team support, underscoring the need to strengthen disaster preparedness and management strategies to support nurses' roles (Açık & Yeşilyurt Sevim, 2025).

Another review of the literature found that continuing education programs and undergraduate nursing courses should consider whether theoretical and practical training in disaster nursing competence is appropriate (Hung et al., 2021). The literature also highlighted concerns about the preparedness of emergency department nurses for disaster response and their capacity to transition to working in a disaster situation, and that disaster training and education improve nurses' knowledge, readiness, and skills (Özden, 2026).

The current study demonstrated the significance of the nursing role in disaster management, indicating that patient assessment and care were the most important and commonly adopted roles among nurses. However, the emergency nurse role has taken precedence, followed by the leadership role, which focuses on directing the responding team and managing efforts, key to disaster management success. According to the participants, the fourth most important job in disaster management was nurses' resuscitation, while the least important was the psychological care and support of victims.

In the current survey, almost one-third of the nurses strongly agreed that emergency nurses are crucial players in disaster management, the highest level of belief among participating nurses. Following that was the idea that emergency nurses are confident and knowledgeable in responding to crises, and that their primary duty during disasters is to provide general patient assessment and care. The highest mean scores were observed for 'Key disaster role' (3.75 ± 1.29) and 'Disaster response confidence' (3.60 ± 1.37), indicating that nurses generally perceive themselves as central actors in disaster management and feel reasonably confident in their ability to respond effectively. In contrast, comparatively lower mean scores were found for 'Clinical response' (3.05 ± 1.21), Disaster prevention' (3.10 ± 1.29), and 'Psychological care' (3.13 ± 1.32), suggesting areas where nurses may feel less confident or view their role as less prominent. These findings highlight the need to strengthen nurses' competencies and engagement in preventive activities, hands-on clinical disaster response, and provision of psychological support to disaster victims.

In general, slightly more than half of the participants in the current study agreed or strongly agreed with the 12 statements describing the main roles of emergency nurses in disaster management. At the same time, roughly one-third disagreed or strongly disagreed. Overall, nurses in the eastern region of Saudi Arabia had a good general understanding of emergency nurses' roles in disaster management.

According to Alzahrani and Kyratsis (2017), most emergency nurses in Mecca's public hospitals appeared confident and knowledgeable about their roles in responding effectively to disasters and mass gatherings. They saw their main role as providing general assessment and care, with a timely response, including resuscitation, triage, and initial consultation. They reported high levels of proper communication with others during emergencies.

Another Saudi study found that during Hajj and Umrah seasons, the key aspects required to be implemented with proficiency by emergency nurses during disaster management included risk assessment, public health surveillance, regulations, legislation, and policy; emergency planning and response; environmental health; public health awareness; strengthening communication; and internal organization (Ridda et al., 2021).

4.1 Gaps in Preparedness, Prevention, and Psychological Care

In the present study, participants showed the least agreement on emergency nurses' roles in disaster prevention, clinical response, and psychological treatment, suggesting uncertainty about the scope and priority of these tasks within their practice. This ambiguity may reflect gaps in formal disaster training and limited emphasis on prevention and psychosocial care in existing curricula and in-service programs, which traditionally prioritize immediate life-saving interventions and logistical coordination. A recent scoping review of 13 studies showed that, despite Saudi Arabia's high disaster risk, nurses' training and preparedness remain suboptimal and uneven, underscoring the need for more robust, standardized disaster education and capacity-building. It concludes that future research should prioritize experimental and interventional studies to test which educational and training strategies most effectively improve nurses' disaster readiness (Alsolmi, 2024).

From a practice perspective, this finding is concerning, as international frameworks for disaster nursing highlight nurses' roles across the full disaster cycle, including risk reduction, evidence-based clinical management, and provision of psychological support to victims and families. Limited clarity or perceived lower priority for these domains among emergency nurses in the Eastern Region of Saudi Arabia may translate into suboptimal implementation of prevention strategies and psychosocial interventions during real events. Therefore, targeted educational initiatives and institutional protocols are needed to explicitly define and reinforce nurses' responsibilities in prevention, clinical response, and mental health support as integral components of disaster readiness.

Compared to studies conducted in Saudi Arabia, fewer emergency nurses saw their role in a mass-gathering disaster as providing surveillance, prevention, leadership, or psychological care, despite all of these roles being labeled in the hospital's emergency plans for disaster response (Almutairi & Alodhialah, 2024; Alzahrani & Kyratsis, 2017). Emergency nurses' roles in disasters include competencies in communication, preparation and planning, incident management, safety and security, and intervention, as identified through a review of 15 articles from 2006 to 2022 (Motsepe & Schmollgruber, 2025). Furthermore, an Iranian study found that overall disaster preparedness knowledge among hospital and pre-hospital emergency nurses was low, but nurses with higher disaster preparedness knowledge demonstrated better triage decision-making skills (Azizpour et al., 2022).

4.2 Predictors of Disaster Readiness

In the current study, only marital status significantly predicted nurses' perception of disaster management ($B = 0.512$, $p = 0.008$), with married nurses scoring higher than single nurses (3.50 ± 0.95 vs. 2.88 ± 1.01). This difference may reflect greater life experience, family responsibilities, and perceived obligations to protect and support others, which could heighten married nurses' sense of responsibility and engagement in disaster situations. It is also possible that married nurses, who are often older and more established in their careers, have greater exposure to disaster-related training or real-life events, which may enhance their perceived roles and confidence in disaster management. These hypotheses warrant further investigation in future studies using designs that can more directly explore the social and psychological mechanisms underlying this association.

That was supported by a previous study that found that marital status significantly predicted nurses' perceptions of disaster management, with married nurses scoring significantly higher than single nurses among 211 nurses (Erkin et al., 2023). On the contrary, a study found no statistically significant differences in nurses' attitudes and familiarity with disaster preparedness by marital status, contradicting the claim that marital status significantly predicts nurses' perceptions of disaster management. The study involved 88 nurses and used a quasi-experimental design with pre-and post-tests (AlOtaibi et al., 2024). Disaster preparedness knowledge was significantly predicted by triage decision-making ability, age, place of residence, previous disaster preparedness training, having worked during a disaster, and the type of organization providing training. These results indicate that both individual characteristics and training-related factors influence nurses' disaster preparedness, and the authors recommend that educational and healthcare managers tailor disaster training programs to nurses' demographic and experiential profiles to enhance their preparedness (Azizpour et al., 2022).

5. Conclusions

The study concluded that the emergency nurses' usual and most frequently adopted roles during disaster management at eastern region hospitals were general patient assessment and care, followed by triage, leadership roles, resuscitation, and, finally, psychological care and support for disaster victims.

Measuring emergency nurses' knowledge of their roles in disaster management is regarded as one of the most significant concepts and standards for effective disaster management, as nursing is the largest and most extensive health sector. They stand on the front lines to deal with emergencies and disasters. Overall, nurses had sufficient awareness of emergency nurses' functions and roles in disaster management and a positive perception of their essential roles.

6. Implications for practice

The limited agreement on emergency nurses' roles in disaster prevention, clinical response, and psychological care may hinder timely, coordinated, and holistic care during actual disasters, particularly in providing psychosocial support to patients and families.

In clinical practice, institutions should explicitly delineate nurses' roles across all phases of disaster management and integrate these expectations into local protocols, disaster plans, and regular drills. Simulation-based training and interprofessional exercises should specifically emphasize prevention activities, evidence-based clinical management, and psychological support as core nursing functions—not optional tasks.

For education, the results highlight the need to strengthen and standardize disaster nursing content in undergraduate curricula and continuing professional development programs. Structured, competency-based education on disaster preparedness, including psychosocial care, would help align nurses' perceived roles with international best practices.

At the policy level, the findings support the development of national or regional standards for disaster nursing competencies tailored to the Saudi context, including those related to mass gatherings. Such standards can guide curriculum design, institutional training priorities, and accreditation requirements, ensuring that disaster readiness becomes an integral and measurable component of emergency nursing practice.

7. Recommendations

The study recommends replicating this research using a mixed-methods design and more in-depth longitudinal data collection, with a larger sample of emergency nurses from both public and private hospitals across different regions of Saudi Arabia, to enhance the generalizability of the results. The findings can inform the development of targeted educational and training programs that emphasize nurses' specific roles in disaster response. It is further recommended that standardized disaster nursing curricula be developed and integrated across nursing schools in Saudi Arabia to ensure consistent knowledge and competencies among future nurses. In addition, healthcare institutions should implement regular disaster drills and workshops to strengthen nurses' practical competencies and readiness for real disaster situations. Overall, strengthening emergency nursing training and familiarizing nurses with disaster management plans are essential to improving preparedness, optimizing resource utilization, and minimizing the adverse impacts of future disasters.

8. Limitations

This study has several limitations. The use of self-report, Likert-type questionnaire (12 items) may have introduced respondent bias, and the cross-sectional design limits the ability to infer causality. Additionally, the use of a non-probability convenience sample and a relatively small number of participants from a single region in Saudi Arabia restricts the generalizability of the findings. Future research incorporating observational checklists, either alone or alongside questionnaires, is recommended to obtain more objective and reliable assessments of nurses' disaster management competencies and performance.

9. Declarations:

Data Availability Statement: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The author declares no conflict of interest.

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Integrated Analysis of Sustainable Building Efficiency and Implementation Challenges in Modern Urban Projects in Saudi Arabia: A Regional Comparative Perspective

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Abstract
This study presents an integrated analysis of sustainable building efficiency and the implementation challenges faced by modern urban projects in Saudi Arabia, with a regional comparative perspective. The research aims to evaluate the performance of sustainable buildings, identify gaps between design expectations and actual operational outcomes, and extract actionable recommendations to enhance urban sustainability in hot-arid climates. A multi-step methodology was adopted, including a comprehensive literature review, identification of Key Performance Indicators (KPIs), case study analysis of representative Saudi urban projects, stakeholder consultations with architects, developers, and sustainability experts, and a regional comparative analysis with similar projects in neighboring countries. Quantitative and qualitative data were combined to assess energy, water, materials, and operational efficiency, as well as technical, regulatory, and practical challenges affecting sustainable building adoption. The findings reveal significant variations in building performance, with energy efficiency emerging as the most critical factor, followed by water management and materials efficiency. A persistent gap between design and operational performance was observed, primarily due to technical limitations, regulatory constraints, insufficient stakeholder integration, and high initial costs. Regional comparisons highlighted best practices in smart building management, early stakeholder engagement, and effective use of incentives, which could inform improvements in Saudi projects. Based on these results, several recommendations are proposed: strengthen regulatory enforcement and monitoring, enhance technical training and capacity building, promote early and continuous stakeholder integration, adopt digital and smart building solutions, and leverage lessons learned from regional projects. Implementing these strategies can enhance building performance, reduce environmental impacts, and contribute to the achievement of Saudi Vision 2030 goals for sustainable urban development

Keywords: Sustainable Building - Building Efficiency - Implementation Challenges - Urban Projects

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1. INTRODUCTION

The construction industry forms the cornerstone of economic and urban development in the Kingdom of Saudi Arabia, particularly with the accelerated pace of urban transformation and rapid population growth over the past two decades. Sustainable construction has become one of the fundamental pillars for achieving environmental, social, and economic development goals embedded in Saudi Vision 2030, which emphasizes improving energy efficiency and reducing carbon emissions in new urban projects. In this context, the sustainable building market in Saudi Arabia is witnessing significant growth, with market size expected to reach USD 33 billion by 2030, driven by government policies and the shift toward environmentally sustainable construction practices [1].

The concept of sustainable building efficiency refers to the optimal use of energy, water, and materials throughout a building's lifecycle, from design and construction to operation and maintenance, aiming to reduce environmental impacts and enhance users' quality of life. Recently, Saudi regulatory frameworks have adopted sustainability assessment tools that enable developers and engineers to measure the environmental performance of projects at different stages, with a noticeable increase in the number of projects undergoing sustainability evaluations in recent years.

International rating systems, most notably LEED (Leadership in Energy and Environmental Design), play a crucial role in promoting global green building standards. LEED aims to reduce energy consumption and operational costs, improve indoor air quality, and minimize the environmental footprint of buildings. In Saudi Arabia, LEED has been used as a reference framework to evaluate the performance of sustainable buildings, with a marked increase in the number of projects achieving LEED certification in major cities such as Riyadh and Jeddah [2].

Despite significant progress in policies and regulatory frameworks, a gap still exists between theoretical design and actual building performance on the ground. This gap is attributed to several factors, including limited technical expertise among some implementing parties, financial constraints, and gaps in stakeholder engagement, particularly among architects, developers, and sustainability specialists who possess critical insights into building performance during practical implementation. Many researchers note that involving expert stakeholders in the early stages of design and construction can help reduce the gap between expected and actual performance, effectively contributing to the adoption of feasible and sustainable solutions [3].

Furthermore, a regional comparative perspective is a valuable tool for situating Saudi Arabia's performance within a broader context, particularly in the Middle East and North Africa (MENA) region, which shares similar hot-arid climatic conditions. Regional comparisons help identify best practices and lessons learned from projects in neighboring countries, contributing to improved sustainability strategies and overcoming shared challenges in such climates.

With the increasing number of large-scale urban projects that require integration of operational efficiency and environmental considerations, it has become essential to conduct a comprehensive analysis of sustainable building efficiency and to identify the obstacles that hinder the effective implementation of these practices. This study aims to provide an integrated assessment of performance and challenges, along with practical recommendations to enhance sustainability in urban projects in Saudi Arabia, while benefiting from regional expertise and experiences

1.1 Towards Green Urban Development: Efficiency and Implementation Challenges in Saudi Buildings

Green buildings have gained significant attention in Saudi Arabia over the past decade, driven by the Kingdom's commitment to sustainable development and the objectives of **Vision 2030**. These buildings are designed to minimize environmental impacts, optimize energy and water consumption, and provide healthier indoor environments for occupants. Saudi Arabia has witnessed a growing number of LEED-certified projects in major cities such as Riyadh, Jeddah, and Dhahran, ranging from commercial complexes to educational and governmental buildings. Initiatives by organizations like Tarshid, KAFD, and KAUST have set benchmarks for energy efficiency, water conservation, and waste reduction. Green building standards are not only reducing operational costs and carbon footprints but are also promoting awareness among developers, architects, and policymakers about the importance of sustainable urban development. Despite progress, challenges remain in implementing green practices widely, including technical expertise gaps, higher upfront costs, and the need for greater stakeholder engagement. Nonetheless, the Kingdom's green building movement is steadily transforming its urban landscape toward environmentally responsible and resource-efficient development [4], [5].

Economic activities in Saudi Arabia and neighboring countries lead to a wide range of environmental impacts, from deforestation and habitat destruction in mining and extraction sectors to high energy consumption and industrial waste in manufacturing, CO_2 emissions in transportation and construction, and resource depletion throughout the building lifecycle. Waste management and recycling also pose significant challenges, including landfill decomposition, groundwater contamination, and greenhouse gas emissions such as methane. To align with Vision 2030 and regional sustainable development strategies, Saudi Arabia and neighboring countries are promoting environmentally sustainable practices across all sectors. These efforts include regulating natural resource use, expanding reforestation and environmental protection programs, transitioning to green industries, improving energy and water efficiency in buildings and facilities, implementing sustainable building codes, adopting smart maintenance and digital facility management, developing national and regional recycling centers, and investing in waste-to-energy technologies. These measures aim to reduce environmental impact, enhance resource efficiency, and support sustainable development goals at both national and regional levels [6].

1.2 The Role of LEED in Advancing Sustainable Buildings in Saudi Arabia and the Regional Context

LEED (Leadership in Energy and Environmental Design) has played a significant role in advancing sustainable building practices in Saudi Arabia and across the wider regional context, particularly in countries with hot-arid climatic conditions. As an internationally recognized green building rating system, LEED provides a comprehensive framework for improving energy efficiency, water conservation, indoor environmental quality, and sustainable site development. In Saudi Arabia, the adoption of LEED has supported national sustainability goals aligned with Vision 2030 by encouraging developers and policymakers to integrate environmentally responsible practices into urban projects. Regionally, LEED has facilitated knowledge transfer and benchmarking among neighboring countries, enabling the comparison of building performance and the identification of best practices suited to similar climatic and environmental challenges. Despite variations in regulatory frameworks and market readiness across the region, LEED continues to serve as a valuable tool for promoting sustainable construction, enhancing building performance, and supporting the transition toward low-carbon and resource-efficient urban development [7], [8].

2. PURPOSE OF THE STUDY

The purpose of this study is to conduct an integrated assessment of sustainable building efficiency and the key implementation challenges associated with modern urban projects in Saudi Arabia. The study aims to evaluate environmental performance across different stages of the building lifecycle, with particular emphasis on energy efficiency, resource utilization, and compliance with sustainability frameworks such as LEED. In addition, this research seeks to identify technical, regulatory, and stakeholder-related barriers that hinder the effective adoption of sustainable building practices. To place the Saudi experience within a broader context, a regional comparative perspective is adopted, allowing for the identification of best practices and shared challenges among countries with similar climatic and urban conditions. Ultimately, the study aims to provide practical insights and recommendations to support policymakers, developers, and practitioners in advancing sustainable urban development in Saudi Arabia and the wider region

3. RESEARCH STRATEGY

This study adopts a structured research methodology to evaluate sustainable building efficiency and examine implementation challenges in modern urban projects in Saudi Arabia, with a regional comparative perspective. The methodology is organized into four key steps and context as shown in Table 1:

1. **Literature Review and Framework Development**

Relevant literature on sustainable building practices, **LEED standards**, and regional studies are reviewed to define key performance indicators and establish the conceptual framework for analysis.

2. **Case Study Selection and Performance Assessment**

Representative urban projects in Saudi Arabia are selected as case studies. Quantitative analysis is conducted to evaluate energy efficiency, water usage, material consumption, and operational performance across the building life cycle.

3. **Stakeholder Consultation and Implementation Analysis**

Qualitative data are collected through interviews and consultations with architects, developers, and sustainability professionals to identify technical, regulatory, and practical challenges affecting the adoption of sustainable building practices.

4. **Regional Comparative Analysis and Synthesis**

The Saudi case studies are compared with similar projects in the regional context to identify best practices, common challenges, and actionable recommendations for enhancing sustainable urban development.

This methodology integrates both quantitative and qualitative approaches to provide a comprehensive understanding of sustainable building efficiency and implementation challenges, while situating Saudi Arabia's experience within the broader regional

Table 1: Research Methodology Steps for Evaluating Sustainable Building Efficiency and Implementation Challenges

Step	Description	Purpose / Outcome
1. Literature Review & Framework Development	Review of sustainable building literature, LEED standards, and regional studies	Define key performance indicators and establish the conceptual framework
2. Case Study Selection & Performance Assessment	Select representative urban projects in Saudi Arabia and conduct quantitative analysis of energy, water, materials, and operational performance across the building lifecycle	Evaluate sustainable building efficiency in practice
3. Stakeholder Consultation & Implementation Analysis	Collect qualitative data through interviews and consultations with architects, developers, and sustainability experts	Identify technical, regulatory, and practical challenges affecting sustainable building adoption
4. Regional Comparative Analysis & Synthesis	Compare Saudi case studies with similar projects in neighboring countries	Extract best practices, common challenges, and actionable recommendations for sustainable urban development

Step 2: Literature Review and Framework Development

The first step of this study focuses on an in-depth **literature review** and the development of a conceptual framework to guide the research. The purpose of this step is to establish a solid foundation by understanding both theoretical and practical aspects of sustainable building efficiency in Saudi Arabia and the regional context.

Key elements of this step include:

1. Comprehensive Literature Review:

A substantial body of research examines sustainable building practices in hotarid climates, which are directly relevant to the Saudi Arabian context due to its extreme temperatures, high cooling demands, and arid environment. A systematic review of recent literature reveals that passive design strategies, such as strategic landscaping and greenery integration, significantly contribute to improving outdoor and indoor thermal comfort and reducing energy loads in residential complexes within hotarid regions [9].

In Saudi Arabia, several studies focus on optimizing energy efficiency through architectural design adjustments sensitive to climatic challenges. For example, research in Jeddah highlights how building form and urban morphology influence energy consumption and suggests optimizing design parameters to support sustainable energy use in residential buildings, aligning with broader Vision 2030 sustainability goals [10].

International green building standards, particularly LEED (Leadership in Energy and Environmental Design), are widely recognized as benchmarks for sustainable construction. Research shows that Riyadh has experienced a significant increase in LEEDcertified projects over the past decade, indicating growing adoption of green building practices in line with national sustainability objectives. Moreover, literature on green building rating systems in Saudi Arabia identifies principal barriers including lack of awareness, technical expertise deficits, and regulatory constraints that affect LEED implementation, while also proposing strategies to advance green building adoption in both the kingdom and globally [11].

Regional comparative analyses emphasize that climatic conditions in the Middle East, characterized by hot and arid environments, pose unique design and performance challenges requiring contextspecific solutions. Studies note that Saudi Arabia accounts for a significant proportion of LEEDcertified projects in the region, positioning it as a representative case for analyzing green building adoption and barriers in environments similar to the Gulf Cooperation Council (GCC) states.

Finally, advanced research highlights the importance of building performance beyond certification alone, noting that integrating technologies such as Building Information Modeling (BIM) can enhance assessment and implementation of green building criteria under LEED frameworks, though its application in Saudi Arabia remains relatively underexplored [12].

2. Identification of Key Performance Indicators (KPIs):

The second step of the research methodology focuses on identifying measurable indicators that reflect sustainable building efficiency. This ensures that the study can effectively assess the environmental and operational performance of modern urban projects in Saudi Arabia and the regional context.

Key elements of this step include:

1. Determination of Measurable Indicators:

- **Energy Consumption:** Measuring the efficiency of energy use in buildings, including cooling, heating, and lighting systems.

- **Water Usage:** Evaluating water consumption and the effectiveness of reuse and greywater treatment systems.
- **Materials Efficiency:** Studying the use of sustainable materials and minimizing waste during construction and operation.
- **Indoor Air Quality:** Assessing factors affecting environmental comfort and occupant health.
- **Operational Performance:** Evaluating building operation efficiency, including maintenance practices and the use of smart technologies such as Building Management Systems (BMS).

2. Review of Regional Adaptations of Sustainability Standards:

- Analyzing how **LEED** and other green building standards are adapted to hot-arid climatic conditions in Saudi Arabia and neighboring countries.
- Ensuring that the selected KPIs are aligned with regional practices and national regulations, such as the **Saudi Sustainable Building Code**.

Expected Outcome:

This step provides a clear set of KPIs that can be used in quantitative performance analysis of projects. It also ensures the study's relevance to local and regional contexts, allowing for comparative analysis between Saudi buildings and similar projects in neighboring countries. This contributes to identifying best practices and understanding the practical challenges of implementing sustainable building principles

3. Gap Analysis:

Research Gaps to Highlight

Performance Gap Between Design and Reality:

- Many studies focus on designing sustainable buildings according to LEED or other frameworks, but there is a lack of research comparing actual building performance post-occupancy with the expected design performance.
- Example: Actual energy consumption may exceed predictions due to poor implementation or inadequate system maintenance.

Stakeholder Engagement Gap:

- There is limited research on the role of architects, developers, environmental consultants, and LEED assessors during the design and construction stages.
- Weak stakeholder engagement often results in a gap between theoretical design and practical application.

Regional Data Gap:

- There are few comparative studies between Saudi Arabia and neighboring countries with hot-arid climates (e.g., UAE, Qatar, Kuwait).
- A shortage of field data and empirical studies on actual environmental performance exists.

Technology and Infrastructure Gap:

- Limited research on the application of smart technologies such as **Building Information Modeling (BIM)** and Building Management Systems (BMS) in Saudi buildings [6].
- A lack of comprehensive assessment on how these technologies improve environmental performance.

Regulatory and Legal Gap:

- Few studies link legal frameworks, the Saudi Sustainable Building Code, and LEED requirements to practical implementation challenges in projects.

Areas Requiring Further Research

Enhanced Stakeholder Engagement:

- Investigate the impact of involving all stakeholders in early design and construction stages on the effectiveness of sustainability initiatives.

Regional Comparative Analysis:

- Compare Saudi building performance with similar projects in Gulf countries and other hot-arid regions to identify transferable best practices.

Operational and Technological Efficiency:

- Explore the adoption of modern technologies, such as **BIM** and BMS, to improve energy and resource efficiency in sustainable buildings.

Regulatory and Financial Constraints Analysis:

- Study the effect of financial and legal constraints on the implementation of sustainable projects and propose solutions to enhance compliance with environmental standards.

Long-term Sustainability Assessment:

- Investigate the environmental performance of buildings over time, after several years of operation, to evaluate the durability and effectiveness of implemented sustainable practices

4. Conceptual Framework Development:

- Based on the literature and KPIs, develop a framework that will guide subsequent research steps, including case study selection, data collection, performance assessment, and stakeholder analysis.
- Ensure the framework integrates both quantitative (performance metrics) and qualitative (implementation challenges) aspects, providing a structured roadmap for the study [13].

Outcome:

By the end of this step, the research will have a well-defined theoretical foundation, clearly identified performance indicators, and a structured conceptual framework. This ensures that subsequent analyses are grounded in existing knowledge, regionally relevant, and capable of addressing both efficiency and implementation challenges in sustainable urban projects in Saudi Arabia

Step 2: Case Study Selection & Performance Assessment

1. Selection of Representative Urban Projects

To ensure that the study reflects the Saudi and regional context:

- **Selection Criteria:**
  - Modern urban projects (residential, commercial, or mixed-use).
  - Compliance with sustainability standards such as LEED or the Saudi Sustainable Building Code.
  - Projects located in hot-arid climates to allow for regional comparability.
- **Number of Projects:** Typically, 5–10 representative projects are selected to ensure data diversity and cover different building types.
- **Data Collection:** Information on building design, materials used, energy and water consumption, ventilation and cooling systems, and building management features is gathered.

2. Quantitative Performance Assessment

- **Analysis Areas:**

1. Energy Efficiency:

- Measure annual energy consumption for each building (electricity, cooling, heating).
- Compare results with design expectations and LEED or Saudi Sustainable Building Code standards.

2. Water Usage:

- Analyze daily water consumption, reuse, and greywater treatment systems.

3. Materials Efficiency:

- Evaluate the use of sustainable materials and minimize waste during construction and operation.

4. Operational Performance:

- Examine building management systems (BMS), smart maintenance, and operational efficiency of equipment.
- **Measurement Methods:**
  - Use **actual operational data** from selected projects (energy meters, BMS records).
  - Apply **simulation models** (e.g., Energy Plus or Design Builder) to compare expected and actual performance.
  - Collect **monthly and annual statistics** on energy and water consumption to assess building efficiency [14].

3. Expected Outcome:

- Determine the actual sustainable building efficiency compared to theoretical standards.
- Identify gaps between expected and actual performance for each project.
- Provide clear quantitative data to support regional comparative analysis and formulate recommendations for improving sustainable building performance

Step 3: Stakeholder Consultation & Implementation Analysis

1. Purpose:

This step aims to collect qualitative data from key stakeholders to understand the technical, regulatory, and practical challenges affecting the adoption of sustainable building practices in Saudi Arabia and the regional context.

2. Stakeholders to Consult:

- **Architects:** To gain insights into sustainable building design and design constraints.
- **Developers:** To understand financial and economic considerations and challenges in applying sustainability standards.
- **Sustainability Experts / LEED Consultants:** To gather knowledge on standard implementation, performance assessment, and problem-solving.

- **Civil and Energy Engineers:** To analyze technical challenges related to infrastructure, mechanical, and electrical systems.

3. Data Collection Methods:

- **Questionnaires / Surveys:**
  - Distributed surveys with both closed and open-ended questions to evaluate perspectives on building efficiency, obstacles, and best practices.

4. Key Elements / Sample Questions:

A. Technical Challenges:

- What are the main technical difficulties in designing a sustainable building?
- Are there limitations in materials or mechanical/ electrical systems that prevent achieving sustainability standards?

B. Regulatory / Legal Challenges:

- How do local regulations and the Saudi Sustainable Building Code affect your projects?
- Have you faced difficulties obtaining permits or LEED certification?

C. Practical / Implementation Challenges:

- What are the main obstacles during implementation compared to theoretical design?
- Are there skill or training gaps among project teams that affect execution?

D. Opportunities & Best Practices:

- What practices have proven effective in improving sustainable building performance?
- How can stakeholder engagement be enhanced during early design and construction stages?

5. Outcome / Expected Result:

- Identify **technical, regulatory, and practical obstacles** limiting sustainable building implementation.
- Collect **rich qualitative data** to complement quantitative case study analyses.
- Provide **practical insights** to develop actionable recommendations for enhancing sustainable building efficiency and overcoming challenges in Saudi Arabia and neighboring countries

Step 4: Regional Comparative Analysis & Synthesis

1.Purpose:

This step aims to situate the performance of sustainable buildings in Saudi Arabia within a regional context by comparing selected projects with similar initiatives in neighboring countries. The goal is to extract best practices, common challenges, and actionable recommendations to advance sustainable urban development.

2. Selection of Regional Projects:

- Identify comparable urban projects in Gulf and neighboring countries with hot-arid climates (e.g., UAE, Qatar, Kuwait).
- Select projects that have undergone formal sustainability assessments, such as LEED or similar local frameworks, to ensure comparability.
- Focus on projects similar in size, usage type, and applied sustainable technologies.

3. Comparative Analysis Methodology:

1. Quantitative Comparison:

- Compare Key Performance Indicators (KPIs) between Saudi projects and regional projects, including:
  - Energy and water consumption
  - Materials efficiency
  - Operational performance of buildings

2. Qualitative Comparison:

- Analyze common practical, technical, and regulatory challenges across projects.
- Examine how stakeholders address these challenges in different regional contexts.
- Use data from **interviews and surveys** to support qualitative insights.

3. Synthesis of Best Practices:

- Identify practices and technologies proven effective in enhancing sustainability at the project level.
- Extract lessons learned from regional experiences that can be applied to future Saudi projects.

4. Outcome / Expected Result:

- **Identify common gaps and regional challenges:** Understand factors limiting the adoption of sustainable building practices across hot-arid climates.
- **Extract best practices:** Techniques and approaches for improving sustainable building efficiency.
- **Provide actionable recommendations:** Strategies for Saudi urban projects to enhance sustainability and operational performance.
- **Support final analysis:** Offer a robust comparative foundation for policy and strategic recommendations at the local and regional level

4. FINDINGS AND DISCUSSION

This section presents the findings derived from both quantitative and qualitative analyses of sustainable building efficiency in modern urban projects in the Kingdom of Saudi Arabia, while situating these results within the regional context of hot-arid climates. The results are structured based on an integrated methodological framework that includes a comprehensive literature review, evaluation of Key Performance Indicators (KPIs), case study analysis, stakeholder consultations, and regional comparative assessment. The findings reveal noticeable variations in the environmental performance levels of the investigated buildings. Several projects demonstrated significant improvements in energy and water efficiency compared to conventional practices, particularly those that achieved sustainability certifications such as **LEED** or complied with the Saudi Sustainable Building Code. However, the results also indicate a clear gap between the anticipated performance during the design phase and the actual operational performance, which aligns with previous studies highlighting implementation challenges in hot-arid environments. Analysis of the Key Performance Indicators shows that energy efficiency is the most influential factor in achieving building sustainability, especially in relation to cooling and air-conditioning systems, followed by water consumption and materials management. Furthermore, insights from stakeholder consultations reveal that the challenges extend beyond technical issues to include regulatory constraints, high initial costs, limited availability of specialized expertise, and insufficient integration between the design, construction, and operational phases. At the regional level, comparisons with similar projects in neighboring countries reveal substantial similarities in climate-related challenges. Nevertheless, some countries exhibit more advanced practices in implementing smart building management systems, engaging stakeholders during early project stages, and leveraging governmental incentives to support green building initiatives. These regional comparisons have enabled the identification of valuable lessons that can be adapted to enhance sustainable building performance in Saudi Arabia. Overall, this section provides an in-depth analysis of the results by linking actual building performance with implementation challenges within a regional comparative framework. This analysis lays the foundation for proposing practical recommendations aimed at improving sustainable building efficiency and supporting the achievement of **Saudi Vision 2030** objectives related to sustainable urban development [16].

4.1 Sustainability Performance Overview of Saudi Urban Buildings

As show in Table 2, Analysis of the sustainability performance of urban buildings in Saudi Arabia indicates that certified green buildings are achieving measurable improvements in key performance areas. For example, Saudi green buildings on average reduce energy consumption by approximately 25% compared to conventional buildings, reflecting enhanced energy efficiency through the adoption of sustainable design and operational practices. Similarly, water efficiency improvements of around 11% have been reported, highlighting gains in conservation measures such as low-flow fixtures and improved water management systems. At the project level, highperformance buildings such as the KAPSARC complex in Riyadh achieved reductions in energy consumption of over 30% and potable water use of 40%, through advanced HVAC systems, lowflow plumbing, and rainwater harvesting.

Additionally, large sustainable developments such as those in the King Abdullah Financial District (KAFD) contribute substantially to Saudi Arabia's green building landscape, with the district alone representing nearly 60% of the Kingdom's total LEEDcertified gross floor area, demonstrating broad adoption of high sustainability standards in mixeduse urban design. Overall, these improvements are accompanied by increased uptake of LEED certification in Saudi projects, with over 1,100 projects recognized and more than 200 achieving Platinum certification in recent years, underscoring the country's commitment to sustainable urban development [17].

These results confirm that while significant sustainability gains are being made in energy, water, and operational performance in Saudi urban buildings, there remains scope for further improvement particularly in areas such as smart building management, resource reuse, and performance monitoring to fully realize the potential of green building practices across the built environment

Table2: Sustainability Performance Metrics for Selected Green Buildings in Saudi Arabia

Project	Energy Efficiency	Water Efficiency	Materials / Waste Management	Certification Status
KAPSARC (Riyadh)	~35% reduction in energy use (annual audits)	~30% water consumption reduction	94% solid waste diverted from landfill	5 × LEED EBOM Platinum
KAFD (King Abdullah Financial District)	Integrated energyefficient infrastructure (no precise % reported)	Water conservation systems integrated districtwide	+500,000 m² green/ public space, waste reduction strategies	LEEDND Stage 2 Platinum (largest LEED certified district)

Table 3 summarizes the observed performance of key sustainability indicators (KPIs) across the studied urban buildings. The analysis shows that energy efficiency has improved moderately to highly, with cooling systems being the main contributor to overall energy demand. Water efficiency demonstrated moderate improvements, although the reuse of greywater remains limited. The use of sustainable materials varied among projects, with a notable dependence on imported construction materials. Indoor air quality (IAQ) was generally acceptable, closely linked to the effectiveness of HVAC systems. Finally, operational efficiency, particularly through the use of building management systems (BMS), remained limited, indicating a need for wider adoption of smart monitoring technologies. Overall, the table highlights areas of strength and ongoing challenges, suggesting targeted interventions are needed to further enhance building performance and sustainability outcomes [18].

Table 3. Summary of Sustainable Building Performance Indicators (KPIs)

Performance Aspect	Key Indicator	Observed Performance	Key Observation
Energy Efficiency	Energy Use Intensity (EUI)	Moderate–High improvement	Cooling systems dominate energy demand
Water Efficiency	Water Consumption Rate	Moderate improvement	Limited reuse of greywater
Materials	Sustainable Material Use	Variable	Dependence on imported materials
Indoor Environment	Indoor Air Quality (IAQ)	Generally acceptable	Performance linked to HVAC efficiency
Operational Efficiency	Building Management Systems	Limited application	Lack of smart monitoring systems

4.2 Gap Between Design Expectations and Actual Performance Based on Surveys and Interviews

Table 4 presents the gaps between design expectations and actual performance of urban buildings in Saudi Arabia, based on 10 surveys with key stakeholders, including architects, developers, and sustainability experts. The results indicate that energy consumption, although designed for high efficiency, performed at a medium level in 7 out of 10 surveys, reflecting a noticeable gap influenced by operational and usage factors. Water management strategies, while optimized in design, were only partially implemented according to 6 out of 10 participants, resulting in a moderate gap. Responses from 8 out of 10 participants showed that operational control systems were not fully automated, relying mostly on manual or semi-automated operations, representing a significant performance gap. Regarding maintenance strategies, 9 out of 10 participants indicated that the approach was reactive rather than preventive, creating a high gap between planned and actual performance. These results clearly illustrate the discrepancy between design intentions and practical implementation, emphasizing the need to enhance stakeholder engagement during design and execution phases, adopt smart monitoring systems, and implement preventive maintenance strategies to improve the efficiency and sustainability of urban buildings in Saudi Arabia

Table 4. Gap Between Design Expectations and Actual Performance

Performance Area	Design Target	Actual Performance	Performance Gap
Energy Consumption	High efficiency	Medium efficiency	Noticeable gap
Water Management	Optimized use	Partial implementation	Moderate gap
Operational Control	Automated systems	Manual / semi-automated	Significant gap
Maintenance Strategy	Preventive	Reactive	High gap

4.3 Stakeholder-Identified Implementation Challenges

Table 5 summarizes the key implementation challenges in sustainable urban buildings in Saudi Arabia as identified by stakeholders through 10 surveys and interviews. The results reveal that technical challenges, such as limited expertise in sustainable systems, were highlighted by 8 out of 10 participants, mainly engineers and contractors, indicating a significant barrier in achieving optimal energy, water, and operational performance. Regulatory challenges, including the lack of mandatory enforcement of sustainability standards, were reported by 7 out of 10 respondents, particularly developers and authorities, reflecting gaps in policy implementation and oversight. Economic challenges, such as high initial costs for green building technologies, were identified by 6 out of 10 stakeholders, emphasizing financial constraints that can slow adoption despite long-term operational benefits. Operational challenges, including weak post-construction coordination, were reported by 7 out of 10 facility managers, indicating that the transition from design to operation is often fragmented. Finally, knowledge gaps were noted by 6 out of 10 participants, especially architects and operators, pointing to insufficient training and awareness in sustainable practices. Overall, the survey results indicate that while Saudi Arabia has made progress in green building policies and certifications, the practical implementation of sustainable practices faces multiple, interrelated challenges. Addressing these challenges requires targeted strategies, including enhanced training programs, stricter regulatory enforcement, early engagement of technical experts, and better coordination mechanisms post-construction to ensure that design intentions are fully realized in practice

Table 5. Stakeholder-Identified Implementation Challenges

Challenge Category	Description	Stakeholders Involved
Technical	Limited expertise in sustainable systems	Engineers, Contractors
Regulatory	Lack of mandatory enforcement	Developers, Authorities
Economic	High initial costs	Developers
Operational	Weak coordination post-construction	Facility Managers
Knowledge	Insufficient training	Architects, Operators

4.4 Regional Comparison and LEED Adoption in Saudi Arabia and Neighboring Countries

Table 6 and Figure 1 presents a comparative overview of sustainable building practices between Saudi Arabia and selected regional projects in neighboring countries with similar hot-arid climates. The analysis indicates that climate adaptation measures in Saudi buildings show moderate implementation, comparable to regional counterparts, highlighting shared challenges in managing heat, solar exposure, and water scarcity. LEED adoption in Saudi Arabia is steadily increasing, though regional projects generally demonstrate more mature adoption of green building certifications, suggesting that Saudi projects could benefit from lessons learned in neighboring countries. The use of smart building systems in Saudi Arabia remains limited compared to regional projects, indicating a significant opportunity for improvement in energy management, automation, and performance monitoring. Similarly, stakeholder engagement in Saudi projects is more fragmented, whereas regional projects demonstrate integrated involvement of architects, developers, and sustainability experts from early design to operational stages, underscoring the critical role of early engagement in achieving high-performance sustainable buildings. Statistical data further highlights the regional differences in LEED adoption. Saudi Arabia leads the Middle East with 1,029 certified projects, reflecting its growing commitment to sustainability and alignment with the goals of Saudi Vision 2030. It is followed by the United Arab Emirates with 749 certified projects, benefiting from early adoption of green building standards in cities like Dubai and Abu Dhabi. Qatar ranks third with 162 certified projects, many associated with modern infrastructure and sustainable stadium developments. Kuwait has 23 certified projects, indicating room for further expansion in green building adoption. Overall, this regional comparison highlights both strengths and areas for improvement in Saudi sustainable building practices. Leveraging regional expertise, adopting advanced smart systems, and promoting early stakeholder involvement could help bridge performance gaps, enhance operational efficiency, and accelerate the adoption of high sustainability standards in Saudi urban projects [19].

Table 6. Regional Comparison of Sustainable Building Practices

Aspect	Saudi Arabia	Regional Projects	Comparative Insight
Climate Adaptation	Moderate	Moderate High	Similar climatic challenges
LEED Adoption	Increasing	More mature	Regional experience advantage
Smart Systems	Limited	Wider adoption	Opportunity for improvement
Stakeholder Engagement	Fragmented	Integrated	Early involvement is critical

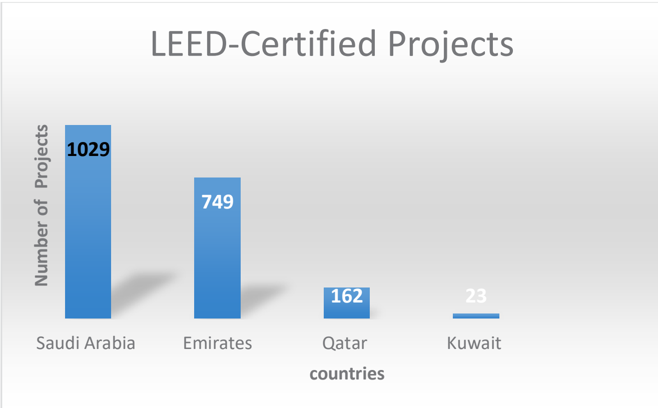

Fig. 1. LEED Certification Trends in Saudi Arabia and Surrounding Countries [20].

4.5 Survey-Based Results on Sustainable Building Performance

The results presented in Table (7) are directly based on the adopted research methodology, which relied on ten structured questionnaires distributed to architects, structural engineers, and facility managers working on urban building projects within the Kingdom of Saudi Arabia. The questionnaire findings revealed that 7 out of 10 respondents (70%) identified energy efficiency as the most influential factor affecting sustainable building performance, with particular emphasis on cooling and air-conditioning systems. This outcome aligns with the methodological focus on operational performance indicators, especially energy consumption associated with hot-climate conditions. The results further indicated that 6 respondents (60%) reported a clear gap between anticipated design targets and actual operational performance. This finding supports the existence of a design–operation gap, which was identified through a systematic comparison between design intentions and real-world operational practices. Participants primarily attributed this gap to the limited implementation of post-occupancy evaluation and the insufficient adoption of smart building management systems. Regarding stakeholder involvement, 8 out of 10 respondents (80%) emphasized that the early engagement of all relevant stakeholders during the initial design stages directly contributes to improved sustainability outcomes and reduces operational challenges at later stages. In addition, 5 respondents (50%) highlighted that leveraging regional neighboring experiences plays an important role in enhancing building performance, particularly in the areas of smart building systems and energy management. Overall, the questionnaire results demonstrate that the adopted methodology was effective in linking the quantitative analysis of stakeholder perceptions with the qualitative assessment of performance indicators, enabling a coherent interpretation of the findings and their practical implications. Furthermore, the results provide a clear foundation for identifying future improvement priorities for sustainable buildings within the Kingdom

Table7. Key Findings and Practical Implications

Key Finding	Implication for Practice
Energy efficiency is the dominant factor	Focus on cooling and HVAC optimization
Design–operation gap exists	Strengthen post-occupancy evaluation
Stakeholder role is critical	Early integration improves outcomes
Regional experience is valuable	Adapt proven regional solutions

5. Conclusions and recommendations

5.1 Conclusions

This study conducted an **integrated analysis of sustainable building efficiency and implementation challenges** in modern urban projects in Saudi Arabia, with a regional comparative perspective. The key findings can be summarized as follows:

1. Sustainability Performance Variability:

- The analyzed Saudi projects demonstrated significant variations in sustainability performance across energy, water, materials, and operational indicators.
- Energy efficiency, particularly in cooling and HVAC systems, was identified as the most critical factor influencing overall building sustainability.

2. Design Operation Gap:

- A clear gap exists between the projected performance during design and the actual operational outcomes.
- Factors contributing to this gap include limited technical expertise, regulatory constraints, insufficient stakeholder integration, and high initial costs.

3. Stakeholder Involvement is Critical:

- Interviews and surveys highlighted that early engagement of architects, developers, engineers, and sustainability consultants significantly enhances the feasibility and success of sustainable building initiatives.

4. Regional Insights and Best Practices:

- Comparative analysis with neighboring countries revealed shared challenges in hot-arid climates but also demonstrated advanced practices in smart building management, stakeholder engagement, and incentive utilization.
- These regional lessons offer opportunities for adaptation and improvement in Saudi urban projects.

5. Policy and Implementation Gaps:

- While Saudi Arabia has made significant strides through the Sustainable Building Code and LEED adoption, further efforts are required to enforce regulations, provide technical training, and promote smart monitoring and maintenance systems.

5.2 Recommendations

- Based on the study findings, the following recommendations are proposed to enhance sustainable building efficiency and implementation in Saudi Arabia:

1. Strengthen Regulatory Enforcement:

- Enforce compliance with the **Saudi Sustainable Building Code** and promote mandatory performance monitoring for certified buildings.
- Introduce incentives for developers who achieve or exceed sustainability benchmarks.

2. Enhance Technical Capacity and Training:

- Develop specialized training programs for architects, engineers, and facility managers focusing on sustainable design, energy-efficient systems, and smart building technologies.
- Encourage knowledge sharing with regional projects that demonstrate best practices.

3. Promote Stakeholder Integration:

- Involve all key stakeholders, including developers, architects, consultants, and facility managers, from the early design phase through operation.
- Implement structured coordination mechanisms to minimize the design–operation gap.

4. Adopt Smart and Digital Solutions:

- Integrate **Building Management Systems (BMS)** and digital monitoring tools to optimize energy, water, and material use.
- Utilize real-time data to inform operational adjustments and maintenance strategies.

5. Leverage Regional Lessons:

- Apply successful strategies from regional hot-arid projects, such as smart HVAC design, greywater reuse, and stakeholder collaboration frameworks.
- Use comparative analysis to guide policy development and project planning.

Encourage Post Occupancy Evaluation:

- Conduct systematic performance reviews after building occupancy to identify gaps and refine future designs.
- Incorporate lessons learned into updates to design standards and sustainability guidelines.

5.3 Final Remarks

This study underscores that achieving sustainable urban development in Saudi Arabia requires an integrated approach combining **technical performance, stakeholder engagement, regulatory enforcement, and regional learning**. By implementing the recommendations above, policymakers, developers, and practitioners can enhance building efficiency, reduce environmental impacts, and support the objectives of **Saudi Vision 2030** for sustainable cities and communities

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Density Functional Theory Study of The Reaction Mechanism of the Elimination of n-butyrophenone

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Abstract
The reaction mechanism of elimination of n-butyrophenone has been investigated by theoretical approaches using density functional theory B3LYP/6-31+g(d) level of theory in the gas phase . The mechanism for elimination reaction is Norrish type II. The proposed mechanism of elimination reaction of n-butyrophenone takes place via a six-membered cyclic transition state to give a mixture of (1-phenylethenol, which tautomerizes to acetophenone) and ethene. Analysis of the progress along the reaction coordinate, in terms of geometrical parameters suggest these reactions are dominated by the abstraction of a hydrogen atom from the g-carbon by the carbonyl oxygen to give the diradical, and together with an important cleavage of Ca-Cb bond in the transition state through a single-step reaction mechanism. The results indicate that the transition state has an intermediate character between reactants and products. According to the results obtained in the energy profile for the elimination of n-butyrophenone and in the Intrinsic Reaction Coordinate (IRC) analysis, the reaction is endothermic. The energy barriers of n-butyrophenone to form six-membered ring transition state (TS) was found to be 54.75 kcal mol-1 and the energy barriers to form products (1-phenylethenol and ethene) was found to be 20.25 kcal mol-1. The calculated kinetic and thermodynamic parameters are in reasonable agreement with the reported experimental values.

Keywords: n-butyrophenone, Six-membered ring transition state, Density Functional Theory.

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1. INTRODUCTION

Ketones are a major class of organic chemicals and are widely used as solvents. They are important in the chemistry of the atmosphere and in combustion systems from direct emissions and as intermediates[1,2]. Their photodissociation in the lower atmosphere results in formation of free radicals and may influence the atmospheric oxidation capacity. Ketones are also used as fuel tracers for monitoring fuel properties, such as, temperature, concentration, density, pressure, velocity, and distribution, using laser-induced fluorescence [1,2] and as fuel additives in reducing soot emissions [3,4] .

Chemical kinetics and dynamics of unimolecular reactions of isolated molecules in the gas phase are well understood [5,6]. The framework of a unimolecular process is often applied, at least as an idealization, to condensed phase processes although the effects of the environment on the process can be profound [7,8].

Photochemical reactions of ketones are initiated when a photon promotes an electron from a non-bonding (n) orbital to a π* antibonding orbital in the carbonyl group, forming an excited state. This excited state can then undergo one of several characteristic reactions: Norrish Type I (α-cleavage), which breaks a carbon-carbon bond adjacent to the carbonyl; Norrish Type II (intramolecular hydrogen abstraction), where a hydrogen atom is transferred to the carbonyl oxygen; or photoreduction, where the excited ketone abstracts a hydrogen atom from a solvent molecule. Other reactions include Paterno-Büchi cycloaddition to form oxetanes and rearrangement reactions like lumiketone and di-π-methane rearrangements. Photo induced hydrogen abstraction reaction, which is better known as the Norrish type II reaction, has been a highlight in the development of a general picture of how photochemical reactions occurs [9]. The rate constant for internal hydrogen abstraction depends on electronic configuration, on C-H bond strength or inductive substituent effects, and on conformational factors [9]. These factors will determine the observed product ratios of photoreactions where more than one product is possible [9].

Carbonyl compounds are widespread in the atmosphere. Certain carbonyls are directly emitted by various sources, but the vast majority of them are produced in the atmosphere by oxidation of hydrocarbons [10]. Photolysis is an important removal pathway for atmospheric carbonyls. In the lower atmosphere, where the availability of radiation is limited to a wavelength of above 290 nm, the photolysis of carbonyls is driven by their weak absorption band in the wavelength range 240–360 nm as a result of a dipole forbidden n →π* transition [10,11].

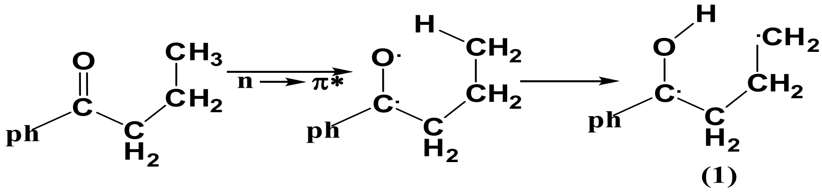
The initial photo excitation processes available to molecules with labile leaving groups, may directly populate a so-called $^1n\sigma^*$ or $^1\pi\sigma^*$ state, i.e., a state formed by promoting an electron from a non-bonding (n) or bonding π valence orbital to an antibonding σ* orbital [12, 13 ,14,15,16,17 and 18]. In many other cases, the primary photo excitation may involve a strongly absorbing π*←π transition; light-driven bond fission in such cases only occurs after non-adiabatic coupling between the ππ* state and an (n/π)σ* continuum.

The activation energies for singlet and triplet states of saturated ketones are about 80–85 and 75–80 kcal/mol, respectively, whereas of unsaturated ketones, these are in the range of 45–75 kcal/mol. For this reason, the photoreactions of saturated ketones occur in the UV region, 270–290 nm, and of unsaturated ketones in the UV region, 310–330 nm[19]. The excited carbonyl compounds have radical characters at both carbon and oxygen atoms of the carbonyl group, and hence most of their photoreactions proceed through radical intermediates. The important photoreactions of carbonyl compounds are the reduction of carbonyl compounds by hydrogen abstraction, fragmentation including the Norrish types I and II[19].

Photolysis of Ketones, that have at least one γ-hydrogen atoms on a chain connected to the carbonyl group such as *n*-butyrophenone in this pathway, undergoes the Norrish type II process (intramolecular elimination), as shown in equation (1) [20,21,22], the cleavage occurs at the Cα-Cβ bond to give, as the major product, phenyl ketone of shorter chain length and an alkene. Thus for *n*-butyrophenone is known to occur through the following pathways in equation (1):

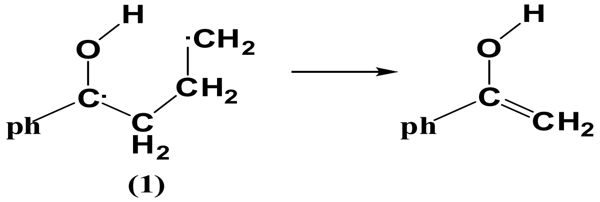
$$\mathrm{Ph\text{-}\overset{\overset{\Large O}{\|}}{C}CH_2CH_2CH_3} \xrightarrow[n \rightarrow \pi^*]{h\nu} \mathrm{Ph\text{-}\overset{\overset{\Large O}{\|}}{C}CH_3 + CH_2{=}CH_2} \text{-------------}(1)$$

This reaction occurs in an interesting way. Whatever the nature of the n →л* excited state, S1 or T1, the primary photochemical reaction is the abstraction of a hydrogen atom from the γ-carbon by the carbonyl oxygen to give the diradical (1), as in equation (2):



--------------(2)

The subsequent dark reactions readily are understood as typical of diradicals, cleavage of diradicals (1) at Cα-Cβ gives ethene and 1-phenylethenol, as in equation (3), 1-phenylethenol which tautomerizes to acetophenone.



--------------(3)

Although the reaction occurs from both the singlet and the triplet states of n, л* transition, the quantum yield from the singlet state is generally lower than that form the triplet state. In the our case which involve aryl-alkyl ketones, the reaction occurs only with the triplet state because aromatic ketones can undergo rapid intersystem crossing.

A large number of gas-phase unimolecular reaction, which have been studied, appeared to take place by way of 4-centre and 6-centre cyclic activated complexes [23].

Serinyel et al [24]. for example, have published on the combustion kinetics of 3-pentanone and used thermochemistry and kinetic parameters corresponding to studies on acetone in their model development. Several studies on the fundamental thermochemistry of the intermediate radicals on ketones or their elementary oxidation kinetics have recently appeared. Sebbar et al.[25]. published on the thermochemistry of 2-butanone and show that although the primary C−H bond on butanone adjacent to the carbonyl is similar to acetone, the secondary C−H bond energy is more than 5 kcal mol^{-1} weaker. Hudzik and Bozzelli [26] have also reported on thermochemical parameters of ketones series as a function of temperature and reveal problems with matching entropy and experimental data of heat capacity with vibration analysis using only frequencies from DFT and ab initio methods.

In this work, the mechanism of unimolecular elimination reaction of *n*-butyrophenone to give ethene and 1-phenylethenol which tautomerizes to acetophenone, will be discussed theoretically using density functional theory B3LYP/6-31+g(d) level of theory in the gas phase by means of the description of the energy, the geometry, and the stability of transition state structures involved in such reaction. This information provides a detailed energy profile for *n*-butyrophenone elimination, that supports results which have been obtained experimentally.

2. METHOD OF CALCULATIONS

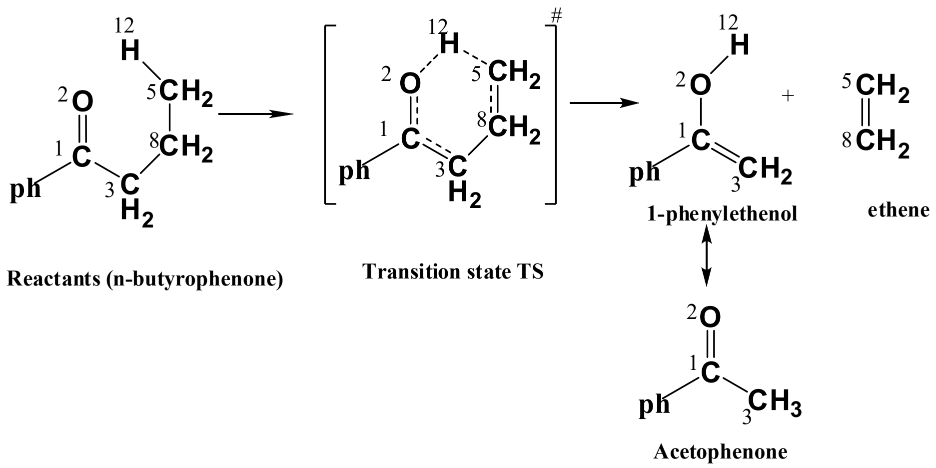
n-butyrophenone was chosen as model molecule to investigate the mechanism of intramolecular elimination reaction. The calculations were done with the Gaussian09 [27] software packages, at B3LYP/6-31+g(d) level. All structures were fully optimized in gas phase at the same mentioned method . The B3LYP/6-31+g(d) level of theory is widely used, efficient DFT approach for investigating hydrogen abstraction mechanisms and locating transition states (TS)[28,29]. It offers a good balance between computational cost and accuracy for characterizing structural and energetic parameters, including the inclusion of diffuse functions that are often necessary to describe radical species involved in hydrogen transfer.

The geometries of the reactants, intermediates, transition and products, involved in the reactions were all fully optimized by using the methods B3LYP/6-31+g(d). The structures thus obtained were subjected to vibrational analysis calculations toward their characterization as local minima (all positive force constants) or transition states (one imaginary force constant only). The Intrinsic Reaction Coordinate IRC[30] calculations for the later structures, were performed along the transition vector defined by the vibration mode of this imaginary frequency should be assess that the saddle point structure connected downhill the corresponding forward and backward minima. This methodology allowed the identification of the reaction intermediates and transition state structures along the reaction path. The standard state is 1 atm and 298.15 K, which are default in Gaussian calculations.

3. RESULTS AND DISCUSSION

The elimination reaction of ketones is a Norrish type II reaction, which generally is the photochemical intramolecular abstraction of a γ-hydrogen by the carbonyl group to produce a 1,4-biradical as a primary photoproduct through cyclic transition state.

The mechanism of intramolecular elimination reaction of *n*-butyrophenone to give ethene and 1-phenylethenol which tautomerizes to acetophenone as can be explained above in equations (1-3), scheme 1 shows the atoms directly involved in the reaction and the overall process. Figure 1 explains the energy profiles for the process in the gas phase with B3LYP/6-31+g(d). Tables 1 and 3 show the relative energies, ΔHº, ΔGº and ΔSº data for the structures involved, and table 2 shows the bond length for each steps of the structures of the reaction path from reactants to products in Angstrom.



Scheme 1: Proposed mechanism of Intramolecular elimination Reaction of *n*-butyrophenone

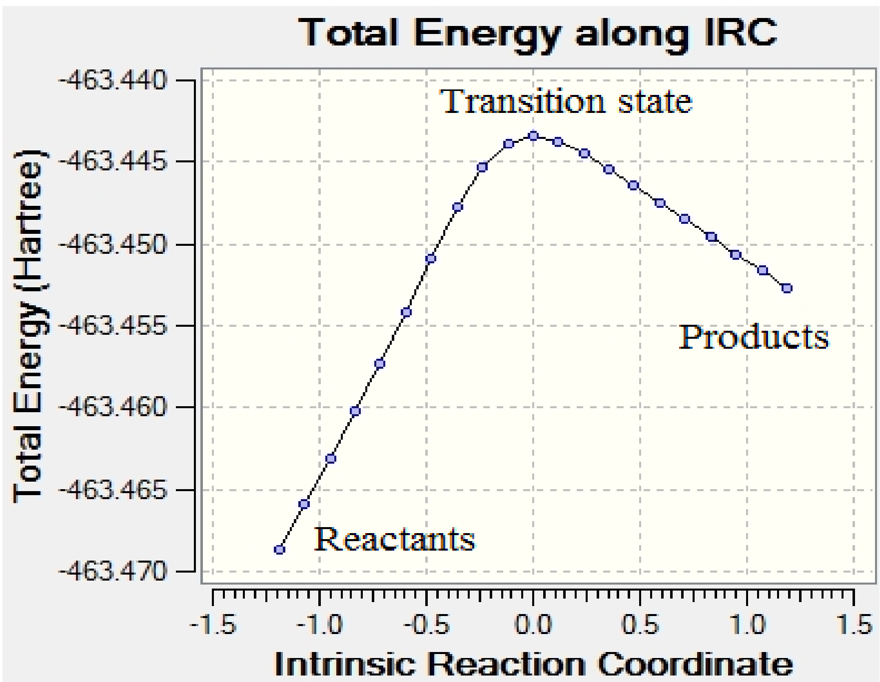


Figure 1. Intrinsic Reaction Coordinate (IRC) analysis of six-membered ring transition state using B3LYP/6-31+g(d) methods, Explained the energy profile for the elimination of *n*-butyrophenone, Energy for each of the structures in a.u.

Table 1. Energies (B3LYP) for each of the structures of the reaction path from the standard thermochemistry output of a frequency calculation [a]

Structure	ENERGY E(B3LYP)
Reactants[b]	-463.469
Transition state	-463.443
Products	-463.453

[a] The standard thermochemistry output calculations are available as supplementary material (see Table S2). Energy in a.u.
[b] Reactants, cyclic transition state-TS, and product respectively (refer to Scheme 1).

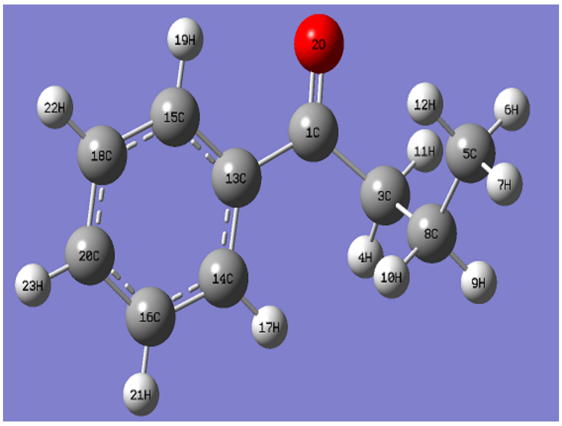
3.1 Six-membered ring Transition state Formation:

The starting point for this step process is structure 1(scheme1) where the incoming carbonyl oxygen (O2) of *n*-butyrophenone is the site of the intramolecular γ-hydrogen abstraction, where the hydrogen atom (H12) abstracted from the γ -carbon by the carbonyl oxygen (O2). The distance H12-O2 is 2.939 Å at the start in the reactant molecule (table 2 and scheme 1), which shortened to 1.165 Å in transition state molecule, simultaneously the bond H12…C5 (1.095 Å) in the reactant, stretched to 1.454 Å in the transition state, the bond C8…C5,which distance is 1.533 Å is shortened to 1.402 Å, partial formation of double bond between C8…C5 (Figure 2, table 2 and table S1), the carbonyl bond C1…O2 distance is 1.225 Å, which stretched to 1.314 Å i.e bond weakening and rehybridization in the transition state between C1…O2 (figure 2), simultaneously there is a partial formation of the double between C1…C3, from 1.523 Å to 1.388 Å. The bond between C3…C8, starts to break from 1.548 Å to 2.213 Å in the transition state (Figure 2, table 2 and table S1). The γ -hydrogen transfer to the oxygen atom has been shown to be intramolecular. This mechanism occurs via six-membered ring transition state TS as can be shown in figure 2. The calculated result of the vibrational analysis shows that there is only one strong imaginary frequency in the transition states, and the imaginary frequency of TS is −1235.525 cm^{-1}. The imaginary mode corresponds to γ -hydrogen transfer and C3…C8 bond cleavage, and the six membered ring cyclic transition state contraction. The transition state are verified by the intrinsic reaction coordinate (IRC) analysis, that is, TS connects directly the reactant and product in the reaction path as can be shown in figure 1. The reaction pathway includes only a one-step elementary reaction process, see figure 1.

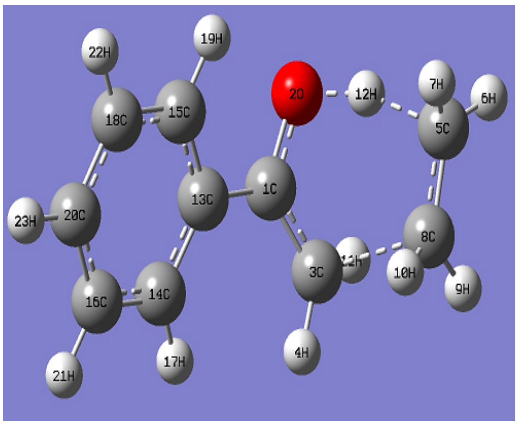
The energy barriers for the elimination reaction of *n*-butyrophenone to form six-membered ring transition state (TS) is 54.75 kcal mol^{-1} (table 3), downhill from these transition state structure, the system evolves to form products (scheme1) via the formation of an C5-C8 double bond and complete transfer of the (H12) to oxygen (O2), and complete breaking of C3-C8 bond to form ethene and 1-phenylethenol which tautomerizes to acetophenone. The energy barriers for the these products is equal 20.25 kcal mol^{-1} (table 3), scheme 1 and figure 2.

Table 2. Bond length for the structures of the reaction path from reactants to products for the bonds involved in six-membered transition state in Angstrom

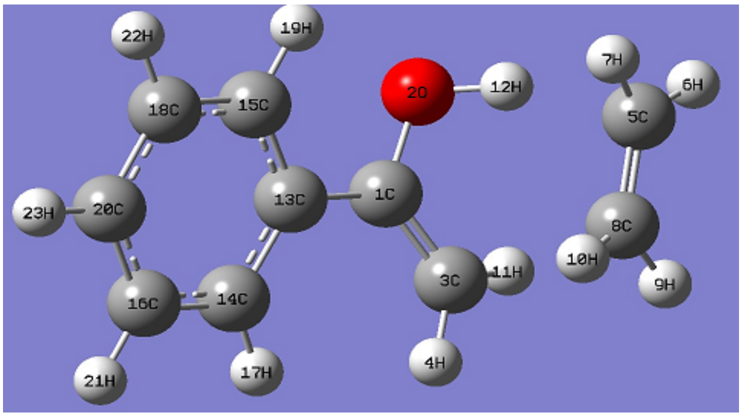
Bond length in Å	Reactants	Transition state TS	Products
O2…H12,	2.939	1.165	1.007 (in 1-phenylethenol)
H12…C5,	1.095	1.454	**1.757 (no bonding)**
C5…C8,	1.533	1.402	1.355 (in ethene)
C8…C3,	1.548	2.213	**2.376 (no bonding)**
C3…C1,	1.523	1.388	1.344(in 1-phenylethenol)
C1…O2,	1.225	1.314	1.354(in 1-phenylethenol)



Reactants



Transition state -TS



Products

Figure 2. Optimized structures of reactants, six-membered ring transition state-TS, and products calculated by B3LYP/6-31+g(d).

According to the results obtained above in the energy profile for the elimination of *n*-butyrophenone, figure 1, and Intrinsic Reaction Coordinate (IRC) analysis, and Table 3, the reaction is endothermic.

Table 3:Calculated energies of reactants, six-membered ring transition states, and products using B3LYP/6-31+g(d) in kcal mol^{-1} [a,b] of elimination of *n*-butyrophenone

Compound	ΔE kcal mol^{-1}	ΔG kcal mol^{-1}	ΔH kcal mol^{-1}	ΔS Cal mol^{-1}K^{-1}
Reactants[c]	0	0	0	0
Transition state	54.75	55.92	54.75	-3.93
Products	20.25	32.62	19.65	-43.49

[a] **All structures were fully optimized. Cartesian coordinates of all structures are available as supplementary material(see Table S1).**

[b] **Energies reported relative to the sum of energies of separated reactants(see Table S2 in supplementary material).**

[c] **Reactants, cyclic transition state and product refer to Scheme 1.**

If we consider the energy values (table 3) calculations (B3LYP) show that the initial elimination has energy barrier of 54.75 kcal mol^{-1}, less than that of 2-pentanone in our previous work (56.13 kcal mol^{-1} [31], whereas the potential energy barrier to form the product is 20.25 kcal mol^{-1}. This suggests that the elimination reaction of *n*-butyrophenone is endothermic and a single-step process. Similar conclusions for this type of reaction have been drawn from the theoretical and experimental results for other simple ketones [32] and theoretical results for 2-pentanone [31].

If Gibbs energy is considered, B3LYP calculations show barriers of 55.92 kcal $mol^{-1}$for elimination of *n*-butyrophenone to form six-membered ring transition state and 32.62 kcal mol^{-1} to form the ethene and 1-phenylethenol which tautomerizes to acetophenone.

4. CONCLUSIONS

On the bases of our elimination model of *n*-butyrophenone to form six-membered ring transition state, carbonyl oxygen(O2) is main role to which hydrogen transfer (H12) from γ -carbon to form biradical through six-membered ring transition state, which can be investigated by theoretical approaches using density functional theory B3LYP/6-31+g(d) level of theory in the gas phase.

Intramolecular elimination of *n*-butyrophenone take place by Norrish type II elimination reaction by a single-step reaction mechanism. According to thermodynamic point of view the reaction is endothermic reaction. Similar results for this type of reaction have been drawn from the theoretical results for 2-pentanone [31].

The energy barriers for the elimination reaction of *n*-butyrophenone to form six-membered ring transition state (TS) was found to be 54.75 kcal mol^{-1}, and the energy to form products ethene and 1-phenylethenol which tautomerizes to acetophenone was found to be 20.25 kcal mol^{-1}. From this work, we can conclude that theoretical investigations of mechanisms of the elimination reaction of *n*-butyrophenone improve the understanding of photoinduced hydrogen abstraction reaction, would be helpful to validate the proposed mechanisms in the literature and model mechanism of more complicated ketones.

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Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this article.

SUPPLEMENTARY INFORMATIONS

Supplementary information (output results of B3LYP calculations) are available free of charge, on request.

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Supplementary data

Density Functional Theory Study of The Reaction Mechanism of the Elimination of n-butyrophenone

Table S1: Bond length of reactants (n-butyrophenone), transition state and products (1-phenylethenol and ethene) using B3LYP/6-31+g(d) methods

n-butyrophenone		Transition state		1-phenylethenol		ethene	
Bond length		Bond length		Bond length		Bond length	
C(1)-O(2)	1.225	C(1)-O(2)	1.314	C(1)-O(2)	1.354	C(5)-H(6)	1.088
C(1)-C(3)	1.523	C(1)-C(3)	1.388	C(1)-C(3)	1.344	C(5)-H(7)	1.088
C(1)-C(13)	1.503	C(1)-C(13)	1.484	C(1)-C(13)	1.481	C(5)-C(8)	1.355
C(3)-H(4)	1.096	O(2)-H(12)	1.165	O(2)-H(12)	1.007	C(8)-H(9)	1.085
C(3)-C(8)	1.548	C(3)-H(4)	1.085	C(3)-H(4)	1.082	C(8)-H(10)	1.085
C(3)-H(11)	1.095	C(3)-C(8)	2.213	C(3)-H(11)	1.087		
C(5)-H(6)	1.096	C(3)-H(11)	1.084	C(13)-C(14)	1.406		
C(5)-H(7)	1.096	C(5)-H(6)	1.090	C(13)-C(15)	1.405		
C(5)-C(8)	1.533	C(5)-H(7)	1.089	C(14)-C(16)	1.393		
C(5)-H(12)	1.095	C(5)-C(8)	1.402	C(14)-H(17)	1.085		
C(8)-H(9)	1.098	C(5)-H(12)	1.454	C(15)-C(18)	1.396		
C(8)-H(10)	1.097	C(8)-H(9)	1.085	C(15)-H(19)	1.084		
C(13)-C(14)	1.405	C(8)-H(10)	1.086	C(16)-C(14)	1.399		
C(13)-C(15)	1.406	C(13)-C(14)	1.407	C(16)-H(21)	1.087		
C(14)-C(16)	1.396	C(13)-C(15)	1.406	C(18)-C(20)	1.396		
C(14)-H(17)	1.085	C(14)-C(16)	1.394	C(18)-H(22)	1.087		
C(15)-C(18)	1.393	C(14)-H(17)	1.086	C(20)-H(23)	1.087		
C(15)-H(19)	1.085	C(15)-C(18)	1.395				
C(16)-C(20)	1.397	C(15)-H(19)	1.085				
C(16)-H(21)	1086	C(16)-C(20)	1.398				
C(18)-C(20)	1.399	C(16)-H(21)	1.087				
C(18)-H(22)	1.087	C(18)-C(20)	1.398				
C(20)-H(123)	1.087	C(18)-H(22)	1.087				
		C(20)-H(123)	1.087				

Table S2: Standard thermochemistry output results of a frequency calculations using B3LYP/6-31+g(d) methods

output results of frequency calculation of reactants (n-butyrophenone)

```
                        (Hartree/Particle)
 Zero-point correction=                              0.195646
 Thermal correction to Energy=                       0.206079
 Thermal correction to Enthalpy=                     0.207023
 Thermal correction to Gibbs Free Energy=            0.158448
 Sum of electronic and zero-point Energies=       -463.342934
 Sum of electronic and thermal Energies=          -463.332501
 Sum of electronic and thermal Enthalpies=        -463.331557
 Sum of electronic and thermal Free Energies=     -463.380132
                    E (Thermal)            CV               S
                     KCal/Mol        Cal/Mol-Kelvin    Cal/Mol-Kelvin
 Total                 129.316             39.099        102.235
```

output results of frequency calculation of transition state

```
                      (Hartree/Particle)
 Zero-point correction=                              0.188177)
 Thermal correction to Energy=                       0.198113
 Thermal correction to Enthalpy=                     0.199058
 Thermal correction to Gibbs Free Energy=            0.152353
 Sum of electronic and zero-point Energies=       -463.255186
 Sum of electronic and thermal Energies=          -463.245249
 Sum of electronic and thermal Enthalpies=        -463.244305
 Sum of electronic and thermal Free Energies=     -463.291009
                     E (Thermal)            CV               S
                     KCal/Mol       Cal/Mol-Kelvin    Cal/Mol-Kelvin
           Total     124.318           39.427             98.297
```

output results of frequency calculation of 1-phenylethenol

```
                       (Hartree/Particle)
 Zero-point correction=                              0.138033)
 Thermal correction to Energy=                       0.145690
 Thermal correction to Enthalpy=                     0.146634
 Thermal correction to Gibbs Free Energy=            0.105437
 Sum of electronic and zero-point Energies=       -384.746058
 Sum of electronic and thermal Energies=          -384.738402
 Sum of electronic and thermal Enthalpies=        -384.737458
 Sum of electronic and thermal Free Energies=     -384.778655
                     E (Thermal)            CV               S
                     KCal/Mol        Cal/Mol-Kelvin    Cal/Mol-Kelvin
 Total                 91.422             30.171           86.70
```

output results of frequency calculation of ethene

```
                              (Hartree/Particle)
 Zero-point correction=                              0.051103
 Thermal correction to Energy=                       0.054146
 Thermal correction to Enthalpy=                     0.055090
 Thermal correction to Gibbs Free Energy=            0.028914
 Sum of electronic and zero-point Energies=        -78.542166
 Sum of electronic and thermal Energies=           -78.539123
 Sum of electronic and thermal Enthalpies=         -78.538179
 Sum of electronic and thermal Free Energies=      -78.564355

         E (Thermal)            CV               S
          KCal/Mol        Cal/Mol-Kelvin    Cal/Mol-Kelvin
 Total     33.977              8.101           55.092
```

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Analytical Solutions of Fractional Stochastic Wazwaz-Benjamin-Bona-Mahony Equations

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Abstract
This study examines a group of fractional stochastic Wazwaz-Benjamin-Bona-Mahony (FSWBBM) Equations, which incorporate both fractional and stochastic perturbations. The Wazwaz-Benjamin-Bona-Mahony (WBBM) Equations are widely adopted to describe the nonlinear behaviors of waves in dispersive media. The main objective in this study is to develop exact travelling wave solutions through an advanced analytical technique. In this framework, the Riccati-Bernoulli sub-ODE (R-B S-ODE) method is applied, replacing the classical derivatives with a conformable fractional derivative of order $\vartheta \in (0,1]$. At the same time, the family is subjected to Gaussian white noise. Employing a travelling wave transformation reduces the FSWBBM equations to nonlinear fractional stochastic ordinary differential equations. The R-B S-ODE approach is then used to obtain closed-form analytical solutions. This method generates various families of explicit solutions, including hyperbolic, trigonometric, and rational functions, depending on the fractional order and stochastic strength ϱ . The physical characteristics of the resulting waveforms are illustrated through two-dimensional and three-dimensional plots produced with MATLAB software. The findings confirm that the R-B S-ODE method provides a robust analytical tool for solving higher-dimensional fractional stochastic equations.

Keywords: Wazwaz-Benjamin-Bona-Mahony Equations (WBBMEs), Stochastic Partial Differential Equations, Riccati-Bernoulli Sub-ODE Method, Conformable fractional derivative, Travelling wave solutions.

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1. Introduction

Fractional partial differential equations (FPDEs) are utilized to model complicated phenomena across diverse areas, like viscoelastic media [1], control systems and signal processing [2], and biological systems [3], among others. Fractional derivatives, enabling the modeling of systems with non-integer order. They are widely applied in viscoelasticity, physics, and biology, and can be expressed in various forms, including the Grünwald-Letnikov, Hadamard, Riesz, Riemann-Liouville, Caputo and Conformable derivatives [4, 8].

Fractional stochastic partial differential equations (FSPDEs) are an advanced class of mathematical models that combine fractional calculus with stochastic processes to capture system exhibiting anomalous diffusion, non-integer order, and intrinsic randomness. These models generalize classical partial differential equations by incorporating derivatives of non-integer order, which enable more accurate modeling of complex behaviors found in physics, finance, and biology [9-11].

This work focuses on a family of FSWBBM equations formulated within the framework of stochastic calculus. The governing equations incorporate both conformable fractional derivative (CFD) and Gaussian white noise, driven by a standard Wiener process. The family under study includes nonlinear interactions and higher-order mixed spatial-temporal derivatives, making it analytically rich and challenging. Our objective in this study is to develop exact solutions to FSWBBM equations using R-B S-ODE technique.

Consider the following set of equations:

$$\mathfrak{D}_t^{\vartheta}\mathcal{H} + \mathfrak{D}_x^{\vartheta}\mathcal{H} + \mathcal{H}^2\mathfrak{D}_y^{\vartheta}\mathcal{H} - \mathfrak{D}_{xzt}^{3\vartheta}\mathcal{H} = \frac{\varrho}{2}(\mathcal{H} - \mathfrak{D}_{xz}^{2\vartheta}\mathcal{H})dW(t), \quad (1.1)$$

$$\mathfrak{D}_t^{\vartheta}\mathcal{H} + \mathfrak{D}_z^{\vartheta}\mathcal{H} + \mathcal{H}^2\mathfrak{D}_x^{\vartheta}\mathcal{H} - \mathfrak{D}_{xyt}^{3\vartheta}\mathcal{H} = \frac{\varrho}{2}(\mathcal{H} - \mathfrak{D}_{xy}^{2\vartheta}\mathcal{H})dW(t), \quad (1.2)$$

$$\mathfrak{D}_t^{\vartheta}\mathcal{H} + \mathfrak{D}_y^{\vartheta}\mathcal{H} + \mathcal{H}^2\mathfrak{D}_z^{\vartheta}\mathcal{H} - \mathfrak{D}_{xxt}^{3\vartheta}\mathcal{H} = \frac{\varrho}{2}(\mathcal{H} - \mathfrak{D}_{xx}^{2\vartheta}\mathcal{H})dW(t), \quad (1.3)$$

Here $\mathcal{H}$, is a function of the spatial variables *x, y, z* and time *t* . The operators $\mathfrak{D}_x^{\vartheta}, \mathfrak{D}_y^{\vartheta}, \mathfrak{D}_z^{\vartheta}$ and $\mathfrak{D}_t^{\vartheta}$ denote the first-order CFD of order ϑ with respect to spatial variables and time, respectively. The second-order mixed derivative is defined as $\mathfrak{D}_{xz}^{2\vartheta}\mathcal{H} = \mathfrak{D}_x^{\vartheta}(\mathfrak{D}_z^{\vartheta}\mathcal{H})$, while the third-order mixed derivative is given by $\mathfrak{D}_{xyt}^{3\vartheta}\mathcal{H} = \mathfrak{D}_x^{\vartheta}(\mathfrak{D}_y^{\vartheta}(\mathfrak{D}_t^{\vartheta}\mathcal{H})$.

Here $W(t)$ is a standard Wiener process (SWP), and ϱ is noise strength. The SWP satisfies the following conditions [12]

- $W(0) = 0$.
- $W(t)$ is continuous.
- $W(t)$ has independent increments.
- $W(t) - W(\tau) \sim N(0, t-\tau)$ for $0 \le \tau \le t$, and , $N(0, t-\tau)$ represents a normal distribution.

Consequently, the expectation satisfies $E[e^{\varrho W(t)}] = e^{\left(\frac{\varrho^2}{2}t\right)}$.

In addition to these properties, it is important to emphasize that a SWP, being a Gaussian stochastic process, can be expressed as a linear combination of independent normally distributed random variables [12, 38, 39].

R-B S-ODE method is recognized as a powerful and efficient analytical method for deriving exact solutions of various NLPDEs [13]. A notable characteristic of this approach is its ability to derive an infinite set of solutions through the application of a Bäcklund transformation. The method has been applied to numerous nonlinear models arising in diverse areas such as fluid mechanics, plasma, and nonlinear optics [14-16]. In this study, the R-B S-ODE method is employed to derive analytical solutions to FSWBBM equations.

In the limiting case $\vartheta = 1$, $\varrho = 0$, Eqs. (1.1)-(1.3) reduces to the classical WBBM [17] equations.

$$\mathcal{H}_t + \mathcal{H}_x + \mathcal{H}^2\mathcal{H}_y - \mathcal{H}_{xzt} = 0. \quad (1.4)$$

$$\mathcal{H}_t + \mathcal{H}_z + \mathcal{H}^2\mathcal{H}_x - \mathcal{H}_{xyt} = 0. \quad (1.5)$$

$$\mathcal{H}_t + \mathcal{H}_y + \mathcal{H}^2\mathcal{H}_z - \mathcal{H}_{xxt} = 0. \quad (1.6)$$

Various methods have been developed to obtain solutions to Eqs. (1.4)-(1.6), these include tanh-sech method [17], modified extended tanh-function approach [18], Sardar-subequation techniques [19], the tanh-coth approach [20], several auxiliary equation-base techniques [21-23]. Other approaches involve the simple ansatz procedure [24], the modified exp-function strategy [25], the modified simple equation and R-B S-ODE methods [26], the exp ($-\phi(\psi)$)-expansion technique [27]. Additionally, expansion techniques such as the (G'/G^2)-expansion techniques [28, 29], the Sine-Gordon expansion technique [30], generalized Kudryashov method and optimal homotopy asymptotic strategy [31]. Moreover, numerical solutions based on the Sinc-collocation method have been used [32].

Furthermore, numerous research efforts have been devoted to the study of stochastic WBBM equations. For instance, [33] investigated the bifurcation solutions, while [34, 35] applied modified tanh-coth methods. In [36], $\mathcal{G}'/(\mathcal{G}' + \mathcal{G} + \mathcal{A})$-expansion and the modified $\mathcal{G}'/\mathcal{G}^2$-expansion methods are used. The authors of [37] employed the F-expansion method.

The application of the R-B S-ODE method to the FSWBBM equations has received limited attention in the existing literature. Accordingly, this study is devoted to deriving diverse novel exact solutions of the FSWBBM equations, thereby enhancing our understanding of their physical behaviors.

The article is structured as follows: Section2, introduces the CFD. Section 3 outlines the steps of the method. Section 4 presents exact solutions of the family of FSWBBM equations. Section 5 provides a discussion. Finally, Section 6 summarize the conclusion drawn from the study.

2. Foundation

This section presents the CFD and summarize its fundamental characteristics.

Definition [8]. Let $\mathcal{M}(t)$ be real-valued function defined on $[0,\infty)$. The CFD of order $\vartheta\in(0,1]$ for $\mathcal{M}$ is defined as

$$\mathfrak{D}_t^{\vartheta}\mathcal{M}(t)=\lim_{\delta\to 0}\frac{\mathcal{M}(t+\delta t^{1-\vartheta})-\mathcal{M}(t)}{\delta},\forall\delta>0.$$

If this limit exists, for $\mathcal{M}$ and $\mathcal{N}$, then

$$\mathfrak{D}_t^{\vartheta}t^k=kt^{k-\vartheta},k\in\mathbb{R},$$

$$\mathfrak{D}_t^{\vartheta}\mathscr{b}=0,$$

$$\mathfrak{D}_t^{\vartheta}(\mathscr{b}\mathcal{M}+d\mathcal{N})=\mathscr{b}\mathfrak{D}_t^{\vartheta}\mathcal{M}+d\mathfrak{D}_t^{\vartheta}\mathcal{N},$$

$$\mathfrak{D}_t^{\vartheta}(\mathcal{M}\mathcal{N})=\mathcal{M}\mathfrak{D}_t^{\vartheta}\mathcal{N}+\mathcal{N}\mathfrak{D}_t^{\vartheta}\mathcal{M},$$

$$\mathfrak{D}_t^{\vartheta}\left(\frac{\mathcal{M}}{\mathcal{N}}\right)=\frac{\mathcal{N}\mathfrak{D}_t^{\vartheta}\mathcal{M}-\mathcal{M}\mathfrak{D}_t^{\vartheta}\mathcal{N}}{\mathcal{N}^2},$$

$$\mathfrak{D}_t^{\vartheta}\mathcal{M}(t)=t^{1-\vartheta}\mathcal{M}',$$

$$\mathfrak{D}_t^{\vartheta}\mathcal{M}[\mathcal{N}(t)]=t^{1-\vartheta}\mathcal{N}'(t)\mathcal{M}'[\mathcal{N}(t)],$$

where $\mathscr{b}$ and d are constants.

The conformable fractional derivative is adopted in this work because, in contrast to the Caputo and Riemann–Liouville derivatives, it preserves many structural properties of the classical derivative, the detailed discussion and comparative remarks can be found in [8, 40, 41]. Moreover, the CFD admits a clear physical and geometrical interpretation as discussed in [42]. The motivation underling the main advantages and key limitations of CFD is discussed in detail, and the reader is referred to the relevant literature; see for example references [8, 41].

3. Description of the R-B S-ODE method [13]

Consider the following space-time FPDE:

$$G\left(\mathcal{M},\mathfrak{D}_t^{\vartheta}\mathcal{M},\mathfrak{D}_x^{\vartheta}\mathcal{M},\mathfrak{D}_y^{\vartheta}\mathcal{M},\mathfrak{D}_z^{\vartheta}\mathcal{M},\mathfrak{D}_{tt}^{2\vartheta}\mathcal{M},\mathfrak{D}_{tx}^{2\vartheta}\mathcal{M},\ldots\right)=0,\qquad 0<\vartheta\le 1,\quad (3.1)$$

where G represents a polynomial in $\mathcal{M}(x, y, z, t)$ and its associated derivatives. The R-B S-ODE method is carried out through the following steps.

(1) Using the transformation $\mathcal{M}(x,y,z,t)=\mathcal{M}(\xi)$, with $\xi=(px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta})/\vartheta$, where p,q,r and ω are constants. Eq. (3.1) transformed to an ODE:

$$Q(\mathcal{M},\mathcal{M}',\mathcal{M}'',\ldots)=0,\qquad (3.2)$$

where $\mathcal{M}'=\frac{d\mathcal{M}}{d\xi}$.

(2) Assume that Eq. (3.2) has similar solution as R-B equation

$$\mathcal{M}'=\hbar M^{2-n}+k\mathcal{M}+\ell\mathcal{M}^n,\qquad (3.3)$$

where the constants $h,k,\ell,$ and n are to be identified. The higher derivatives of Eq. (3.3) gives

$$\left.\begin{aligned}\mathcal{M}''&=\hbar k(3-n)\mathcal{M}^{2-n}+\hbar^2(2-n)\mathcal{M}^{3-2n}+n\ell^2\mathcal{M}^{2n-1}+k\ell(n+1)\mathcal{M}^n+(2\hbar\ell+k^2)\mathcal{M}\\ \mathcal{M}'''&=\begin{bmatrix}\hbar k(3-n)(2-n)\mathcal{M}^{1-n}+\hbar^2(2-n)(3-2n)\mathcal{M}^{2-2n}+n\ell^2(2n-1)\mathcal{M}^{2n-2}\\ +k\ell n(n+1)\mathcal{M}^{n-1}+(2\hbar\ell+k^2)\end{bmatrix}\mathcal{M}'\end{aligned}\right\}.\quad(3.4)$$

The following set are solutions of Eq. (3.3)

Set-1. For $n=1$,

$$\mathcal{M}=\mathcal{C}e^{(\hbar+k+\ell)\xi}.\qquad (3.5)$$

Set-2. For $n\neq 1$ and $k=\ell=0$,

$$\mathcal{M}=\sqrt[n-1]{\hbar(n-1)(\xi+\mathcal{C})}.\qquad (3.6)$$

Set-3. For $n\neq 1$, $k\neq 0$ and $\ell=0$,

$$\mathcal{M}=\sqrt[n-1]{\mathcal{C}e^{k(n-1)\xi}-\frac{\hbar}{k}}.\qquad (3.7)$$

Set-4. For $n\neq 1$, $\hbar\neq 0$, and $k^2-4\hbar\ell<0$

$$\mathcal{M}=\left(-\frac{k}{2\hbar}+\frac{\sqrt{4\hbar\ell-k^2}}{2\hbar}tan\left(\frac{(1-n)\sqrt{4\hbar\ell-k^2}}{2}(\xi+\mathcal{C})\right)\right)^{\frac{1}{1-n}},\qquad (3.8)$$

and

$$\mathcal{M}=\left(-\frac{k}{2\hbar}-\frac{\sqrt{4\hbar\ell-k^2}}{2\hbar}cot\left(\frac{(1-n)\sqrt{4\hbar\ell-k^2}}{2}(\xi+\mathcal{C})\right)\right)^{\frac{1}{1-n}}.\qquad (3.9)$$

Set-5. For $n\neq 1$, $\hbar\neq 0$, and $k^2-4\hbar\ell>0$

$$\mathcal{M}=\left(-\frac{k}{2\hbar}-\frac{\sqrt{k^2-4\hbar\ell}}{2\hbar}tanh\left(\frac{(1-n)\sqrt{k^2-4\hbar\ell}}{2}(\xi+\mathcal{C})\right)\right)^{\frac{1}{1-n}},\qquad (3.10)$$

and

$$\mathcal{M}=\left(-\frac{k}{2\hbar}-\frac{\sqrt{k^2-4\hbar\ell}}{2\hbar}coth\left(\frac{(1-n)\sqrt{k^2-4\hbar\ell}}{2}(\xi+\mathcal{C})\right)\right)^{\frac{1}{1-n}}.\qquad (3.11)$$

Set-6. For $n\neq 1$, $\hbar\neq 0$, and $k^2-4\hbar\ell=0$

$$\mathcal{M}=\sqrt[1-n]{\left(\frac{1}{\hbar(n-1)(\xi+\mathcal{C})}-\frac{k}{2\hbar}\right)},\qquad (3.12)$$

where $\mathcal{C}$ is constant.

(3) Placing Eqs. (3.3) and (3.4) into Eq. (3.2) results in an algebraic equation in term of $\mathcal{M}$, whose solution yields $\hbar$, k and ℓ, these are then substituted into Eqs. (3.5)-(3.12) to provides the travelling wave solutions for Eqs. (1.1)-(1.3).

Let $\mathcal{M}_{m-1}(\xi)$ and $\mathcal{M}_m(\xi)=\mathcal{M}_m(\mathcal{M}_{m-1}(\xi))$ and be solutions of Eq. (3.3). Then, we have the following relation

$$\frac{d\mathcal{M}_m(\xi)}{d\xi}=\frac{d\mathcal{M}_m(\xi)}{d\mathcal{M}_{m-1}(\xi)}\frac{d\mathcal{M}_{m-1}(\xi)}{d\xi}=\frac{d\mathcal{M}_m(\xi)}{d\mathcal{M}_{m-1}(\xi)}\left(\hbar\mathcal{M}_{m-1}^{2-n}+\Bbbk\mathcal{M}_{m-1}+\ell\mathcal{M}_{m-1}^{n}\right),$$

which leads to

$$\frac{d\mathcal{M}_m(\xi)}{\hbar\mathcal{M}_m^{2-n}+\Bbbk\mathcal{M}_m+\ell\mathcal{M}_m^{n}}=\frac{d\mathcal{M}_{m-1}(\xi)}{\hbar\mathcal{M}_{m-1}^{2-n}+\Bbbk\mathcal{M}_{m-1}+\ell\mathcal{M}_{m-1}^{n}}.$$

Integrating with respect to ξ and simplifying, we get

$$\mathcal{M}_m(\xi)=\left(\frac{-\ell\mathcal{A}_1+\hbar\mathcal{A}_2(\mathcal{M}_{m-1}(\xi))^{1-n}}{\Bbbk\mathcal{A}_1+\hbar\mathcal{A}_2+\hbar\mathcal{A}_1(\mathcal{M}_{m-1}(\xi))^{1-n}}\right)^{\frac{1}{1-n}}, \tag{3.13}$$

where $\mathcal{A}_1$ and $\mathcal{A}_2$ being constants.

Once the solution of Eq. (3.3) is known, the Bäcklund transformation (3.13) is used to generate an infinite sequence of new solutions. Consequently, an endless sequence of solutions to Eqs. (1.1)-(1.3) can also be constructed.

4. Application of the R-B S-ODE to FSWBBM equations

Consider the wave transform

$$\mathcal{H}(x,y,z,t)=\mathcal{M}(\xi)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},\ \xi=\left(px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}\right)/\vartheta, \tag{4.1}$$

where $\mathcal{H}$ is a real function. Utilizing the CFD, the travelling wave transformation, and properties of SWP, we obtain

$$\mathfrak{D}_t^{\vartheta}\mathcal{H}=\left(-\omega\mathcal{M}'+\frac{\varrho}{2}\mathcal{M}\,d\mathcal{W}(t)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)}. \tag{4.2}$$

$$\mathfrak{D}_x^{\vartheta}\mathcal{H}=p\,\mathcal{M}'e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},\ \mathfrak{D}_y^{\vartheta}\mathcal{H}=q\mathcal{M}'e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},\ \mathfrak{D}_z^{\vartheta}\mathcal{H}=r\mathcal{M}'e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)}. \tag{4.3}$$

$$\mathfrak{D}_{xx}^{2\vartheta}\mathcal{H}=p^2\mathcal{M}''e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},\mathfrak{D}_{xy}^{2\vartheta}\mathcal{H}=pq\mathcal{M}''e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},\mathfrak{D}_{xz}^{2\vartheta}\mathcal{H}=pr\mathcal{M}''e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)}. \tag{4.4}$$

$$\mathfrak{D}_{xxt}^{3\vartheta}\mathcal{H}=\left(-p^2\omega\mathcal{M}'''+\frac{p^2\varrho}{2}\mathcal{M}''d\mathcal{W}(t)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},\mathfrak{D}_{xyt}^{3\vartheta}\mathcal{H}=\left(-pq\omega\mathcal{M}'''+\frac{pq\varrho}{2}\mathcal{M}''d\mathcal{W}(t)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},\mathfrak{D}_{xzt}^{3\vartheta}\mathcal{H}=\left(-pr\omega\mathcal{M}'''+\frac{pr\varrho}{2}\mathcal{M}''d\mathcal{W}(t)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)}. \tag{4.5}$$

4.1 Solutions for the first FSWBBM equation

Inserting Eqs. (4.1)-(4.5) into (1.1) and simplify, we obtain

$$(p-\omega)\mathcal{M}'+q\mathcal{M}^2\mathcal{M}'e^{\left(\varrho\mathcal{W}(t)-\frac{1}{2}\varrho^2t\right)}+pr\omega\mathcal{M}'''=0. \tag{4.6}$$

Taking expectation on both sides of Eq. (4.6) result in

$$(p-\omega)\mathcal{M}'+q\mathcal{M}^2\mathcal{M}'+pr\omega\mathcal{M}'''=0. \tag{4.7}$$

Integrating Eq. (4.7) we get

$$(p-\omega)\mathcal{M}+\frac{q}{3}\mathcal{M}^3+pr\omega\mathcal{M}''=0. \tag{4.8}$$

Substituting Eq. (3.4) into (4.8) and simplify, we get

$$(p-\omega)\mathcal{M}+\frac{q}{3}\mathcal{M}^3+pr\omega\left(\hbar\Bbbk(3-n)\mathcal{M}^{2-n}+\hbar^2(2-n)\mathcal{M}^{3-2n}+n\ell^2\mathcal{M}^{2n-1}+\Bbbk\ell(n+1)\mathcal{M}^n+(2\hbar\ell+\Bbbk^2)\mathcal{M}\right)=0. \tag{4.9}$$

Set $n=0$:

$$(p-\omega)\mathcal{M}+\frac{q}{3}\mathcal{M}^3+pr\omega\left(3\hbar\Bbbk\mathcal{M}^2+2\hbar^2\mathcal{M}^3+\Bbbk\ell+(2\hbar\ell+\Bbbk^2)\mathcal{M}\right)=0. \tag{4.10}$$

By Collecting the like powers of $\mathcal{M}^j$ for $j=0,1,2,3,\ldots$, and equating to zero. We obtain

Coefficient of: $pr\omega\Bbbk\ell=0$.

Coefficient of: $p-\omega+pr\omega(2\hbar\ell+\Bbbk^2)=0$.

Coefficient of: $3\hbar\Bbbk pr\omega=0$.

Coefficient of: $\frac{q}{3}+2\hbar^2pr\omega=0$.

Solving the system yields the following values:

$$\Bbbk=0,\ \hbar=\pm\sqrt{-\frac{q}{6pr\omega}},\ \ell=\frac{\omega-p}{2\hbar pr\omega}. \tag{4.11}$$

When $\frac{\omega-p}{pr\omega}>0$, from Eq. (4.11), Eq. (3.8) and Eq. (3.9), we get

$$\mathcal{H}_{1,1}(x,y,z,t)=\pm\sqrt{\frac{3(p-\omega)}{q}}\tan\left(\sqrt{\frac{\omega-p}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},$$

and

$$\mathcal{H}_{1,2}(x,y,z,t)=\pm\sqrt{\frac{3(p-\omega)}{q}}\cot\left(\sqrt{\frac{\omega-p}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},$$

where $\mathcal{C}$ is constant.

When $\frac{\omega-p}{pr\omega}<0$, we get

$$\mathcal{H}_{1,3}(x,y,z,t)=\pm\sqrt{\frac{3(\omega-p)}{q}}\tanh\left(\sqrt{\frac{p-\omega}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},$$

and

$$\mathcal{H}_{1,4}(x,y,z,t)=\pm\sqrt{\frac{3(\omega-p)}{q}}\coth\left(\sqrt{\frac{p-\omega}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},$$

where $\mathcal{C}$ is constant.

When $n\neq1$, $\Bbbk=\ell=0$, we obtain

$$\mathcal{H}_{1,5}(x,y,z,t)=\pm\left(\sqrt{-\frac{q}{6pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)^{-1}e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},$$

where $\mathcal{C}$ is constant.

Appling the transformation (3.13) to the above solutions yields the following new solutions to Eq. (1.1),

$$\mathcal{H}_{1,1}^{*}(x,y,z,t)=\left(\frac{\frac{3(\omega-p)}{q}\pm\mathcal{A}\sqrt{\frac{3(p-\omega)}{q}}\tan\left(\sqrt{\frac{\omega-p}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)}{\mathcal{A}\pm\sqrt{\frac{3(p-\omega)}{q}}\tan\left(\sqrt{\frac{\omega-p}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)}\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},$$

$$\mathcal{H}_{1,2}^{*}(x,y,z,t)=\left(\frac{\frac{3(\omega-p)}{q}\pm\mathcal{A}\sqrt{\frac{3(p-\omega)}{q}}\cot\left(\sqrt{\frac{\omega-p}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)}{\mathcal{A}\pm\sqrt{\frac{3(p-\omega)}{q}}\cot\left(\sqrt{\frac{\omega-p}{2pr\omega}}\left(\frac{px^{\vartheta}+qy^{\vartheta}+rz^{\vartheta}-\omega t^{\vartheta}}{\vartheta}+\mathcal{C}\right)\right)}\right)e^{\left(\frac{\varrho}{2}\mathcal{W}(t)-\frac{1}{4}\varrho^2t\right)},$$

$$\mathcal{H}^*_{1,3}(x,y,z,t)=\left(\frac{\frac{3(\omega-p)}{q}\pm\mathcal{A}\sqrt{\frac{3(\omega-p)}{q}}\tanh\left(\sqrt{\frac{p-\omega}{2pr\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)}{\mathcal{A}\pm\sqrt{\frac{3(\omega-p)}{q}}\tanh\left(\sqrt{\frac{p-\omega}{2pr\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)}\right)e^{\left(\frac{\varrho}{2}W(t)-\frac{1}{4}\varrho^2t\right)},$$

$$\mathcal{H}^*_{1,4}(x,y,z,t)=\left(\frac{\frac{3(\omega-p)}{q}\pm\mathcal{A}\sqrt{\frac{3(\omega-p)}{q}}\coth\left(\sqrt{\frac{p-\omega}{2pr\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)}{\mathcal{A}\pm\sqrt{\frac{3(\omega-p)}{q}}\coth\left(\sqrt{\frac{p-\omega}{2pr\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)}\right)e^{\left(\frac{\varrho}{2}W(t)-\frac{1}{4}\varrho^2t\right)},$$

$$\mathcal{H}^*_{1,5}(x,y,z,t)=\left(\frac{\frac{3(\omega-p)}{q}\pm\mathcal{A}\left(\sqrt{-\frac{q}{6pr\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)^{-1}}{\mathcal{A}\pm\left(\sqrt{-\frac{q}{6pr\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)^{-1}}\right)e^{\left(\frac{\varrho}{2}W(t)-\frac{1}{4}\varrho^2t\right)},$$

where $\mathcal{A}$ and $\mathcal{C}$ are constants.

The above solutions, when combined with the transformation given in Eq. (3.13), allow generation of additional solutions and so on.

The solutions of Eq. (1.2) can be derived by applying the same methodology outlined above. Accordingly, we obtain

$$\mathcal{H}_{2,1}(x,y,z,t)=\pm\sqrt{\frac{3(r-\omega)}{p}}\cot\left(\sqrt{\frac{\omega-r}{2pq\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}W(t)-\frac{1}{4}\varrho^2t\right)},\ \frac{\omega-r}{pq\omega}>0,$$

$$\mathcal{H}_{2,2}(x,y,z,t)=\pm\sqrt{\frac{3(\omega-r)}{p}}\tanh\left(\sqrt{\frac{r-\omega}{2pq\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}W(t)-\frac{1}{4}\varrho^2t\right)},\ \frac{\omega-r}{pq\omega}<0,$$

where $\mathcal{C}$ is constant.

Similarly, the solutions of Eq. (1.3) are obtained as

$$\mathcal{H}_{3,1}(x,y,z,t)=\pm\sqrt{\frac{3(q-\omega)}{r}}\tan\left(\sqrt{\frac{\omega-q}{2p^2\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}W(t)-\frac{1}{4}\varrho^2t\right)},\ \frac{\omega-q}{p^2\omega}>0,$$

and

$$\mathcal{H}_{3,2}(x,y,z,t)=\pm\sqrt{\frac{3(\omega-q)}{r}}\coth\left(\sqrt{\frac{q-\omega}{2p^2\omega}}\left(\frac{px^\vartheta+qy^\vartheta+rz^\vartheta-\omega t^\vartheta}{\vartheta}+\mathcal{C}\right)\right)e^{\left(\frac{\varrho}{2}W(t)-\frac{1}{4}\varrho^2t\right)},\ \frac{\omega-q}{p^2\omega}<0,$$

where $\mathcal{C}$ is constant.

4.2 Boundedness of the obtained solutions

Boundedness of the solutions to Eq. (1.1)-(1.3) is determined by the deterministic component $\mathcal{M}(\xi)$. Hyperbolic tanh-type solutions are uniformly bounded in space and yield physically admissible localized waves. In contrast, trigonometric solutions involving tan and cot, as well as coth-type and rational solutions, exhibit singularities at finite values of ξ and therefore remain unbounded, except on restricted domains. Boundedness is interpreted structurally with respect to the travelling wave variable ξ, while stochastic forcing only modulates amplitudes and does not alter the spatial structure or eliminate existing singularities.

5. Results and Discussion

5.1 Comparisons:

In this subsection, we compare our obtained solutions with those derived using other methods. First, we consider the results reported in [18] where a modified extended tanh-function method was employed. By setting ϱ=0, and rewriting the nonlinear terms in Eqs. (1.1)-(1.3) as $\mathfrak{D}^\vartheta_y\mathcal{H}^3$, $\mathfrak{D}^\vartheta_x\mathcal{H}^3$, and $\mathfrak{D}^\vartheta_z\mathcal{H}^3$ respectively, the trigonometric (tan, cot) and hyperbolic (tanh, coth) solutions families coincide with those presented in [18]. On the other hand, by employing the Bäcklund transformation, our method yields an infinite family of exact solutions.

Next, we compare our results with those presented in [19], where solitary wave solutions were derived using the Sardar sub-equation method. By choosing ϱ=0 and ϑ=1, the corresponding trigonometric and hyperbolic solutions reported in [19] are recovered as special cases of our results. The remaining solutions obtained in this study are not found in the literature using previously applied techniques. This highlights the robustness and effectiveness of the R-B S-ODE method in generating novel exact solutions.

5.2 Influence of white noise (WN) and fractional derivative (FD) on the solution of FSWBBM equations:

In this subsection, the influence of WN and FD on the solutions of Eqs. (1.1)-(1.3) is analyzed. Analytical solutions have been worked out for different noise strengths ϱ and fixed fractional order ϑ. The following parameters will be fixed: $\mathcal{C}=0$, $y=0$, $z=0$, $\mathcal{A}=-1$, with $x,\ t\ \in\ [-5,5]$. The simulations and corresponding visualizations are generated using the MATLAB software.

Influence of WN: Figure 1-5 illustrate the effect of multiplicative white noise on different wave profiles. In all cases, panels (I)-(IV) presented three-dimensional surfaces corresponding to increasing noise strengths ϱ=0, 0.7, 1.2, 1.7, and while panel (V) displays the associated two-dimensional profiles at a fixed time. As the noise strength increases, the wave amplitude is progressively increased, often leading to extreme peaks or singular behavior. Significantly, this amplification leaves the underlying spatial structure of each wave remains unchanged, indicating that stochastic forcing primarily acts as an amplitude-scaling process rather than altering the inherent wave structure.

Figure 1. Exhibits the space-time evolution of $\mathcal{H}^*_{1,3}$. The deterministic case exhibits a localized singular structure with a sharp downward spike. Increasing noise strength amplifies the wave magnitude, resulting in a singular-kink structure dominated by extreme amplitudes.

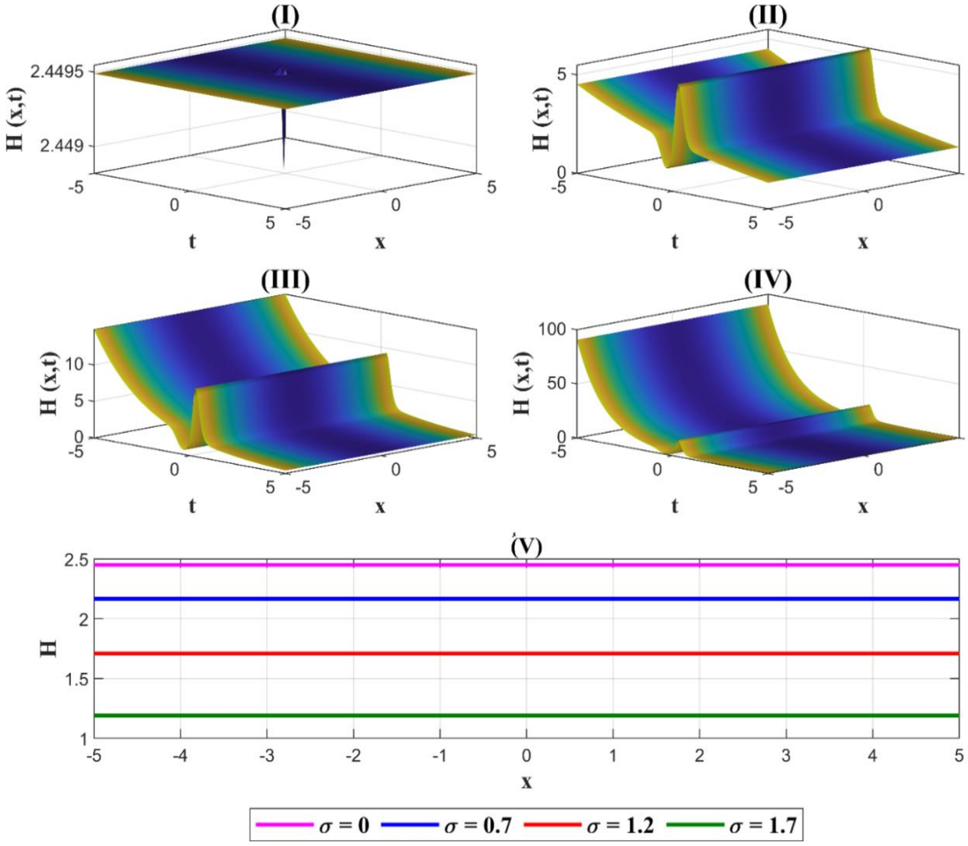

Figure 1. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}^*_{1,3}$ with $\wp = 1,\ q = 1,\ r = -\frac{1}{3}, \omega = -1,\ \vartheta = 0.25$, (I) $\varrho = 0$, (II) $\varrho = 0.7$, (III) $\varrho = 1.2$, and (IV) $\varrho = 1.7$ and panel (V) corresponding 2D-curves at $t = 2$.

Figure 2. Show the evolution of the wave profile $\mathcal{H}_{2,2}$. The solution forms a singular-kink wave whose spike height increases progressively with noise strength.

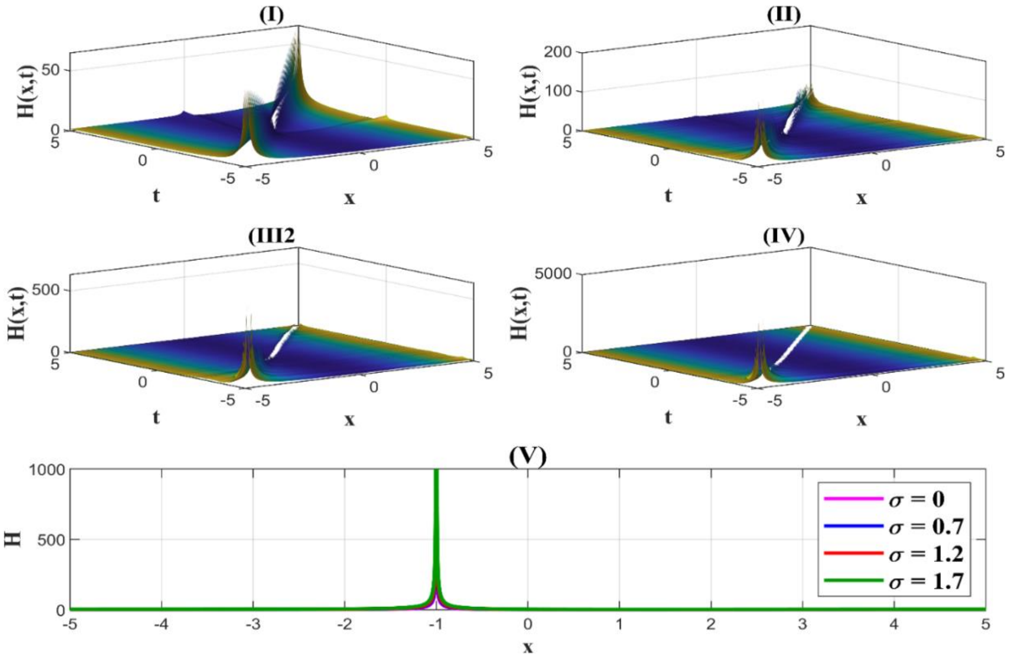

Figure 2. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}_{2,2}$ for $\wp = 1,\ q = 1,\ r = 0.1,\ \omega = 1,\ \vartheta = 0.5$, (I) $\varrho = 0$, (II) $\varrho = 0.7$, (III) $\varrho = 1.2$, and (IV) $\varrho = 1.7$ and panel (V) corresponding 2D-curves at $t = -1$.

Figure 3. Displays the evolution of $\mathcal{H}_{2,3}$. The deterministic solution corresponds to a stable kink connecting two distinct amplitude levels. Increasing noise preserves the kink shape while amplifying the peak amplitudes.

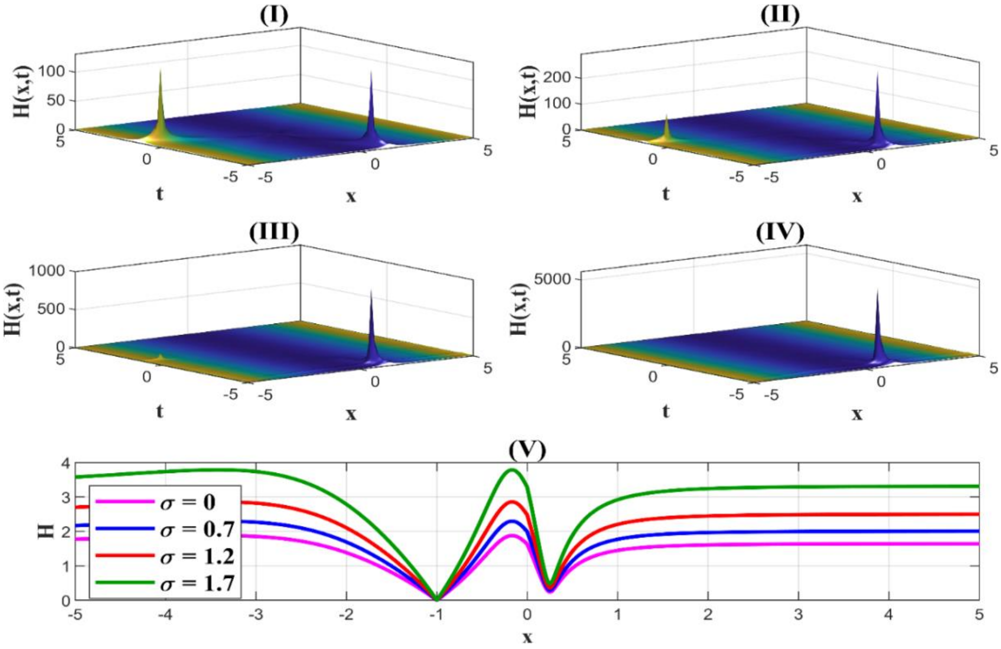

Figure 3. Panels: (I)-(IV) 3D-shape of $\mathcal{H}_{2,3}$ with $\wp = 1,\ q = -\frac{1}{3},\ r = 0.1,\ \omega = 1,\ \vartheta = 0.25,$ (I) $\varrho = 0$, (II) $\varrho = 0.7$, (III) $\varrho = 1.2$, and (IV) $\varrho = 1.7$ and panel (V) corresponding 2D-curves at $t = -1$.

Figure 4. Presents wave dynamics of $\mathcal{H}_{3,1}$. The solution exhibits a singular periodic structure with bright singular spikes. Noise amplification strengthens the wave magnitude without modifying the periodic singular pattern.

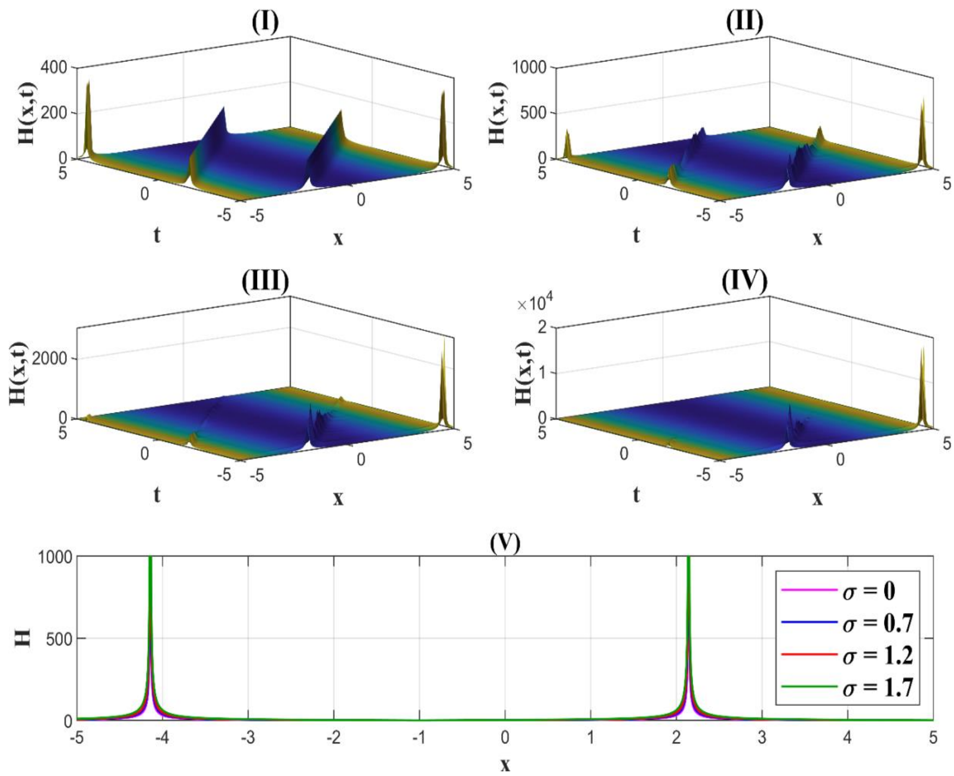

Figure 4. Panels: (I)-(IV) 3D-shape of $\mathcal{H}_{3,1}$ with $\wp = 1,\ q = 0.5,\ r = -0.3,\ \omega = 1,\ \vartheta = 1,$ (I) $\varrho = 0$, (II) $\varrho = 0.7$, (III) $\varrho = 1.2$, and (IV) $\varrho = 1.7$ and panel (V) corresponding 2D-curves at $t = -1$.

Figure 5. The wave surface of $\mathcal{H}_{3,4}$. The wave displays a bright singular structure that preserves its spatial structure under stochastic forcing, while exhibiting progressively stronger amplitude amplification and more pronounced peaks.

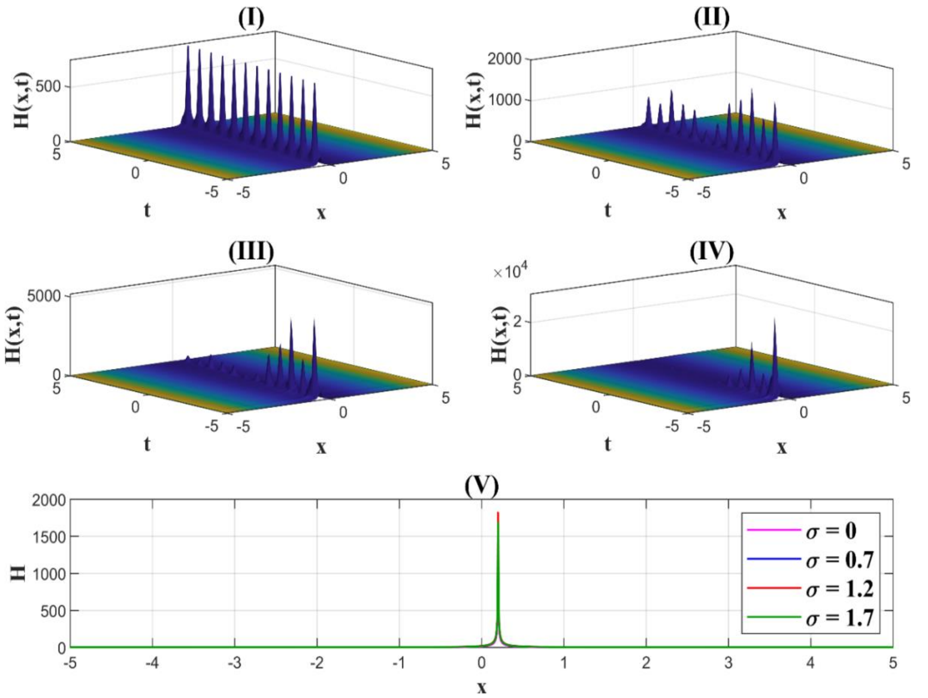

Figure 5. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}_{3,4}$ with $p = 5,\ q = 1,\ r = -0.3,\ \omega = 0.5,\ \vartheta = 1$, (I) $\varrho = 0$, (II) $\varrho = 0.7$, (III) $\varrho = 1.2$, and (IV) $\varrho = 1.7$ and panel (V) corresponding 2D-curves at $t = 2$.

Influence of CFD: Figures 6-10 demonstrate the effect of varying the conformable fractional order ϑ on the wave solutions. Panels (I)-(IV), present three-dimensional profiles corresponding to different values of order $\vartheta = 0.25, 0.5, 0.8$, and 1, while panel (V) shows the corresponding two-dimensional profiles. The results indicate that the fractional order significantly influences wave existence, shape, and stability, as well as the occurrence or absence of singular properties. In general, increasing ϑ tends to stabilize the wave profiles, leading to more regular structures and weaker singular characteristic.

Figure 6. Illustrates the wave profiles of $\mathcal{H}^{*}_{3,1}$. The lower fractional orders produce singular bright solitary-wave like structures, whereas higher values of ϑ yield smoother bright soliton-like profiles.

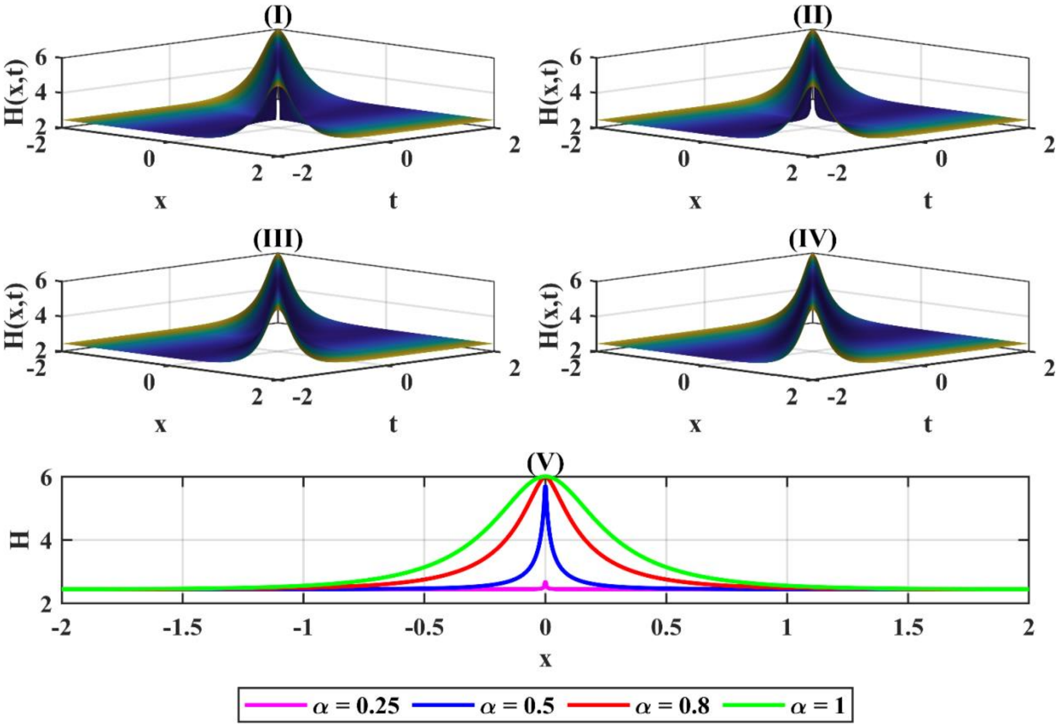

Figure 6. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}^*_{1,3}$ with $p = 1,\ q = 1,\ r = -\frac{1}{3},\ \omega = -1,\ \varrho = 0,$ and $A = -1$. (I) $\vartheta = 0.25$, (II) $\vartheta = 0.5$, (III) $\vartheta = 0.8$, (IV) $\vartheta = 1$ and panel (V) corresponding 2D-curves at $t = 0$.

Figure 7. Shows the evolution of singular structures under varying ϑ. The solution transitions from localized singular spike waves to singular solitary waves with kink-like skewness.

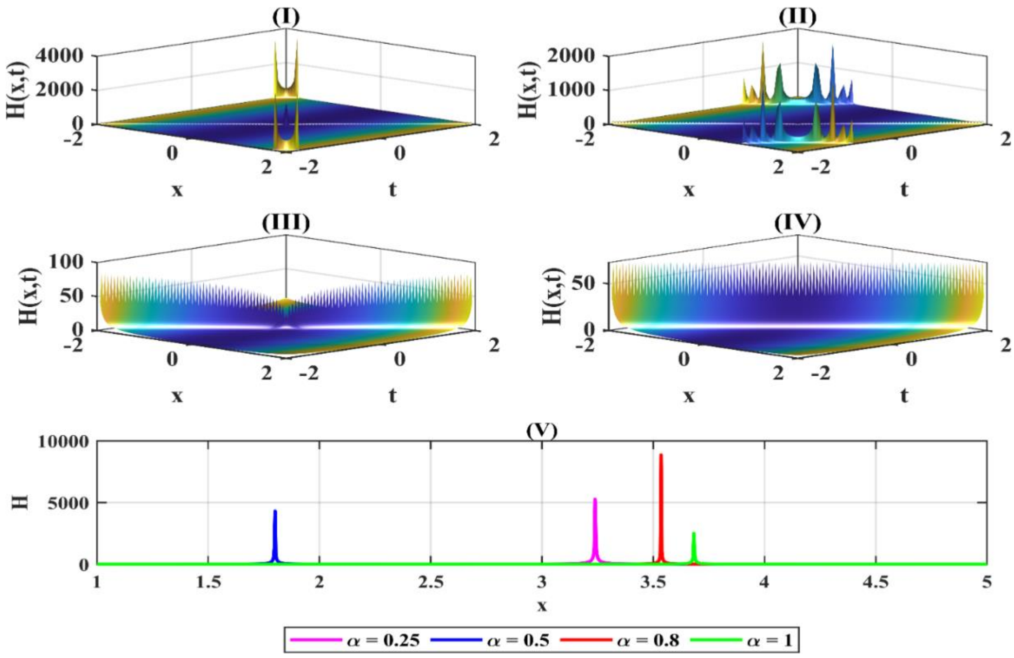

Figure 7. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}_{2,2}$ with $p = 1,\ q = 1,\ r = 0.1,\ \omega = 1,\ \varrho = 0$, (I) $\vartheta = 0.25$, (II) $\vartheta = 0.5$, (III) $\vartheta = 0.8$, (IV) $\vartheta = 1$ and panel (V) corresponding 2D-curves at $t = -1$.

Figure 8. Presents the wave dynamics of $\mathcal{H}_{2,3}$. At low ϑ, the solution exhibits a pronounced singular dark soliton, which evolves into a smooth dark soliton-like structure as ϑ increases.

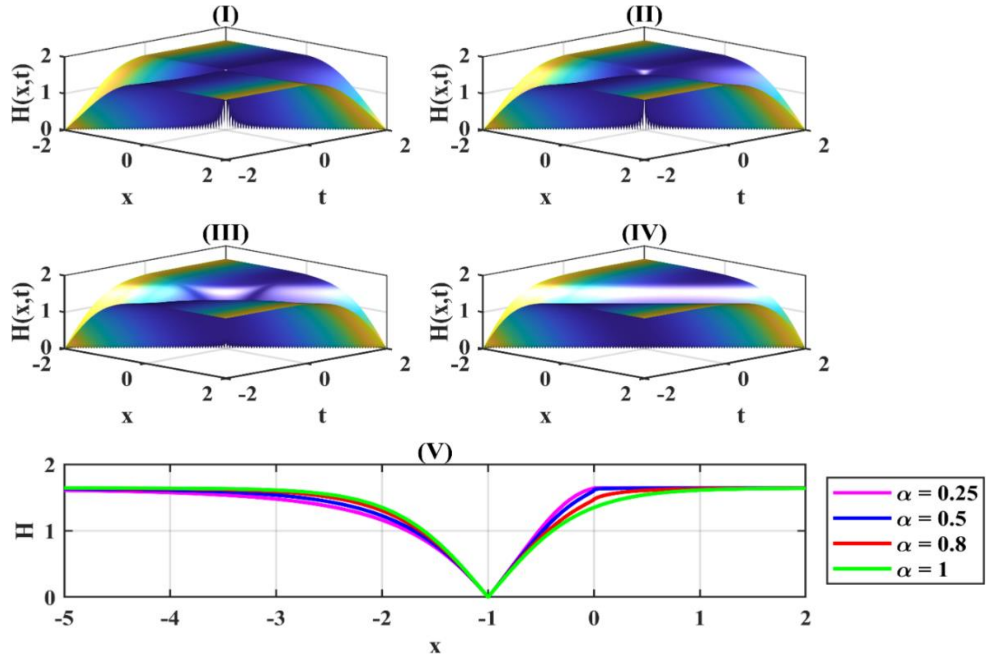

Figure 8. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}_{2,3}$ with $p = 1,\ q = -\frac{1}{3},\ r = 0.1,\ \omega = 1,\ \varrho = 0$, (I) $\vartheta = 0.25$, (II) $\vartheta = 0.5$, (III) $\vartheta = 0.8$, (IV) $\vartheta = 1$ and panel (V) corresponding 2D-curves at $t = -1$.

Figure 9. Depicts the wave profiles of $\mathcal{H}_{3,1}$ for different fractional orders. Singular solitary-wave structures dominate at lower ϑ, while higher values lead to a singular kink-type form.

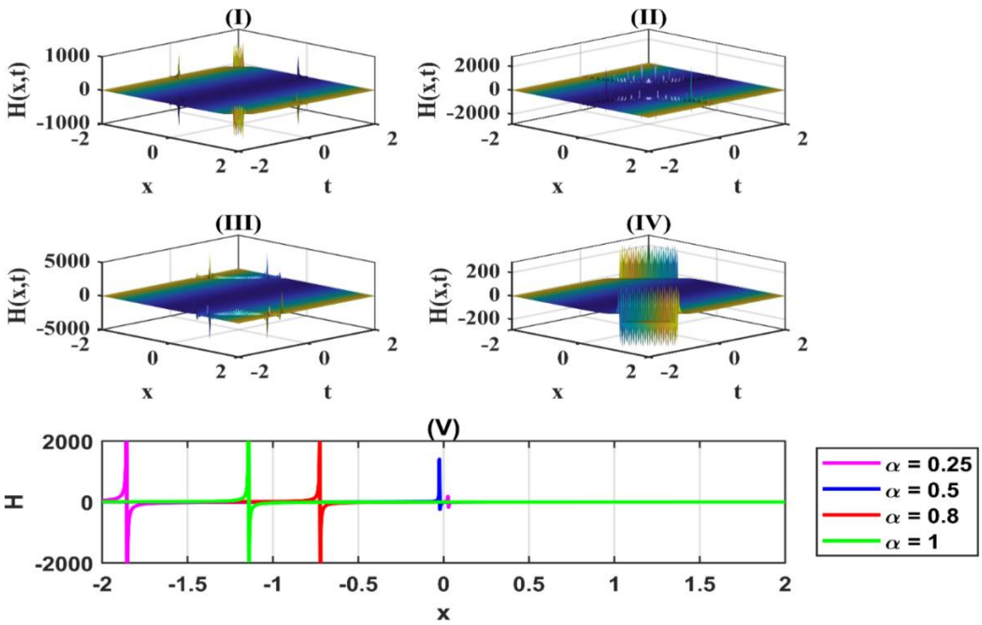

Figure 9. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}_{3,1}$ with $p = 1,\ q = 0.5,\ r = -0.3,\ \omega = 1,\ \varrho = 0$, (I) $\vartheta = 0.25$, (II) $\vartheta = 0.5$, (III) $\vartheta = 0.8$, (IV) $\vartheta = 1$ and panel (V) corresponding 2D-curves at $t = 2$.

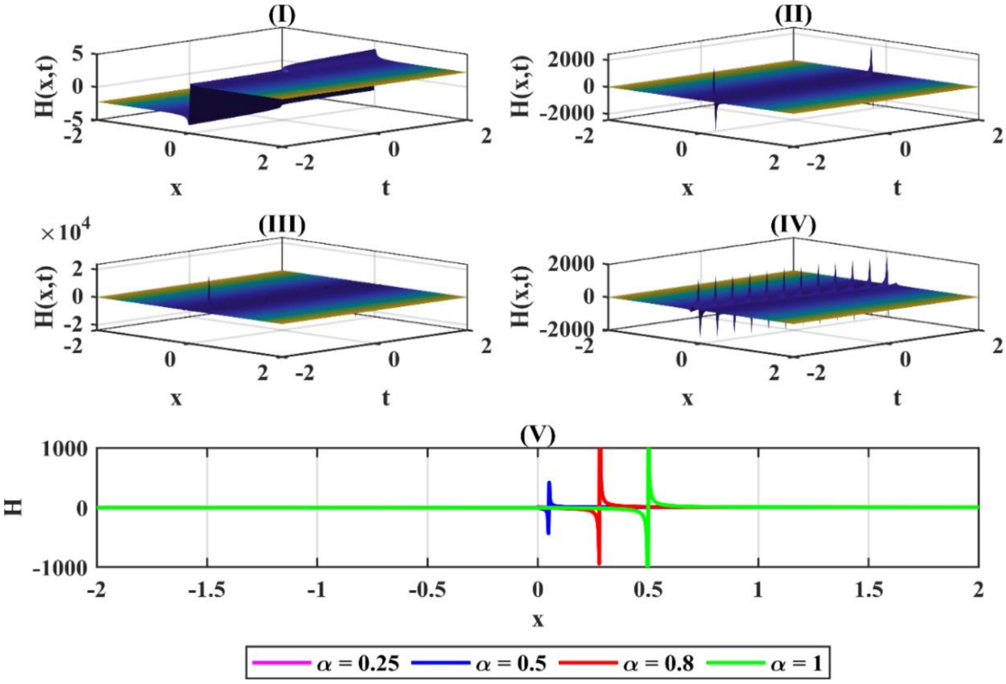

Figure 10. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}_{3,4}$ with $\mathscr{p} = 5,\ \mathscr{q} = 1,\ \mathscr{r} = -0.3,\ \omega = 0.5,\ \varrho = 0,$ (I) $\vartheta = 0.25$, (II) $\vartheta = 0.5$, (III) $\vartheta = 0.8$, (IV) $\vartheta = 1$ and panel (V) corresponding 2D-curves at $t = 5$.

Figure 10. displays singular wave patterns for varying ϑ. The solution exhibits a transition from single singular kinks to strong multi-singular spike structures, with spatial locations remaining fixed and amplitudes varying progressively.

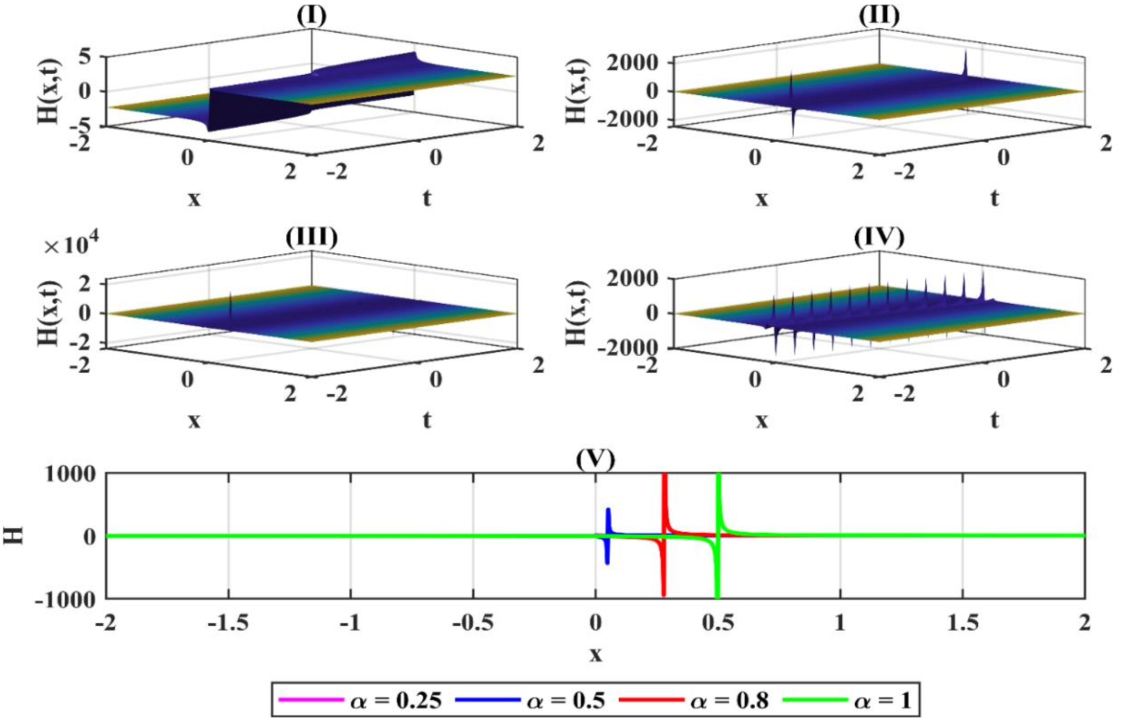

Figure 10. Panels: (I)-(IV) shows 3D-shape of $\mathcal{H}_{3,4}$ with $\mathscr{p} = 5,\ \mathscr{q} = 1,\ \mathscr{r} = -0.3,\ \omega = 0.5,\ \varrho = 0,$ (I) $\vartheta = 0.25$, (II) $\vartheta = 0.5$, (III) $\vartheta = 0.8$, (IV) $\vartheta = 1$ and panel (V) corresponding 2D-curves at $t = 5$.

6. Conclusions

In this paper, the influence of WN and fractional order on the solutions of the FSWBBM equations have been investigated. A variety of travelling waves solutions for the FSWBBM equations were obtained using R-B S-ODE method. These solutions include bright, periodic bright, a combination of bright and dark singular periodic, and singular dark waves. 2D and 3D plots of these solutions are presented to illustrate the physical behavior. Based on the findings, the R-B S-ODE method possesses several advantages: it is simple, computationally efficient, and capable of yielding an infinite sequence of exact solutions. As such, it proves to be a robust scheme for resolving FSWBBM equations. Future research will extend the outcomes of this investigation to explore exact solutions of complex FSPDEs models arising in mathematics and physics.

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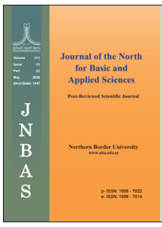

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Emerging Insights on Probiotics and Their Functional Benefits for Human Health

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Abstract
Probiotics have emerged as a central component of strategies aimed at improving human health through modulation of the gut microbiome. Growing evidence demonstrates that specific bacterial and yeast strains exert diverse functional benefits, ranging from enhancing gastrointestinal stability to regulating immune, metabolic, dermatological, and neuropsychological processes. This review reports current insights into mechanisms and therapeutic applications of probiotics, highlighting how these microorganisms promote colonization resistance, strengthen the intestinal barrier, modulate inflammatory and oxidative pathways, and influence gut–brain–skin communication. We summarize the most clinically relevant probiotic strains and their documented benefits across major health conditions, including digestive disorders, metabolic dysfunction, immune dysregulation, skin inflammation, and mental health. Furthermore, we discuss the safety considerations, regulatory landscape, and future directions in developing next-generation probiotics and personalized microbiome-based interventions. By integrating mechanistic understanding with clinical evidence, this review provides a comprehensive yet concise resource for advancing probiotic research and guiding their effective use in human health.

Keywords: Probiotics; Gut microbiota; Immune modulation; Metabolic regulation; Microbiome therapies; Next-generation probiotics

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1. Introduction

Probiotics have emerged as one of the most dynamic and influential areas of biomedical and nutritional research, largely due to their profound ability to interact with the human microbiome and shape health outcomes across multiple physiological systems [1]. Historically, probiotics were understood primarily through their use in fermented foods and their association with digestive benefits [2]. However, advances in microbiome sequencing technologies, systems biology, and clinical research have significantly expanded our understanding of these microorganisms [3]. Probiotics are now recognized not merely as digestive aids but as biologically active agents capable of modulating metabolism, immunity, neurological signaling, and dermatological responses [4]. As scientific interest intensifies, probiotics have evolved from traditional dietary components into promising therapeutic candidates that hold relevance in both preventive health and disease management [5].

Our understanding of probiotics has broadened in parallel with discoveries regarding the human gut microbiota, a complex ecosystem that influences nearly every aspect of host physiology [6]. Disruptions to this microbial environment-referred to as dysbiosis-have been associated with numerous chronic conditions, including inflammatory bowel disease, irritable bowel syndrome, metabolic syndrome, obesity, type 2 diabetes, cardiovascular disorders, skin inflammation, and mental health disturbances [7]. Probiotics, through their strain-specific functions, play an essential role in restoring microbial balance and preventing or mitigating the consequences of dysbiosis [8]. Their biological effects extend beyond the gut, highlighting intricate communication pathways such as the gut–brain axis, gut–skin axis, and gut–immune interface [9]. These interconnected systems provide a compelling rationale for examining probiotics not only within gastrointestinal health but as modulators of systemic homeostasis.

In recent years, research has intensified around the molecular and cellular mechanisms underlying probiotic functions [10]. Probiotics can influence the host through multiple pathways, including competitive exclusion of pathogens, enhancement of epithelial barrier integrity, synthesis of antimicrobial metabolites, modulation of inflammatory and oxidative stress pathways, and regulation of host immune signaling [11]. Certain strains can produce neurotransmitter-active compounds, enabling communication with the central nervous system, while others participate in lipid metabolism, glycemic control, and lipid-lowering processes. These multifaceted interactions underscore the importance of understanding the mechanisms of action at strain-specific and molecular levels, as the functional diversity among probiotic species and strains directly influences therapeutic outcomes.

The clinical relevance of probiotics continues to grow as evidence accumulates from randomized controlled trials, meta-analyses, and translational research [12]. Probiotics have demonstrated benefits in managing digestive disorders and antibiotic-associated diarrhea; improving metabolic markers related to obesity, cholesterol regulation, and insulin sensitivity; enhancing immune resilience; reducing inflammatory skin conditions; and supporting psychological well-being [13]. While not all strains exert the same effects, and clinical findings can vary based on dose, formulation, and host factors, the overall trajectory of evidence points to probiotics as powerful modulators of health [1]. Despite their widespread use and promising potential, important challenges remain [14]. Variability in strain efficacy, lack of standardization in manufacturing, inconsistent regulatory frameworks, and limited understanding of long-term safety and host-microbe interactions highlight the need for continued research and refinement [15]. Moreover, the emergence of next-generation probiotics and engineered microbial therapeutics introduces new opportunities and complexities in the field. Against this backdrop, a comprehensive review that consolidates existing evidence, highlights mechanistic insights, examines clinical applications, and outlines safety and future research priorities is essential to guide effective use and inform scientific advancement [16].

This review aims to synthesize current knowledge on the classification, characteristics, and mechanisms of probiotics; examine their functional benefits across gastrointestinal, immune, metabolic, dermatological, and neuropsychological domains; evaluate clinical evidence; present key strains associated with major health conditions; assess safety and regulatory considerations; and discuss future directions including personalized microbiome-based approaches and next-generation probiotic technologies. Through this integrated analysis, the review provides a holistic understanding of probiotics and their expanding relevance to human health.

2. Probiotic Types, Characteristics, and Mechanisms

Probiotics encompass a broad spectrum of microorganisms that confer health benefits when administered in adequate amounts, and their diversity reflects the complexity of the human microbiome itself [17]. These microorganisms include not only lactic acid–producing bacteria traditionally associated with fermented foods but also spore-forming *Bacillus* species, beneficial streptococci, and increasingly explored yeast strains such as *Saccharomyces boulardii* (**Table 1**) [18]. Each group possesses distinct physiological traits, survival capacities, and mechanisms of action, making strain-level characterization essential for determining therapeutic relevance [19]. As microbiome science advances, the classification of probiotics has shifted from broad genus-level categories toward highly specific strain-level assessments, emphasizing the importance of genomic stability, functional attributes, and host interaction capabilities [20]. The following subsections explore the taxonomy, safety criteria, and mechanistic foundations that define the functional potential of probiotic strains.

Table 1: Major Probiotic Strains and Their Primary Health Benefits

Probiotic Strain	Health Benefits	Mechanism of Action	Recommended Dosage	Strength of Evidence	Clinical Evidence	Reference
Lactobacillus rhamnosus	Improves gut health, prevents diarrhea, strengthens immune function	Enhances epithelial barrier, produces lactic acid, modulates immune system	1–10 billion CFU/day	High	Clinical trials show effectiveness in reducing the incidence of antibiotic-associated diarrhea (AAD) and improving gut health	[21]
Bifidobacterium longum	Reduces symptoms of IBS, boosts gut microbiota, supports immune health	Produces SCFAs, modulates gut microbiota, supports immune tolerance	1–5 billion CFU/day	Moderate	Clinical evidence supports improvements in IBS symptoms and inflammatory markers	[22]
Saccharomyces boulardii	Prevents and treats diarrhea, reduces IBD symptoms	Competitive exclusion, enhances gut barrier, reduces inflammation	250–500 mg 2–3 times/day	High	Well-documented in the prevention of AAD and Clostridium difficile infection	[23]
Streptococcus thermophilus	Aids lactose digestion, supports immune health	Ferments lactose, produces antimicrobial peptides, modulates gut flora	1–5 billion CFU/day	Moderate	Evidence in lactose-intolerant individuals showing improved digestion and immune function	[24]
Lactobacillus casei	Enhances gut motility, reduces inflammation, improves immunity	Produces lactic acid, promotes healthy microbiota, stimulates immune responses	5–10 billion CFU/day	High	Effective in managing symptoms of IBS and IBD, supports inflammatory balance in clinical settings	[25]
Bacillus coagulans	Supports digestion, enhances immune response, improves gut health	Forms spores, survives harsh environments, modulates gut microbiota	1–5 billion CFU/day	Moderate	Clinical studies show significant improvements in IBS, IBS-C, and general gut health	[26]
Bifidobacterium infantis	Improves symptoms of colic and constipation	Modulates immune system, increases gut motility, reduces gas production	1–5 billion CFU/day	Low	Well-established in pediatric gastrointestinal health, particularly for colic	[27]
Enterococcus faecium	Improves intestinal barrier function, reduces pathogen colonization	Inhibits pathogens via bacteriocin production, enhances gut barrier integrity	5–10 billion CFU/day	Low	Evidence in improving gut flora balance and reducing pathogen load in clinical trials	[28]

2.1 Classification and Key Strains

2.1.1 Bacterial and Yeast Probiotics

Bacterial probiotics represent the most extensively studied category, with *Lactobacillus* and *Bifidobacterium* at the forefront due to their long history of safe consumption and their natural prevalence in the human gastrointestinal and urogenital tracts [29]. *Lactobacillus* species are well known for producing lactic acid, contributing to pathogen suppression and pH regulation within the gut, while Bifidobacterium species play a crucial role in metabolizing complex carbohydrates, maintaining immune tolerance, and supporting early-life gut development [30]. Beyond these dominant genera, other bacterial groups such as *S. thermophilus, E. faecium, P. freudenreichii*, and various *Bacillus* strains have gained increasing attention. Spore-forming *Bacillus* species, in particular, offer exceptional resilience against environmental stressors, allowing them to survive gastric acidity and reach the intestine intact, where they germinate and exert metabolic and immunological benefits [31].

Yeast probiotics, though fewer in number, offer unique advantages that complement bacterial strains. *S. boulardii* is the most clinically validated yeast probiotic and is widely used for managing antibiotic-associated diarrhea, gastrointestinal infections, and inflammatory gastrointestinal conditions [32]. Its ability to survive antibiotic exposure, produce trophic factors that enhance brush-border enzyme activity, and modulate inflammatory signaling pathways distinguishes it from bacterial probiotics [33]. Yeasts also lack the cell structures associated with horizontal gene transfer, reducing the risk of transmitting antibiotic-resistance genes. Together, bacterial and yeast probiotics represent a multifaceted therapeutic resource, and their diversity highlights the importance of selecting strains based on targeted physiological outcomes rather than relying on broad generalizations about genera (**Figure 1**).

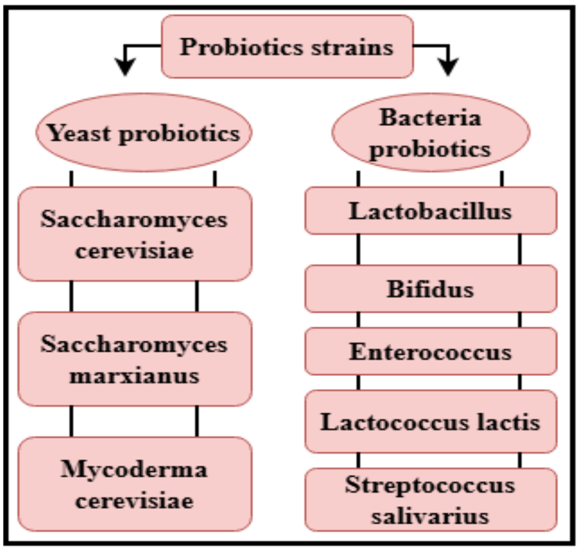

Figure 1: Classification and key strains used as probiotics

2.1.2 Selection and Safety Criteria

The selection of probiotic strains is governed by internationally recognized criteria established by bodies such as FAO/WHO, the European Food Safety Authority, and regulatory agencies across different regions [34]. These guidelines mandate that probiotic strains must be precisely identified using genomic techniques, demonstrate the ability to survive and function within the gastrointestinal environment, and show evidence of beneficial effects through mechanistic studies and clinical trials [35]. Strain-specific documentation is critical, as closely related strains often exhibit significantly different biological activities. Essential functional characteristics include acid and bile tolerance, adhesion to epithelial tissues, antimicrobial activity, and immune-modulating potential. The selection process ensures that only strains with validated biological activity and technological stability are used in supplements and functional foods [36].

Safety assessment is an integral component of probiotic characterization. Many commonly used strains are designated GRAS (Generally Recognized As Safe) or QPS (Qualified Presumption of Safety), based on historical consumption and accumulated toxicological data [37]. However, safety evaluations extend beyond general status and include screening for virulence factors, hemolytic properties, toxin genes, and transferable antibiotic-resistance determinants [38]. Since probiotics interact intimately with the host's immune system and microbiota, it is crucial to assess their behavior in vulnerable populations, including neonates, pregnant women, and immunocompromised patients [39]. Variations in regulatory standards across countries mean that probiotic manufacturers must comply with region-specific requirements for strain identity, dose, labeling, and health claims [40]. These safety and regulatory frameworks collectively ensure that probiotics used in clinical or nutritional applications provide benefits without posing health risks.

2.2 Core Mechanisms of Action

2.2.1 Microbiota Modulation and Colonization Resistance

A central mechanistic principle of probiotic function is their capacity to modulate the structure and activity of the gut microbiota [41]. Probiotics compete directly with pathogenic microorganisms for ecological niches, including adhesion sites on intestinal epithelial cells, thereby reducing the ability of harmful bacteria to colonize the gut [42]. This competitive exclusion is reinforced by the production of organic acids, such as lactic and acetic acid, which lower gut pH and create an unfavorable environment for pathogenic species [43]. Many probiotic strains also secrete bacteriocins, small antimicrobial peptides that target specific pathogenic organisms-enhancing the protective effect. Through these interactions, probiotics support microbial diversity and foster a stable gut ecosystem that resists dysbiosis triggered by antibiotics, infections, stress, or poor diet [44]. These ecological and metabolic modulation positions probiotics as key players in restoring gut homeostasis and preventing a cascade of downstream health issues linked to microbial imbalance. By shaping microbial communities and influencing microbe–microbe interactions, probiotics contribute to improved gastrointestinal function and broader systemic benefits (**Figure 2**).

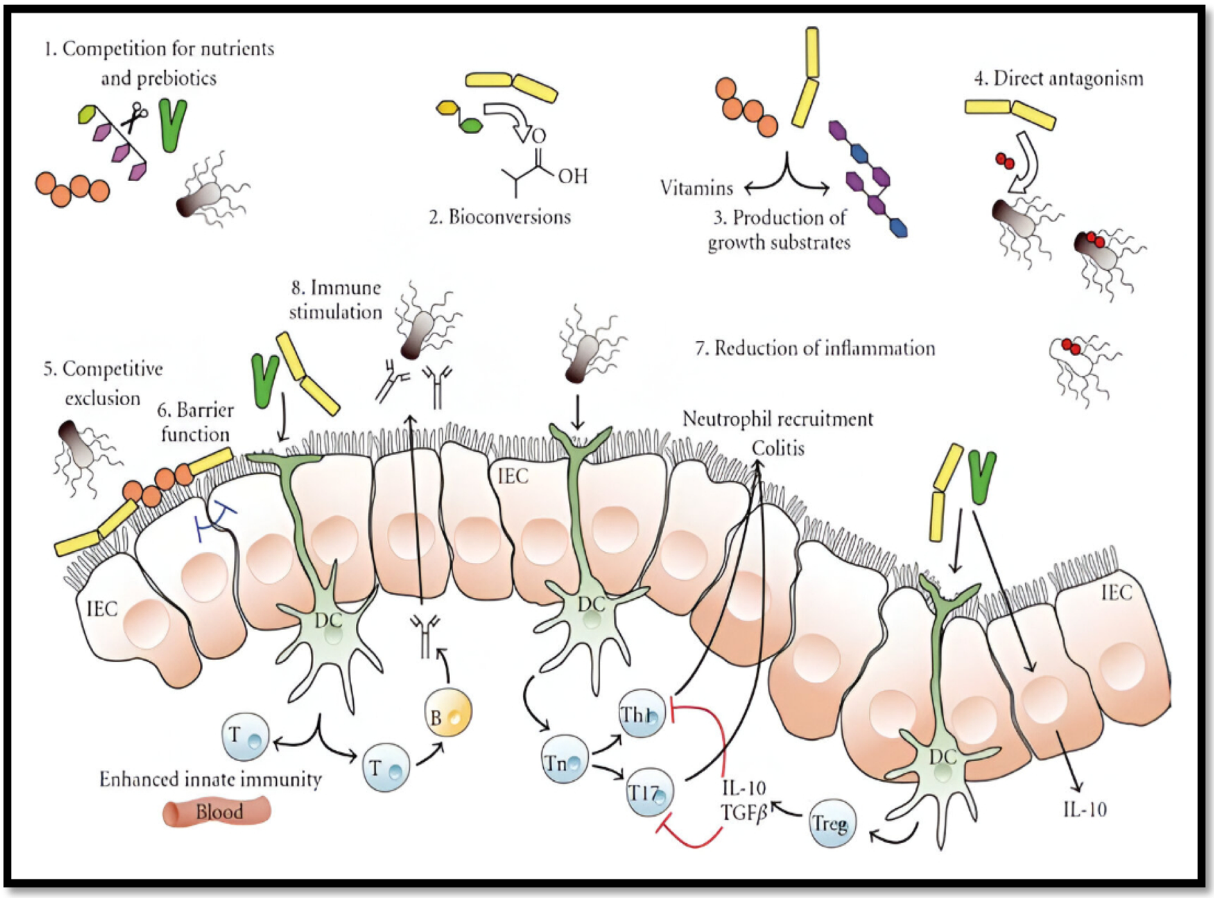

Figure 2: Mechanisms of action of probiotics. Schematic diagram illustrating potential or known mechanisms whereby probiotic bacteria might impact on the microbiota. These mechanisms include (1) competition for dietary ingredients as growth substrates, (2) bioconversion of sugars into fermentation products with inhibitory properties, (3) production of growth substrates (4) direct antagonism by bacteriocins, (5) competitive exclusion for binding sites, (6) improved barrier function, (7) reduction of inflammation, thus altering intestinal properties for colonization and persistence within, and (8) stimulation of innate immune response. Figure adopted from www.customprobiotics.com.

2.2.2 Metabolite Production and Host Signaling

In addition to direct effects on the microbiota, probiotics exert biological activity by producing a wide range of metabolites that act as chemical messengers within the host. SCFAs such as butyrate, propionate, and acetate support epithelial integrity, regulate inflammation, and influence appetite and energy metabolism [45]. Other metabolites, including vitamins, conjugated linoleic acid, and antimicrobial compounds, contribute to host nutrient status and pathogen defense. Some probiotic strains also degrade toxins, reduce oxidative stress, and facilitate the breakdown of complex dietary fibers, enhancing digestive efficiency and metabolic regulation [46].

Several probiotic strains engage directly with receptors on immune cells, including Toll-like receptors, influencing cytokine production and guiding the balance between pro-inflammatory and anti-inflammatory responses [47]. Certain strains modulate neurotransmitter production or regulate the precursors of serotonin, GABA, or dopamine, thereby participating in gut-brain communication and influencing psychological well-being [48]. Other probiotics impact endocrine signaling, lipid metabolism, and glycemic control through interactions with metabolic regulators [49]. Together, these mechanistic pathways reveal that probiotics operate not merely as transient microorganisms but as biologically active agents capable of orchestrating complex, multi-system interactions within the human body.

2.3 Synbiotics

Synbiotics refer to the combination of probiotics (beneficial live microorganisms) and prebiotics (non-digestible food ingredients that selectively stimulate the growth or activity of beneficial microbes). This synergistic combination is designed to enhance the effectiveness of both components, as prebiotics provide the necessary substrate to support the survival and growth of probiotics in the gut, while probiotics help to better utilize and metabolize prebiotics. Synbiotics aim to improve gut health by not only replenishing beneficial microbes but also creating an environment that supports their activity and long-term colonization [50, 51]. Synbiotics have been explored for their potential benefits in metabolic health, skin conditions, and mental health. For example, synbiotics that include specific strains in combination with inulin or fructooligosaccharides (FOS) have shown positive effects on reducing inflammation, improving insulin sensitivity, and supporting skin health [52]. Furthermore, synbiotics are gaining attention for their potential role in mental health and mood regulation, especially in conditions like anxiety, depression, and stress-related disorders. Although the clinical evidence for synbiotics is still emerging, early studies suggest that their therapeutic potential may surpass that of individual probiotics and prebiotics, especially in chronic conditions with multifactorial etiologies. Future research should focus on optimizing synbiotic formulations, determining effective dosages, and understanding the complex interactions between probiotics, prebiotics, and host-specific factors.

However, the evidentiary base for synbiotics should be interpreted with caution, because the term encompasses heterogeneous strain-substrate combinations that are not biologically equivalent. Reported outcomes are frequently contingent on probiotic strain identity, prebiotic type and dose, baseline dietary patterns, and inter-individual microbiome differences, which collectively contribute to substantial variability in efficacy across trials. Moreover, many clinical studies remain limited by short intervention periods, modest sample sizes, and inconsistent endpoint selection, reducing comparability and limiting inference about durability of effects. Importantly, claims of sustained intestinal "colonization" are not always supported; for many strains, observed benefits may reflect transient functional modulation rather than stable, long-term community restructuring. Accordingly, future investigations should emphasize adequately powered randomized controlled designs, explicitly classify products as synergistic versus complementary based on demonstrated metabolic compatibility, and incorporate mechanistic biomarkers alongside standardized clinical outcomes to delineate responder profiles and strengthen causal interpretation.

3. Functional Benefits of Probiotics on Human Health

Probiotics exert a wide range of functional benefits across multiple physiological systems, reflecting their multifaceted roles in maintaining gastrointestinal homeostasis, supporting immune responses, regulating metabolism and influencing dermatological and neuropsychological health [53]. Their ability to modulate microbial communities, strengthen epithelial defenses, produce bioactive metabolites, and regulate host signaling pathways positions them as powerful agents for both preventive and therapeutic applications [54]. Understanding these functional benefits provides the foundation for targeted clinical applications and informs the development of next-generation probiotics for personalized health interventions (**Table 2**).

Table 2: Clinical Applications of Probiotics in Major Human Health Conditions

Health Condition	Probiotic Strain(s)	Mechanism of Action	Clinical Evidence	References
Irritable Bowel Syndrome (IBS)	*Lactobacillus spp., Bifidobacterium spp.*	Modulates gut motility, reduces visceral hypersensitivity	Strain-specific effectiveness shown in reducing IBS-related symptoms	[55]
Inflammatory Bowel Disease (IBD)	*Lactobacillus rhamnosus, Bifidobacterium longum*	Reduces inflammation, promotes mucosal healing, modulates immune response	Studies demonstrate the ability to reduce flare-ups, maintain remission, reduce inflammation	[56]
Antibiotic-Associated Diarrhea (AAD)	*Saccharomyces boulardii, Lactobacillus GG*	Prevents pathogen overgrowth, restores beneficial gut flora, reduces microbial translocation	Strong evidence supporting the prevention and treatment of AAD	[57]
Obesity and Metabolic Syndrome	*Lactobacillus gasseri, Bifidobacterium animalis*	Modulates lipid metabolism, reduces visceral fat, enhances insulin sensitivity	Clinical trials showing reduction in body fat percentage, improved insulin sensitivity	[58]
Skin Health (Eczema, Acne, Psoriasis)	*Lactobacillus rhamnosus, Bifidobacterium bifidum*	Modulates systemic inflammation, regulates immune responses	Evidence in improving skin hydration, reducing eczema symptoms	[59]
Mental Health (Anxiety, Depression, Stress)	*Lactobacillus helveticus, Bifidobacterium longum*	Modulates the gut–brain axis, produces neurotransmitters (GABA, serotonin), reduces cortisol	Revealed potential in improving mood, reducing anxiety, cognitive function	[60]
Respiratory Infections	*Lactobacillus casei, Bifidobacterium animalis*	Stimulates immune responses, enhances mucosal immunity	Reduced incidence of upper respiratory infections	[25]

3.1 Gastrointestinal Health

3.1.1 Digestive Disorders (IBS, IBD, AAD)

In irritable bowel syndrome (IBS), probiotics help modulate gut motility and alleviate symptoms such as bloating and abdominal pain [61]. These improvements are largely attributed to the ability of probiotics to regulate microbial fermentation, reduce gas-producing organisms, and influence neuromuscular signaling pathways. Clinical trials have shown that specific strains of Lactobacillus and Bifidobacterium improve overall IBS symptom severity, highlighting the importance of strain-specific interventions [62]. Inflammatory bowel disease (IBD), which includes Crohn's disease and ulcerative colitis, is characterized by chronic inflammation and an impaired intestinal barrier [63]. Probiotics contribute to IBD management by reducing inflammatory cytokines, enhancing mucosal healing, and promoting regulatory T-cell activation [64]. Certain strains also downregulate NF-κB and other inflammatory pathways, helping restore immune tolerance. Although probiotics are not a replacement for conventional therapies, they serve as supportive agents that may reduce disease flares and maintain remission in select individuals [65]. Antibiotic-associated diarrhea (AAD) represents another well-documented therapeutic area where probiotics are highly effective [66]. By replenishing beneficial microbes disrupted by antibiotic therapy and preventing pathogenic overgrowth-particularly Clostridioides difficile-probiotics significantly reduce the incidence and severity of AAD, making them an essential adjunct in antibiotic regimens.

However, clinical outcomes for IBS and IBD are not uniform across trials. Meta-analyses generally report overall symptom improvement in IBS, but with substantial heterogeneity and frequent null findings-suggesting that benefits are often strain- and endpoint-specific rather than a class effect [12,102]. For IBD, evidence appears more consistent for select settings (e.g., ulcerative colitis remission maintenance or pouchitis) than for Crohn's disease, and variability in enrolled populations and outcome measures complicates comparisons across studies [50,65]. Likely contributors to these inconsistencies include differences in strain selection/combination, viable dose (CFU), formulation and duration, baseline disease severity, concomitant therapies, and trial design (sample size, follow-up length, and outcome definitions) [12,62].

3.1.2 Strengthening the Gut Barrier

The integrity of the intestinal barrier is essential for maintaining gastrointestinal and systemic health, and probiotics play a significant role in reinforcing this barrier at multiple levels [67]. The gut barrier is composed of mucus layers, epithelial cells, tight junctions, and immune defenses that work together to regulate microbial interactions and prevent pathogen translocation [68]. Probiotics enhance the expression of tight-junction proteins thereby strengthening the epithelial barrier and reducing intestinal permeability [69]. This is particularly important in conditions like leaky gut syndrome, celiac disease, and chronic inflammatory disorders, where impaired barrier function leads to heightened immune activation and systemic inflammation [70].

Additionally, probiotics stimulate the production of mucins, glycoproteins that form a protective layer over the intestinal epithelium. Increased mucin secretion enhances the barrier against pathogens and reduces the risk of bacterial translocation [71]. Some probiotic strains also produce short-chain fatty acids, notably butyrate, which serve as an energy source for colonocytes and promote epithelial regeneration. These combined actions support a robust mucosal defense system that protects against infections, reduces antigenic load, and maintains gastrointestinal equilibrium [72]. The ability of probiotics to reinforce barrier function has profound implications for preventing chronic inflammation, metabolic dysfunction, and autoimmune responses linked to barrier impairment (Figure 3).

3.2 Immune and Anti-Inflammatory Effects

3.2.1 Immune Regulation and Cytokine Balance

Probiotics exert significant immunomodulatory effects by interacting with immune cells and influencing cytokine signaling pathways [73]. They engage with pattern recognition receptors, including Toll-like receptors on epithelial and immune cells, which modulate downstream responses such as cytokine production, antigen presentation, and activation of innate and adaptive immunity [74]. Certain probiotic strains promote a shift from pro-inflammatory responses toward regulatory pathways by enhancing the production of IL-10 and other anti-inflammatory cytokines [75]. This makes them particularly valuable in conditions characterized by immune dysregulation, including allergies, respiratory infections, and autoimmune disorders.

Probiotics influence the balance between different T-cell subsets, including Th1, Th2, Th17, and regulatory T cells [76]. This balance is crucial for maintaining immune homeostasis and preventing excessive inflammatory reactions. For example, probiotics can suppress Th17-mediated inflammation while supporting Treg expansion, contributing to reduced tissue damage and improved immune tolerance [77]. These effects help explain the therapeutic potential of probiotics in conditions like atopic dermatitis, asthma, and low-grade systemic inflammation. Through their immunological interactions, probiotics enhance overall immune resilience, reducing susceptibility to infections and supporting long-term health.

3.2.2 Antioxidant and Anti-Inflammatory Responses

Oxidative stress and chronic inflammation are key contributors to the pathogenesis of numerous chronic diseases, including cardiovascular disorders, neurodegeneration, and metabolic syndrome [78]. Probiotics help counteract these processes through both direct and indirect mechanisms [10]. Certain strains produce antioxidant enzymes, such as superoxide dismutase and glutathione peroxidase, which neutralize reactive oxygen species and protect cellular structures from oxidative damage. Others stimulate endogenous antioxidant pathways within host tissues, enhancing overall oxidative defense.

In addition to their antioxidant effects, probiotics reduce the expression of pro-inflammatory cytokines while promoting anti-inflammatory mediators [79]. These immunological shifts help alleviate symptoms of chronic inflammation and reduce systemic inflammatory load. Probiotics also help normalize the gut microbiota, reducing endotoxin-producing bacteria and thus lowering circulating lipopolysaccharides (LPS) that contribute to metabolic inflammation [80]. Together, these antioxidant and anti-inflammatory properties illustrate the potential of probiotics as supportive agents in chronic disease prevention.

3.3 Metabolic and Systemic Health

3.3.1 Obesity, Diabetes, and Metabolic Regulation

Probiotics influence metabolic health through effects on nutrient absorption, energy harvesting, lipid metabolism, and hormonal signaling. Certain strains enhance the production of SCFAs, which regulate appetite, improve insulin sensitivity, and modulate hepatic lipid synthesis [81]. Probiotics also contribute to improved glycemic control by influencing incretin hormones such as GLP-1 and PYY, which regulate insulin secretion and appetite [82]. Clinical studies demonstrate that probiotic supplementation can reduce fasting glucose, improve insulin resistance indices, and support weight management when combined with lifestyle interventions [83]. Probiotics also affect adipocyte metabolism by modulating genes involved in fat storage and lipolysis. These metabolic interactions have implications for managing obesity, metabolic syndrome, and type 2 diabetes [84]. While probiotics are not standalone treatments, they complement dietary and pharmacological therapies, providing an accessible and low-risk strategy for improving metabolic outcomes.

At the same time, clinical trial findings for obesity- and diabetes-related outcomes are mixed. Reviews of human studies often show modest average improvements in glycemic control and some anthropometric markers, but also highlight high between-study heterogeneity and many trials reporting no significant benefit [83,12]. These discrepancies likely reflect strain-dependent metabolic mechanisms, differences in dose, adherence, and intervention duration, the presence (or absence) of co-interventions such as diet and exercise, medication use, and variability in participant phenotype and baseline microbiome status, along with inconsistent endpoints and reporting practices [84,13].

3.3.2 Cardiovascular and Lipid Profile Benefits

Cardiovascular health is closely linked to metabolic function, inflammation, and gut microbiota composition [85]. Probiotics contribute to cardiovascular well-being by lowering LDL cholesterol, reducing systemic inflammation, and improving endothelial function [86]. The cholesterol-lowering effects of probiotics are mediated by bile salt hydrolase activity, which reduces the reabsorption of bile acids and promotes cholesterol utilization for bile synthesis. Additionally, probiotics influence lipid metabolism by modulating hepatic gene expression and reducing circulating triglycerides. Probiotics also support cardiovascular health through anti-inflammatory actions and improvements in vascular function [87]. Chronic inflammation is a major contributor to atherosclerosis, and probiotics help reduce inflammatory mediators involved in plaque formation [88]. Some strains also produce metabolites that enhance nitric oxide availability, improving blood vessel relaxation and reducing blood pressure. These combined effects demonstrate the potential of probiotics as adjunctive therapies for cardiovascular risk reduction.

3.4 Skin and Gut–Brain Axis

3.4.1 Skin Health and Dermatological Effects

Probiotics influence skin health through their ability to regulate systemic inflammation, modulate immune responses, and support the gut-skin axis [89]. The gut–skin connection is mediated by microbial metabolites, immune signaling molecules, and inflammatory mediators that impact skin barrier function and tissue repair. Probiotics help restore balance in immune pathways implicated in atopic dermatitis, psoriasis, and acne, leading to reductions in symptoms such as redness, itching, and inflammation. Some strains enhance skin hydration and reduce transepidermal water loss by strengthening epithelial integrity [90].

Additionally, probiotics contribute to skin health by regulating lipid metabolism and producing metabolites that support barrier recovery. The reduction of systemic inflammatory markers and oxidative stress further promotes healthy skin physiology [91]. Clinical studies have shown that oral probiotic supplementation can improve outcomes in acne and eczema, while topical probiotics offer additional benefits through direct interactions with the skin microbiome [92]. Together, these effects highlight the potential of probiotics as multi-targeted agents for dermatological care.

3.4.2 Mental Health, Mood, and Cognitive Effects

Probiotics play an important role in mental health through their involvement in the gut–brain axis, a bidirectional communication system linking the gastrointestinal tract to the central nervous system [93]. Specific probiotic strains, often called psychobiotics, can influence psychological well-being by producing neurotransmitters such as GABA, serotonin, and dopamine or by regulating their precursors. These interactions help modulate mood, anxiety, stress responses, and cognitive function. Probiotics also reduce systemic inflammation and regulate HPA-axis activity, further influencing psychological resilience [94]. Clinical studies illustrate that probiotics can alleviate symptoms of mild to moderate depression, reduce stress-induced cortisol elevation, and improve cognitive performance in certain populations [95]. By modulating neural signaling and reducing inflammation, probiotics exert protective effects on brain health and support emotional stability [93]. Although research in this area is still growing, psychobiotics represent a promising new avenue for mental health interventions, particularly as part of integrative approaches.

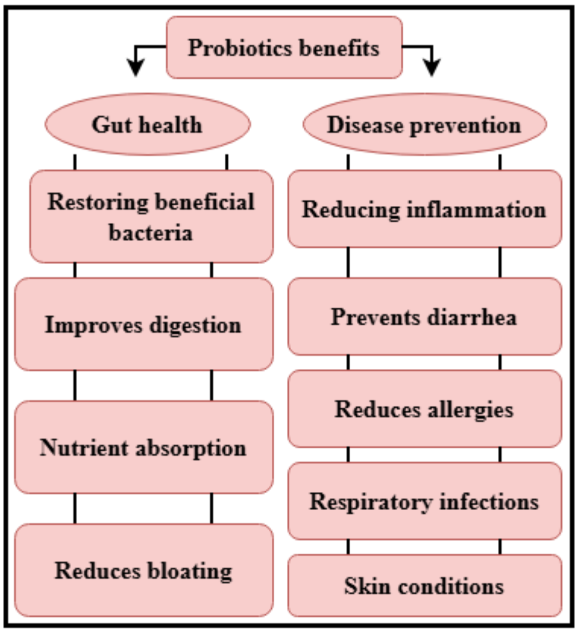

Figure 3: Functional benefits of probiotics

4. Applications, Safety, and Future Perspectives

Probiotics have transitioned from traditional dietary components to scientifically validated therapeutic agents with applications across clinical nutrition, preventive medicine, and personalized healthcare [96]. Their incorporation into foods, supplements, and therapeutic regimens reflects growing evidence of their capacity to modulate gut microbiota, support metabolic and immune functions, and influence systemic health [97]. At the same time, the expanding market for probiotic products underscores the importance of understanding formulation stability, strain viability, safety considerations, and global regulatory frameworks [98]. As the field evolves, probiotics are increasingly integrated into innovative delivery systems, next-generation microbial therapeutics, and precision nutrition strategies. This section examines the current applications of probiotics, and outlines emerging directions that are reshaping the future of probiotics.

4.1 Probiotics in Foods, Supplements, and Clinical Use

Probiotics are widely incorporated into fermented foods, functional beverages, and dietary supplements, serving as accessible tools for enhancing gut health and supporting overall well-being [99]. Fermented products such as yogurt, kefir, miso, kimchi, and kombucha provide natural sources of beneficial microbes, while encapsulated supplements offer more precise dosing and strain-specific formulations [100]. The viability of probiotic organisms during production, storage, and gastrointestinal transit is essential for delivering health benefits, and modern technologies including microencapsulation, freeze-drying, and spore-forming strains, which have greatly enhanced the stability and survivability of probiotics in various delivery formats [101]. Additionally, food-based probiotic interventions offer synergistic benefits by delivering bioactive compounds, fibers, and prebiotics that support microbial growth and metabolic activity.

In clinical settings, probiotics are increasingly used as adjunctive therapies for digestive disorders, metabolic syndrome, allergies, and immune conditions. Physicians prescribe strain-specific probiotics for antibiotic-associated diarrhea, atopic dermatitis, irritable bowel syndrome, and infant colic, among other conditions [102]. These applications rely on clinical evidence demonstrating measurable improvements in symptom severity, microbial balance, immune regulation, and barrier integrity. The integration of probiotics into medical nutrition therapy reflects a paradigm shift toward microbiome-centered healthcare, where dietary and microbial interventions are recognized as key components of disease prevention and recovery [103]. As more clinical trials identify strain-specific benefits and optimal dosing strategies, the role of probiotics in evidence-based healthcare continues to expand.

4.2 Safety, Risks, and Regulatory Challenges

Although probiotics are generally considered safe, particularly those with GRAS or QPS status, safety evaluations remain essential due to the biological complexity of host–microbe interactions [104]. Most probiotics pose minimal risk to healthy individuals; however, immunocompromised patients, elderly populations, neonates, and individuals with central venous catheters may be more susceptible to rare complications such as bacteremia or fungemia. Strain identity, host susceptibility, product purity, and manufacturing quality all influence probiotic safety [105]. The possibility of horizontal gene transfer underscores the need for genetic screening and stringent quality control during production. Ensuring strain stability, genomic integrity, and absence of virulence factors is critical to maintaining safety standards across the industry.

Regulatory frameworks for probiotics vary significantly across countries, creating challenges in standardizing product quality, labeling, health claims, and clinical validation requirements [106]. In some regions, probiotics are regulated as foods or supplements, while in others they fall under pharmaceutical or therapeutic categories, requiring rigorous clinical testing [107]. These disparities can lead to inconsistencies in product potency, accuracy of strain labeling, and consumer expectations. There is a growing call for global harmonization of probiotic regulations, particularly regarding strain identification, minimum viable counts, and evidence for functional claims [108]. Improved regulatory oversight will help ensure that probiotics marketed to consumers are safe, effective, and scientifically substantiated.

While probiotics are generally safe in the short term, limited data exist on their long-term safety, particularly with engineered strains, which may pose unforeseen risks such as gut microbiome alterations or metabolic disruptions. Ongoing post-marketing surveillance is crucial to identify any long-term adverse effects. Additionally, clearer labeling is needed, as many probiotic products lack detailed information on strain-specific efficacy, dosages, and storage conditions, leading to consumer confusion. Regulatory bodies should ensure labels provide accurate strain identity, viable counts, and evidence-supported claims to help consumers make informed choices.

4.3 Next-Generation Directions

4.3.1 Personalized Microbiome Therapies

As understanding of the human microbiome deepens, probiotics are increasingly viewed through the lens of personalized medicine. Individual differences in microbiome composition, genetics, diet, and lifestyle can significantly influence probiotic response, highlighting the need for tailored interventions [109]. Personalized microbiome profiling allows clinicians and researchers to identify deficiencies or imbalances and recommend strain-specific therapies that target specific pathways or physiological needs [110]. Emerging tools including AI-driven predictive models, metagenomic sequencing, and metabolomic signatures enable the design of more precise probiotic regimens with higher therapeutic potential [111]. The shift toward personalized probiotics represents a transformative development, offering targeted interventions capable of addressing unique health challenges and optimizing outcomes at the individual level.

4.3.2 Engineered and Next-Generation Probiotics

Next-generation probiotics, including *Akkermansia muciniphila, Faecalibacterium prausnitzii*, and engineered microbial strains, represent the future of microbiome therapeutics [112]. These organisms possess potent physiological effects, such as enhancing mucin production, regulating inflammation, and producing beneficial metabolites, but often require specialized cultivation and delivery systems [113]. Advances in synthetic biology have opened new possibilities for engineering probiotics with enhanced therapeutic functions, such as targeted metabolite production, pathogen detection and neutralization, or delivery of therapeutic molecules. Engineered strains may be designed to modulate specific cellular pathways, degrade harmful metabolites, or support immune regulation in disease-specific contexts.

These next-generation approaches promise to overcome limitations of traditional probiotics by offering higher specificity, measurable activity, and therapeutic precision [114]. However, they also raise new considerations related to safety, ethical oversight, and regulatory classification. As engineered probiotics move closer to clinical applications, robust frameworks will be required to evaluate their long-term effects, ecological consequences, and interactions within the microbiome [115]. The convergence of synthetic biology, computational modeling, and microbiome science is therefore poised to redefine the scope of probiotic research and open new opportunities for treating complex diseases through targeted microbial interventions.

5. Conclusion

Probiotics have progressed from traditional components of fermented foods to scientifically investigated agents with potential to influence human health across multiple physiological systems. Advances in microbiome research have clarified key mechanisms through which specific probiotic strains modulate gut microbiota composition, enhance intestinal barrier function, and regulate immune, metabolic, and neuroendocrine pathways. These strain-dependent effects underpin reported benefits in gastrointestinal, metabolic, dermatological, and mental health outcomes, supporting the growing interest in probiotics within preventive healthcare and medical nutrition therapy.

Despite these advances, important challenges remain. Clinical evidence is inconsistent for several indications, reflecting variability in probiotic strains, dosages, treatment durations, and study designs. Additional concerns include limited product standardization, the absence of harmonized global regulatory frameworks, and safety considerations in vulnerable populations. Addressing these limitations will require well-designed clinical trials with standardized protocols and clearly defined outcome measures.

Future research should prioritize personalized probiotic strategies that account for individual microbiota profiles, genetic factors, and specific disease contexts. In parallel, emerging technologies such as metagenomics, artificial intelligence, and synthetic biology are enabling the development of next-generation and engineered probiotics with more targeted therapeutic potential. Integrating these approaches may help resolve current inconsistencies in clinical outcomes and advance the translation of probiotic research into effective, evidence-based health interventions.

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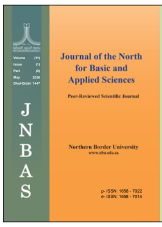

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Transformer-Based Intrusion Detection System for Encrypted Traffic Analysis

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Abstract
The rise of encryption in network communications is absolutely critical for ensuring privacy and confidentiality, and has greatly impacted how traditional intrusion detection systems (IDS) can use packet payload analysis to detect malicious activity. This study addresses the issue by developing a Transformer-based IDS that uses flow, not decrypted content. More specifically, network traffic is presented as tokenised sequences of features (packet length, interarrival time, direction, TCP flags, etc), allowing the self-attention mechanism of the transformer to model both short and long-range dependencies across encrypted sessions. The performance of the system is evaluated using both industry benchmark datasets with respect to machine learning and deep learning baselines, including Random Forest, Support Vector Machine, and LSTM networks. Experimental findings show that after comparison, the Transformer monitors consistently performed better than the baselines to generate 97.3% accuracy with an AUC of 0.985, reducing accordingly the count of false alarm positives/negatives across attack categories. Attention-weight also offers further interpretability over imposed features and their influence in classification decisions. This work indicates how transformers can provide an alternative pathway toward scalable, privacy-preserving, explainable IDS implementation, for historic and current encrypted traffic problems, across modern deep learning architectures and real-world cybersecurity challenges.

Keywords: Intrusion Detection System (IDS), Transformer, Encrypted Traffic, Deep Learning, Explainable AI, Network Security.

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1. Introduction:

In our digitally connected world, network security is vital. Cyber threats continue to grow rapidly, targeting organizations, governments, and individuals. Intrusion detection systems (IDS) are important in protecting our digital assets. IDS monitors network traffic for malicious behaviour or violations of accepted policy; however, the last several years have seen the advent of a major new challenge- the use of encryption in network communications [1]. Encryption is critical for maintaining confidentiality and privacy. It protects our sensitive data from eavesdropping, changes in our data, and unauthorized access. Prior to this shift in transparency, many modern protocols (e.g., HTTPS, TLS) began implementing and applying stringent encryption mechanisms as the default option [2]. While all of this provides additional layers of privacy for the user, this has created a major burden for traditional IDS systems, which use deep packet inspection (DPI) and content-based techniques. In encrypted traffic, the payload may contain malicious code, which is not directly transparent when processed by the IDS; therefore, traditional detection approaches and techniques cannot work [3].

Machine learning and deep learning solutions were proposed to address these limitations through the analysis of flow-based metadata (e.g., packet size, timing, sequence) [4]. Several models, including Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks, are currently utilized extensively in IDS due to their ability to capture spatial and temporal patterns, respectively [5]. Nevertheless, CNNs cannot model variable-length sequences and temporal dependencies, particularly if the traffic patterns are complex and contextual [6], whereas LSTMs can at least acknowledge sequential data, but suffer from issues regarding vanishing gradients, parallelizability, and efficiently modeling long-range dependencies [7].

To address the issues with CNNs and LSTMs, we propose a novel Transformer-based Intrusion Detection System for encrypted traffic analysis. The original Transformer architecture allows for self-attention mechanisms, which allow for modeling relationships between tokens, regardless of their position in the given sequence. The ability to capture these properties is important because modeling network traffic in a global context is crucial for identifying detailed anomalies and attack patterns within encrypted sessions.

The method proposed here characterizes traffic flows as sequences of structured tokens from decrypted packet metadata. Rather than using packet contents, we use decipherable features like packet length, direction, inter-arrival time, and TCP flags to create sequential representations of our input. For sequence data, we use a multi-layer Transformer encoder to build a model. The multi-layer encoder will learn the patterns that are representative of typical or malicious actions, even without any payload data.

The significant contributions of the this study are: we present a unique and efficient Transformer based IDS that can detect intrusion in encrypted traffic which, until now, has been limited by content-inspection based methodologies; we showed a new way to represent network flows as a sequence of tokens that allows the modeling of encrypted communications without decrypting the payload; we demonstrated the efficacy of our work across multiple, real-world datasets with the performance of our detector against established models - CNNs and LSTMs; and we proposed attention-based approach to model interpretability that allows security analysts to understand why our network flow detector made a given prediction as well as increasing operational transparency. Overall, this research work is the bridge between current state-of-the-art deep learning architectures and the urgent demand for effective intrusion detection capabilities in different environments, including encrypted management environments. We combined the advantages of sequence modeling with the need for our approach to be interpretable to demonstrate a scalable, privacy-preserving intrusion detection system for next-generation networked security.

2. Background

Transformer models have fundamentally altered deep learning, given their capability of processing sequences via attention, rather than relying on recurrence or convolutions. The idea of attention was initially proposed by authors in study [8]. Since that time, the success of the transformer architecture has garnered state-of-the-art results on so many tasks, across all domains, but especially in the natural language processing (NLP) domain. The significant innovation of the transformers is their self-attention mechanism, which allows the model to assess all positions in a sequence at the same time while learning dependencies between tokens at any relative distance [9]. The feature of self-attention is necessary in order for transformers to work effectively, especially for modeling complex sequential events (for example, network traffic), where the meaningful patterns may often be non-local and the strength of dependencies is context-dependent.

The Transformer model performs multi-head self-attention to compute a weighted representation of all positions in the input for each token [11]. The model learns attention scores that define the effect of one token on another, allowing the model to focus attention on the most relevant part of the sequence when making a prediction. Each head separately learns different types of dependencies, so they independently compute contributions to the representation and are concatenated and linearly transformed. Positional encoding is added to the input embeddings as a way to help the model understand the order of tokens, as the Transformer does not care about the position. The architecture itself consists of a stack of encoder layers, with each one consisting of a self-attention block followed by a feed-forward network and residual connections with layer normalization. The simple structures lend themselves to learning long-range dependencies, high parallelism, and scaling well to large datasets [12].

The Transformer has several distinct advantages when compared to CNNs and LSTMs. CNNs detect local patterns quite well via fixed-size kernels, but they have limited receptive fields, which hinders their ability to capture long-range dependencies. Stacking layers can help model a larger context, but this increases computational cost as well as the problem of vanishing gradients [13]. LSTMs were specifically designed to model sequences and theoretically can capture long-term dependencies using memory cells; however, they have some drawbacks. They require sequential learning (which limits parallelization), can have difficulty learning long dependencies due to vanishing gradients, and often require more training time. On the other hand, the Transformer can model sequences in parallel and utilize critical advantages to model relations (both short-range and long-range) effectively via attention, which is very effective when modeling more complex time-dependent structures, such as network traffic.

When it comes to encrypted network traffic, traditional IDS techniques have a critical weakness: it doesn't allow for seeing the payload content. For example, in most newer encryption technologies (TLS and VPN), the payload is tied up in a secure tunnel, and the payload itself is inaccessible since the encryption must be broken to see what it contains. There is a fundamental conflict, as breaking the encryption breaks security and privacy for the user. Traditional IDS relies on content-based signatures and deep packet inspection, with encrypted sessions, make these approaches obsolete [13].

The rationale for using Transformer models in this context is reasonable for multiple reasons. First, flow-based features are inherently time series data structures, as network traffic is time-based and occurs in the context of sessions (or flows) [14]. Therefore, we must model sequences with both short-term bursts and long-term dependencies. Transformers are particularly suited to modeling the above-mentioned sequences and dependencies because of their self-attention." Secondly, in the context of encrypted traffic, anomalies or attacks may be established through slight variations in a flow's packet size, timing, or sequence [15]. These features may not be localized, so global context modeling could provide a more informed representation of a packet's properties. Thirdly, Transformers lend themselves to interpretability (attention weights), which permit analysts to see what aspects of the traffic flow contributed to the decision of the model important aspect for security applications where justification and explainability are very important [16].

Based on these benefits, this study proposes to use a Transformer-based architecture for intrusion detection in encrypted traffic environments. Using the observable metadata, it is possible to represent encrypted traffic flows as a sequence of structured tokens that can be used by the Transformer to learn complex temporal and relational patterns without needing to access the content of the packets or their decryption. This allows a privacy-preserving, scalable, and self-adaptive approach to the modern intrusion detection problem in encrypted environments.

3. Related work

The ever-changing field of IDS for encrypted traffic has brought the use of advanced machine learning and deep learning techniques into focus, especially with transformer-based models. Current IDS methods, such as deep packet inspection (DPI), must navigate huge challenges in identifying an optimal balance between efficiency versus security when dealing with encrypted traffic [17]. This is promising, as research has shown that the use of new models allows for attackers to be identified accurately while maintaining computing time [18]. Hybrid deep learning structures appear to be providing results in regards to intrusion detection. Authors [19], proposed the hybrid semantic deep learning (HSDL) model utilizing LSTM, CNN, and SVM models and achieved high levels of accuracy at 99.98% for NSL-KDD and 98.47% for UNSW-NB15 datasets. The author's position on this hybrid model is that all three neural network models provide a better result based on being able to recognize more complex patterns of encrypted traffic. Artificial intelligence-based anomaly detection systems are proposed for the standards and differentiation in traffic, which may allow for real-time detection of certain types of attacks over encrypted traffic. A study by [20], present an AI-based system that is capable of attacking SlowDoS in real-time and validates the effort through real testbeds in the real world, showcasing its success and accuracy. Systems like these will show that AI is able to distinguish changes in encrypted streams and identify these subtle anomalies.

Big data volume, veracity, and variety issues should be considered for network traffic analysis. A study by [21], focused on the quality of data management issues, such as duplicate detection and missing value management, to improve the effectiveness of attack detection. The addition of data preprocessing steps is critical for training models that are robust and can adapt to the constraints of encrypted traffic, which can limit the appropriateness of features. Recently, transformer-based models have gained attention by demonstrating a broader representation of sequential and contextual information. A study by [22] described RTIDS, a transformer-based IDS that digitizes a feature image representation to ensure feature retention and balance dimensionality reduction in imbalanced datasets. RTIDS uses positional embeddings to allow for the retention of sequential dependencies of network flows, which is critical to be able to detect advanced attacks in encrypted streams.

Further progress shows Deep Learning (DL) models for IoT networks and encrypted traffic in the literature. Authors in [23], proposed a protocol-independent DL-based IDS across multiple IoT devices. Authors in study [24], also proposed 3D-IDS used doubly disentangled dynamic features to detect known and unknown threats in encrypted traffic.

Moreover, recent studies show an interest in advanced feature extraction techniques such as the combination of Morlet Wavelet Kernel Function and LSTM for IoT-Cloud intrusion detection. A study by [25], expanded classification performance by using a Differential Evaluation-Based Dragonfly Algorithm for optimal feature selection. These developments show how critical learning-based feature engineering is to transformer-based IDS.

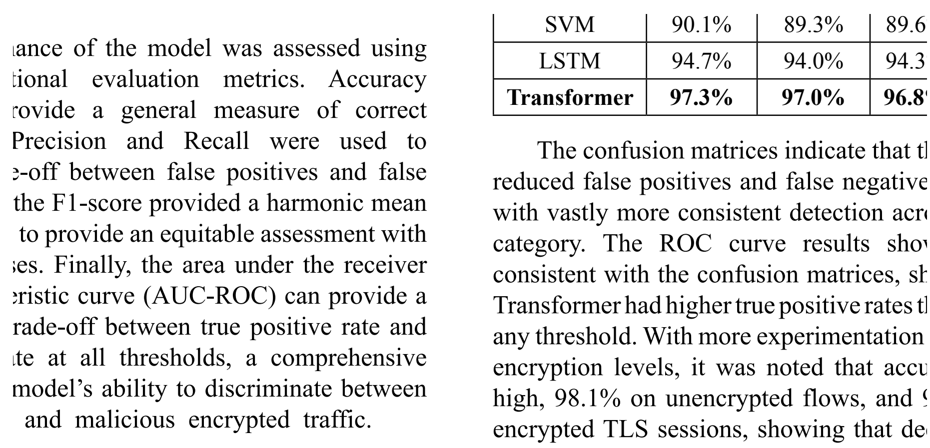
The literature clearly shows a trend towards utilizing transformer architectures and hybrid deep learning models to enhance the intrusion detection of encrypted traffic. These models are focused on leveraging complex, sequential, and contextual information implied in network data to increase detection capacity and robustness in the more and more sophisticated landscape of cyber threats.

4. Methodology

4.1 System Overview

We propose a Transformer-based intrusion detection system framework designed to identify malicious activities in encrypted network traffic. The total pipeline includes sequential stages that carry raw network traffic (from PCAP) to a structured sequence suitable for modeling with a Transformer. The system starts with raw capture of network traffic in the form of packet capture (PCAP) files. The packet captures are pre-processed to obtain session-level flow records, including relevant metadata features. Flows are segmented and tokenized to generate sequences according to selected features while maintaining the temporal structure of the observed communication patterns. The token sequences are input into a Transformer encoder model, which learns the contextual relationships between the tokens based on attention mechanisms. While payloads of encrypted traffic are protected, attack packets often demonstrate patterns that are recognizable through their packet header information and flow metadata. Identifying traffic through flow-based analysis, due to the differences between standard and attack traffic includes differences in the size and timing of packets, as well as the differences in the behaviour of packets when compared to a given standard (or 'normal') traffic profile. Past research clearly indicates identifiable traffic patterns during DoS attacks, repetitive sequences of timing packets during brute-force attacks, and abnormal TCP communication flags during intrusions and therefore is a valid method for detecting these types of attacks without the need for decrypting packets.

The output of the final classification layer produces the output prediction indicating if the observed traffic sequence represents normal or malicious behaviour. The architecture of the proposed approach is depicted in Fig. 1.



ance of the model was assessed using tional evaluation metrics. Accuracy rovide a general measure of correct Precision and Recall were used to e-off between false positives and false the F1-score provided a harmonic mean to provide an equitable assessment with ses. Finally, the area under the receiver eristic curve (AUC-ROC) can provide a rade-off between true positive rate and te at all thresholds, a comprehensive model's ability to discriminate between and malicious encrypted traffic.

SVM	90.1%	89.3%	89.6
LSTM	94.7%	94.0%	94.3
Transformer	**97.3%**	**97.0%**	**96.8**

The confusion matrices indicate that t reduced false positives and false negative with vastly more consistent detection acr category. The ROC curve results sho consistent with the confusion matrices, sh Transformer had higher true positive rates t any threshold. With more experimentation encryption levels, it was noted that accu high, 98.1% on unencrypted flows, and encrypted TLS sessions, showing that de

Fig. 1. Overview of the proposed approach

The method details a simple end-to-end data pathway. Raw catalogued network traffic is initially processed (the raw network) and transformed into sequences of packet-level metadata, that provide information on the packets. These sequences are then tokenized and transformed using embeddings and positional encoding so that they maintain the time correlation of packets (temporal structure). A Transformer encoder is used to learn the global (i.e., across the complete packet stream) and local (packet-to-packet) relationships for the packet sequences, which are then aggregated using a pooling layer. Finally, a classification layer is used to determine if the packet stream is classified as either benign or malicious. The resulting pathway is a 'clean' pathway between encrypted network flow and malicious traffic detection, with no requirement to examine the payloads.

4.2 Data Preprocessing

The first step in the proposed methodology includes collecting encrypted network traffic in PCAP (Packet Capture) format. This includes benign sessions of user traffic along with malicious behaviours such as port scans, denial-of-service (DoS) attacks, brute force attacks, and command-and-control (C2) traffic. Many of these sessions utilize encrypted return via TLS, HTTPS, and/or VPN tunnels, which prevent content 'inspection' while further emphasizing the need for metadata-based analysis. The flow records created by analysing traffic must be reconstructed from PCAP files. PCAP files will be processed with programs such as CICFlowMeter, Wireshark or Tshark. Each specific recorded flow will be identified using the five-tuple standard: source IP, destination IP, source port, destination port, and protocol. Since decrypting and inspecting payload content breaches several encryption and privacy requirements, the system extracts flow-level metadata features describing the structural and behavioural characteristics of the communication without ever decrypting any data.

Table 1: Summarizes the extracted features used for modeling encrypted traffic:

Feature	Description
Packet Length (bytes)	Minimum, maximum, mean, and standard deviation of packet sizes
Inter-arrival Time (ms)	Mean and variance of time gaps between consecutive packets
Flow Duration	Total time duration of the session
Packet Direction	Indicator of packet direction (forward/ reverse)
TCP Flags	Binary indicators for SYN, ACK, FIN, etc.
Packet Count	Total number of packets in forward and reverse directions
Bytes per Direction	Total number of bytes transmitted per direction

Having extracted the features (Table 1), each flow can now be seen as a tokenized sequence of feature vectors, where each token is a packet or a small number of packets. The temporal structure of the network sessions is preserved in the sequences, which are essential for detecting modes of attack behaviour that can develop or occur over a period of time. Given that traffic is encrypted and the payload contents are no longer visible, the modelling of temporal patterns in the flow-based sequences enables the system to identify suspicious activity solely through its metadata. These sequences are either truncated or padded to a fixed sequence length, such that input dimensions for the Transformer-based detection model are uniform across samples.

The chosen features capture the main statistical and time-based behaviour patterns of encrypted flows due to how attackers perform attacks. Attackers modify the packet when launching an attack, so they will change things like the size, timing direction, and flag behaviours of packets. Therefore, the statistical information about packets makes this metadata usable as a reliable feature, even though there is no payload. Furthermore, the features also allow researchers to replicate their studies using different datasets which have been encrypted.

4.3 Transformer Model Design

Tokenized traffic flow sequences from encrypted network sessions are fed to a Transformer-based deep learning architecture. Each token in the sequence is a feature vector describing a packet or a group of packets in a session, and its structural and behavioural attributes without payload. Tokenization has been performed on the packets or micro-flows, so that the temporal order of the packets can be preserved while also retaining the finer granularity of the behaviour patterns that may occur within the encrypted network traffic being analysed. By breaking down each flow into individual tokens, it will assist the Transformer with learning the burst patterns, general timing irregularities and directional shifts that are characteristic of malicious activities. This approach justifies the reproducibility of the tokenization process and provides consistency with the way that encrypted flows change and evolve over time.

Let the input sequence be denoted as:

performance of SQL injection attac (1)

Here, T is the fixed sequence length (number of tokens), and d is the feature dimension of each token (e.g., 8–20 features per token). If categorical identifiers such as port numbers or TCP flags are used, an embedding layer E is applied as given in Eq. (2). Otherwise, the raw numerical feature vectors x_t are normalized and passed directly.

attar, S., Khan, S., Khan, M. I., Akhm (2)

Since the Transformer does not inherently model sequence order, positional encoding is added to each input vector to retain temporal structure. The sinusoidal encoding is given in Eq. (3).

Flowtransformer: A transformer framework for flow-based network intrusion detection (3)

The encoded input as given in Eq. (4) becomes:

M. I. (2022). Anomaly detection in encrypted HTTPS traffic using machine learning (4)

These encoded vectors are passed through stacked Transformer encoder layers. Each encoder layer comprises expressed in Eq. (5-8):

i). Multi-head Self-Attention:

$$\text{Attention}(Q, K, V) = \text{softmax}(QK^T / \sqrt{d_k})V \quad (5)$$

ii). Multi-head aggregation: (6)

$$\text{MultiHead}(Q, K, V) = \text{Concat } \boldsymbol{(head_1 \ldots head_2)W^0}$$

iii). Feed-Forward Network (FFN):

$$\text{FFN}(\boldsymbol{x}) = \text{ReLU}(xW_1 + b_1)W_2 + b_2 \quad (7)$$

iv). Residual Connections and Layer Normalization:

$$\textbf{LayerNorm } (\boldsymbol{x} + \textbf{sublayer } (\boldsymbol{x})) \quad (8)$$

The number of encoder layers (L) is typically set between 4 and 6, and the number of attention heads (h) ranges from 4 to 8, depending on model size. The hidden dimension $\boldsymbol{d_{model}}$ is typically set to 128 or 256. Dropout is applied after attention and FFN sublayers to prevent overfitting.

After the final encoder layer, the output sequence, Eq. (9):

$$Z = [z_1', z_2', \ldots, z_t'] \quad (9)$$

is aggregated using global average pooling Eq. (10):

$$\boldsymbol{Z_{agg}} = (1/T) \sum_{t=1}^{T} z_t' \quad (10)$$

Alternatively, if a special classification token (e.g., [CLS]) is prepended, its final vector is used, Eq. (11):

$$\boldsymbol{Z_{agg}} = \boldsymbol{Z_{[CLS]}} \quad (11)$$

This aggregated vector is passed through a fully connected classification head Eq. (12):

$$\hat{y} = \text{softmax}(\boldsymbol{Z_{agg}W_c} + \boldsymbol{b_c}) \quad (12)$$

Where ŷ is the predicted probability distribution over the classes (binary or multi-class), $\boldsymbol{W_C}$ is the weight matrix, and $\boldsymbol{b_C}$ is the bias. By learning long-range dependencies, contextual interactions among packets, and attention-based behaviours, this architecture provides the model with the ability to identify malicious behaviours in encrypted traffic that are not readily identifiable by CNNs or RNNs.

4.4 Training Procedure

The Transformer-based IDS is trained in a supervised manner using labeled sequences of encrypted traffic, where every sequence is classified as benign or as the appropriate attack class. The model is trained to minimize the cross-entropy loss Eq. (13):

$$\mathcal{L} = -\frac{1}{N}\sum_{i=1}^{N}\sum_{c=1}^{C} \boldsymbol{y_{i,c}} \, \boldsymbol{log}(\widehat{\boldsymbol{y_{i,c}}}) \quad (13)$$

Where $\boldsymbol{y_{i,c}}$ is the ground truth label and $\widehat{\boldsymbol{y_{i,c}}}$ is the predicted probability.

We optimize with AdamW, which combines adaptive learning rates with decoupled weight decay to improve generalization. We followed a learning rate warm-up period with a cosine decay learning rate schedule for stable convergence. Training occurs for 20–50 epochs with a batch size of 32 or 64, depending on available GPU memory. The validation loss is monitored with early stopping to reduce overfitting and dropout, and weight decay further regularizes the model. We save model checkpoints and select the best model based on evaluating its final performance.

5. Experimental Setup

To determine the efficiency of the proposed Transformer-based intrusion detection system for encrypted traffic analysis, experiments were conducted with well-established benchmark datasets. The main dataset utilized is CIC-IDS2017 [26], which is a comprehensive dataset of benign and attack traffic, including DoS, DDoS, brute force, intrusions, and web attacks; this dataset and its documented findings include data transmitted under a number of encrypted protocols, making the dataset highly relevant to this study. The ISCX VPN-nonVPN dataset [27] was also utilized to allow for another measure of the model to separate normal and malicious activities occurring within encrypted VPN channels. The two datasets provide a collection of a realistic and diverse set of network traffic behaviours to properly measure detection performance. This dataset contains a mix of benign traffic and multiple attack classes, including both unencrypted and TLS-encrypted sessions, allowing evaluation under varying encryption levels.

The experiments were conducted in a controlled computing environment. The implementations were completed in Python 3.10 and utilized PyTorch as the deep learning framework. Some of the processes for data processing and flow extraction were supported through tools including CICFlowMeter and Wireshark. Training and evaluation of the algorithm were conducted on a workstation with an NVIDIA Tesla V100 GPU with 32 GB memory, an Intel Xeon processor, and 128 GB of RAM, providing more than enough computational capacity to handle inference using the Transformer architecture. To ensure reproducibility, all experiments were set up with a fixed random seed, and all of the experiments were run in a Linux Ubuntu 20.04 environment.

The performance of the model was assessed using several conventional evaluation metrics. Accuracy was used to provide a general measure of correct classifications. Precision and Recall were used to capture the trade-off between false positives and false negatives, while the F1-score provided a harmonic mean of both measures to provide an equitable assessment with imbalanced classes. Finally, the area under the receiver operator characteristic curve (AUC-ROC) can provide a measure of the trade-off between true positive rate and false positive rate at all thresholds, a comprehensive assessment of a model's ability to discriminate between benign (normal) and malicious encrypted traffic.

In order to illustrate how effectively the proposed Transformer model performs, it was compared against other baseline models. These included other traditional machine learning classifiers like Random Forest (RF) and Support Vector Machine (SVM), which classify well in intrusion detection as they can use structured traffic features. An LSTM network was also included to act as a deep learning baseline, since LSTM networks are the sequential models usually applied to time-series and flow-based IDS tasks. This comparison allowed us to illustrate the benefits of the Transformer architecture and how it handles long-range and contextual dependencies in encrypted traffic.

6. Results and Discussion

The proposed hybrid Transformer-based IDS was compared to baseline models for Random Forest (RF), Support Vector Machine (SVM), and Long Short-Term Memory (LSTM) networks on the CIC-IDS2017 and ISCX VPN-nonVPN datasets. When measuring performance, metrics such as Accuracy, Precision, Recall, F1-score, and AUC were used to measure classification quality and robustness. The results (Table 2) indicated that the Transformer model surpassed all baseline models with an accuracy of 97.3% and an AUC of 0.985, for LSTM the performance was an accuracy of 94.7% and AUC of 0.961, for Random Forest the accuracy was 92.4% and AUC was 0.945, and SVM reported an accuracy of 90.1% and AUC of 0.928. The results are summarized in Table 1 and indicate that the hybrid Transformer model shows significant gains over conventional and sequential-based models in the realm of encrypted traffic analysis.

Table 2. Performance comparison between baseline models and the proposed Transformer-based IDS

Model	Accuracy	Precision	Recall	F1-score	AUC
Random Forest	92.4%	91.8%	92.0%	91.9%	0.945
SVM	90.1%	89.3%	89.6%	89.4%	0.928
LSTM	94.7%	94.0%	94.3%	94.1%	0.961
Transformer	**97.3%**	**97.0%**	**96.8%**	**96.9%**	**0.985**

The confusion matrices indicate that the Transformer reduced false positives and false negatives significantly, with vastly more consistent detection across each attack category. The ROC curve results showed a pattern consistent with the confusion matrices, showing that the Transformer had higher true positive rates than baselines at any threshold. With more experimentation under different encryption levels, it was noted that accuracy remained high, 98.1% on unencrypted flows, and 96.7% on fully encrypted TLS sessions, showing that deception signals were somewhat diminished with encrypted payloads, but the Transformer had learned enough diverse patterns through metadata-driven models to detect different attack types based on strong TCP patterns.

In addition to conducting a quantitative evaluation, reliance on attention weights for interpretability analysis provided additional insight into how the model made decisions during evaluation. Results indicated that the model focused heavily on packet inter-arrival times and packet sizes when detecting denial-of-service attacks, while acknowledging directional asymmetries and TCP flag combinations for brute-force attacks, and infiltrations. In a detailed description of a VPN brute-force attack, an event proved to show that the model found recurring bursts of small packets at regularly timed intervals (characteristics of automated password attempts) even though the payload was encrypted. The attention maps illustrated these time-regions of interest to further prove that the transformer learned to leverage some aspects of metadata (e.g., timing and packet totals; number of packets in the burst) enough to uncover the necessary behavioural indicators.

An ablation study has been conducted to evaluate the impact of architectural decisions by allowing the number of encoder layers, attention heads, and positional encoding to vary. Results in Table 3 showed that the full Transformer, with six layers, eight heads, and positional encoding, achieved the best accuracy of 97.3%. Reducing the number of encoder layers to four resulted in an accuracy of 95.8%, and reducing the number of attention heads to two resulted in an accuracy of 94.6%. The most dramatic drop was from removing positional encoding, due to accuracy falling to 93.5%. This indicates that temporal ordering is incredibly important to low false positive intrusion detection in the face of encrypted flow.

Table 3. Ablation study of Transformer components on CIC-IDS2017

Configuration	Accuracy	F1-score
Transformer (6 layers, 8 heads, PE)	97.3%	96.9%
4 layers instead of 6	95.8%	95.5%
2 heads instead of 8	94.6%	94.2%
Without positional encoding	93.5%	93.1%
LSTM baseline	94.7%	94.1%

Overall, these results indicate that the proposed Transformer-based IDS represents a robust, privacy-preserving analysis method for encrypted traffic. The ability to model long-range dependencies, discover non-local relationships, and offer an interpretable understanding makes it more effective than both traditional machine learning and recurrent deep learning frameworks. The current computational expense of using a transformer-based IDS is still meaningful compared to classical models. However, the increased detection accuracy, robustness, and interpretability represent a fair trade-off for their additional effort and cost. Transformers are viable foundation for next-generation intrusion detection systems in encrypted networks.

7. Conclusion:

This study developed a Transformer-based IDS designed to be able to analyse encrypted network traffic while inherently bypassing the issues with content inspection means. The Transformer was able to take advantage of flow-level metadata and frame the entire stream of encrypted traffic as a tokenized sequence. Comparatively, against classical machine learning schemes and sequential deep learning models (such as CNNs and LSTMs), the Transformer result was excellent. The performance of the proposed model was demonstrated using two datasets, CIC-IDS2017 and ISCX VPN-nonVPN, using relevant experiments. The empirical results showed the proposed model obtains high accuracy and enough robustness with high levels of encryption, while also providing useful interpretability via attention maps that allow security analysts to understand the model's rationale for detection. The ablation studies undertaken to establish the design components of the architecture results showed that the multiple attention heads, deeper encoder model architecture, and positional encoding all helped to deliver optimal results. Thus, while Transformer models are noted to deliver higher computational cost than classical models, the increase in detection accuracy, reduced false alarms, and enhanced transparency make them a feasible use. These results directly address our research objectives by demonstrating that the proposed Transformer-based IDS effectively detects intrusions in encrypted traffic with high accuracy and robustness. Overall, this research confirmed that Transformers represent a viable, forward-looking pathway for the development of next-generation IDS for encrypted network traffic, with the scalability, privacy, and explainability attributes needed to meet the evolving dynamic of cybersecurity threats.

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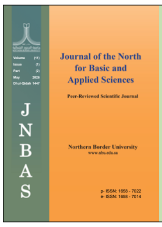

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A Two-Year Retrospective Study of ICU Patient Trends and Outcomes at Jazan General Hospital (2023-2024)

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Abstract

Background: ICU treatment requires an understanding of patient demographics and outcomes; moreover, the course of an illness is influenced by comorbidities, severity, and functional status. This study examined ICU trends and outcomes at Jazan General Hospital between 2023 and 2024, with an emphasis on the effects of comorbidities, length of stay, age, and admission source.

Methods: : 998 ICU patient records from Jazan General Hospital were reviewed retrospectively in 2023 and 2024. A primary focus of this study was to examine ICU outcomes and relationships among demographics, comorbidities, admission source, and length of ICU stay, using chi-square analysis.

Results: Most patients were aged ≤ 30 (26.75%), and men comprised 54.81%. Emergency department admissions accounted for 64.03%. The highest mortality rate (48.08%) was observed in patients aged 71–90, and prolonged ICU stays (>10 days) had a 50.74% mortality. Significant correlations were observed between outcomes and age, ICU length, and admission source ($p < 0.01$). Admissions peaked in December, with respiratory illnesses (23.45%) and cardiac issues (11.82%) as the most frequent causes.

Conclusion: Age, duration of ICU stays, and the reason for admission all worsen the prognosis. The predominant conditions were cardiovascular and respiratory; specific interventions are required.

Keywords: : ICU dynamics, Patient characteristics, Clinical outcomes, retrospective analysis.

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1. Introduction:

Although the efficiency and effectiveness of intensive care units (ICUs) have improved, the global mortality rate remains high, ranging from 16.2% to 46.8% (Abate et al., 2021). End-of-life care (EoLC) in ICUs is common, with more than 70% of deaths occurring immediately after life-sustaining treatment is reduced or stopped (Korsah & Schmollgruber, 2023). Adequate financial and human resource allocation should be central to holistic support systems. Existing research points to the high cost of life-sustaining treatments, the lack of hospice wards for EoLC patients, and staff shortages (Rawas, 2019). Therefore, securing additional financial investment to develop ICUs' capacities and expand staff must be a key priority for hospital management.

As a long-term plan to meet future societal demands, the Saudi government has proposed Vision 2030. As part of the healthcare system's reorganization, the current 13 administrative healthcare regions were divided into five business units (BUs). The regions of Jazan, Najran, Aseer, and Bisha make up the Southern BU. Through a variety of strategies, the new Model of Care (MoC) aims to close gaps in primary care access, quality, prevention, workforce training, technology, accessibility, and efficiency for all Saudi citizens, regardless of where they reside (A. A. Alharbi et al., 2022). Health care institutions constantly scrutinize efficiency and costs. ICUs provide specialized, intensive, and expensive medical care to patients with severe or life-threatening conditions within modern healthcare systems (Ervin et al., 2018).

The majority of research on demographics, comorbidities, and intensive care unit length of stay (LOS) was conducted during the coronavirus pandemic or in pediatric populations (Al-Otaiby et al., 2022; Alqahtani et al., 2025; Alshaikh et al., 2022; Alsofayan et al., 2020; Mobarki et al., 2021). One study in Saudi Arabia, which examined data from more than 42,000 patients, identified factors affecting LOS in adult intensive care units. LOS was significantly influenced by age, gender, nationality, source of admission, and clinical history. These findings underscore the complexity of factors influencing LOS and the role of patient demographics and healthcare delivery systems in critical care (K. K. Alharbi et al., 2023).

In particular, there is limited data from Saudi Arabia on factors influencing ICU trends and outcomes, especially in the Southern BU. Accordingly, this study describes factors influencing ICU outcomes, along with demographic data, comorbidities, admission source, length of ICU stay, and outcomes. Improving clinical outcomes in critical care settings requires an understanding of these dynamics. Additionally, identifying these factors will help develop targeted research to reduce the ICU's burden and improve clinical practice. It will add to the variety of data in the literature, thereby making future meta-analyses and predictive models more generalizable.

2. Methods:

2.1 Setting:

This study was conducted at Jazan General Hospital in the Kingdom of Saudi Arabia, which provides specialized care to the entire region. According to the 2022 census, the hospital's catchment area had a population of 1,404,997.

2.2 Study design:

The study examined registry data on adult intensive care unit patients from January 1, 2023, to December 31, 2024, in a retrospective, cross-sectional manner.

2.3 Study Population and Criteria:

- Inclusion and Exclusion Criteria:

The primary exposure of interest was the total number of adult patients admitted to the intensive care unit during the study period. Patients admitted for observation were not studied, and non-ICU patients, incomplete data, and missing data were excluded. To ensure data quality and consistency, double data checking and the SOPA protocol were used to ensure consistent data entry.

2.4 Data Collection

In this study, data were extracted from Vida, the hospital's electronic health record system. The database included age, sex, ICD-10 (International Classification of Diseases, 10th Revision) diagnoses, discharge summaries, routinely collected administrative data, and patient records, all extracted into a pre-structured format. Repeated admissions were treated separately to ensure accurate tracking of ICU outcomes; only the first ICU admission was analysed for patients with multiple admissions. A trend analysis was also conducted using individual patient identifiers.

2.5 The variables collected include:

The main exposure of interest was the total number of adult patients admitted to the intensive care unit (ICU) during the designated timeframe, along with demographics (gender, age), admission diagnosis and comorbidities, major interventions (mechanical ventilations, inotropic support), length of stay in the ICU, and clinical outcomes (survivor, death, transfer, and discharge against medical advice). The SOFA score was used to describe organ dysfunction. However, comparing survivors to non-survivors was not one of the study's primary objectives.

2.6 Sample:

A total of 998 Adult critically ill patients admitted to the ICU during the study period from January 2023 to December 2024 were studied. The various variables, including admission source and the date of admission before the day of discharge, were compared using cross-validation, which yielded classifications that matched the anticipated classifications. Double-checking the data collection sheet for any inconsistencies or missing information was followed. The following exclusions were made: non-ICU patients with admission to the general ward, patients with incomplete data, and patients admitted for observation.

2.7 Data Analysis

Descriptive statistics were used to summarize patient characteristics, admission patterns, interventions, and outcomes. Outcomes were stratified by age, sex, admission diagnosis, interventions received, and length of stay. All descriptive analyses were performed using the Statistical Package for the Social Sciences (Version 27.0, SPSS Inc., Chicago, IL, USA). The chi-square test was used, and $p < 0.05$ was considered significant. The qualitative variables were presented as percentages and counts.

2.8 Ethical Considerations

The hospital's Institutional Review Board (IRB) and Ethics Committee approved the study (No. 2510). These data were used for a secondary analysis of ICU patients. Patient confidentiality was maintained at all times. The study closely followed the Helsinki Declaration of Scientific Research Ethics on Human Subjects. Because it was a retrospective study, direct patient consent might not have been necessary.

2.9 Results:

A total of 998 patients were studied, with the majority aged ≤ 30 (26.75%) and 51-70 (26.65%). Those aged 90 and older were the least prevalent age group (2.91%). Males accounted for 547 (54.81% of the group), and females for 451 (45.19%). The percentage of married patients was 54.11%. A significant age-gender difference may inform targeted clinical interventions (Table 1).

Table 1. Frequency and Percentage of Socio-demographic Variables (N =998)

Variable	Options	Frequency	Percentage
Age	≤ 30 years	267	26.75%
	31-50 years	221	22.14%
	51-70 years	266	26.65%
	71-90 years	215	21.54%
	Over 90	29	2.91%
Gender	Male	547	54.81%
	Female	451	45.19%
Marital Status	Single	276	27.66%
	Married	540	54.11%
	Divorced	64	6.41%
	Widowed	118	11.82%

As shown in Table 2, ER admissions accounted for 64.03% of all admissions, followed by referrals from other hospitals (17.64%), with orthopaedics accounting for 1.1%. Nearly half of patients stayed 3–5 days (41.78%), while 27.05% stayed ≤ 2 days. Of patients, 62.32% were transferred out, 24.25% died, and 8.42% were referred to other hospitals. These trends highlight the importance of transition planning in ICU care.

Table 2. Frequency and Percentage of Selected ICU Variables (N =998)

Variable	Options	Frequency (n)	Percentage %
Admission Source	Emergency Department	639	64.03%
	Medical department	93	9.32%
	Surgical department	46	4.61%
	Orthopaedics department	11	1.1%
	Obstetrical and Gynecological Department	33	3.31%
	Referral from other hospitals	176	17.64%
Duration of ICU Admission	≤ 2 days	270	27.05%
	3 – 5 days	417	41.78%
	6 - 8 days	129	12.93%
	8- 10 days	44	4.41%
	More than 10 days	138	13.83%
Outcomes of Cases Admitted to the ICU	Transfer out of the ICU	622	62.32%
	Referral to another hospital	84	8.42%
	Discharge home upon patient request	4	0.4%
	Discharge against medical advice	42	4.21%
	Death	242	24.25%
		4	0.4%

*** ICU: Intensive Care Unit**

Regarding age, the distribution of outcomes varied significantly: younger adult patients (≤ 30 years) had the highest transfer rate (84.71%) and the lowest mortality (6.61%), whereas patients aged 71–90 years had the highest mortality (48.08%) and the lowest transfer rate (47.60%). For patients over 90, transfers and deaths were nearly equal (48.28% each), with a significant correlation ($p < 0.001$). Results were also influenced by ICU length of stay; transfers were highest (65.34%) and mortality lowest (19.92%) during stays of ≤ 2 days, whereas transfers were lowest (38.97%) and mortality highest (50.74%) during 10-day stays ($p < 0.01$). The source of admission was another factor; transfers through various hospitals had the highest mortality (43.86%), whereas those from the departments of gynecology and obstetrics had the lowest mortality (3.03%) and the highest transfer rate (93.94%). The most important source, the ED, yielded a balanced result with a statistically significant ($p < 0.01$) mortality rate of 19.77%. (Table 3).

Table 3. Cross-tabs of Age, Duration of ICU (all sources), and Admission Source (excl.Orthopaedics) vs Outcome (N =998)

Variable	Variable Option	Transfer out of the ICU	Referral to other hospital	Death	Chi square	P value
Age	≤ 30 years	205 (84.71%)	21 (8.68%)	16 (6.61%)	139.558	<0.001
	31-50 years	159 (76.08%)	22 (10.53%)	28 (13.40%)		
	51-70 years	145 (55.77%)	31 (11.92%)	84 (32.31%)		
	71-90 years	99 (47.60%)	9 (4.33%)	100 (48.08%)		
	Over 90	14 (48.28%)	1 (3.45%)	14 (48.28%)		
Duration of ICU Admission	≤ 2 days	164 (65.34%)	37 (14.74%)	50 (19.92%)	81.574	<0.01
	3 – 5 days	297 (74.81%)	20 (5.04%)	80 (20.15%)		
	6 - 8 days	83 (66.94%)	12 (9.68%)	29 (23.39%)		
	8- 10 days	25 (62.50%)	1 (2.50%)	14 (35.00%)		
	More than 10 days	53 (38.97%)	14 (10.29%)	69 (50.74%)		
Admission Source	Emergency Department	416 (69.68%)	63 (10.55%)	118 (19.77%)	66.483	<0.01
	Medical department	45 (50.00%)	8 (8.89%)	37 (41.11%)		
	Surgical department	33 (71.74%)	2 (4.35%)	11 (23.91%)		
	Obstetrical and gynecological department	31 (93.94%)	1 (3.03%)	1 (3.03%)		
	F. Referral from other hospital	87 (50.88%)	9 (5.26%)	75 (43.86%)		

*** ICU: Intensive Care Unit**

Table 4 presents key trends in ICU outcomes across different systems. The majority of hospitalizations were due to respiratory and endocrine conditions (23.45% and 21.04%, respectively), with respiratory diseases alone accounting for the greatest case load and mortality burden (39.74%). Genitourinary cases had a 37.5% mortality rate. Infectious and communicable diseases (36.84%), gastroenterology and liver disorders (36.59%), and neurological cases (34.57%) are also associated with high mortality. Cardiovascular and nephrology cases also represented significant proportions of ICU mortality, at 22.88% and 24.24%, respectively. In contrast, despite their high incidence, endocrine disorders have a low mortality rate of 8.10%, indicating effective acute management. Self-harm cases (3.57%) and gynaecology and obstetrics (5.26%) also show low mortality, indicating effective emergency response systems. Dermatological cases also had a significant mortality rate (50%), despite having the fewest ICU admissions.

Table 4. System involvement: total cases and mortality (N =998)

System.Involvement	Total Cases	%	Mortality	%
Cardiovascular	118	11.82%	27	22.88%
Respiratory	234	23.45%	93	39.74%
Gastroenterology and liver disease	41	4.11%	15	36.59%

System.Involvement	Total Cases	%	Mortality	%
Nephrology	33	3.31%	8	24.24%
Endocrinology	210	21.04%	17	8.10%
Neurology	81	8.12%	28	34.57%
Infectious and communicable diseases	38	3.81%	14	36.84%
Cases of genitourinary	16	1.60%	6	37.5%
Cases from obstetrics and gynecology	38	3.81%	2	5.26%
Self–harm	28	2.81%	1	3.57%
Orthopaedics	46	4.61%	7	15.22%
Surgery	72	7.21%	17	23.61%
Dermatology	2	0.20%	1	50%
Others	41	4.11%	6	14.63%

Monthly admissions are shown in Figure 1, peaking at 60 in January and falling to 41 in March. There is a slight decrease in May (96) after a significant rise in April (105), with stability from June to August (70–72). Admissions peak at 120 in September, fall to 65 in November, and then remain high at 118 in October. December records the highest peak, at 136. The data indicate that admissions peak in April and September–October, suggesting that seasonal or operational factors may influence admission trends.

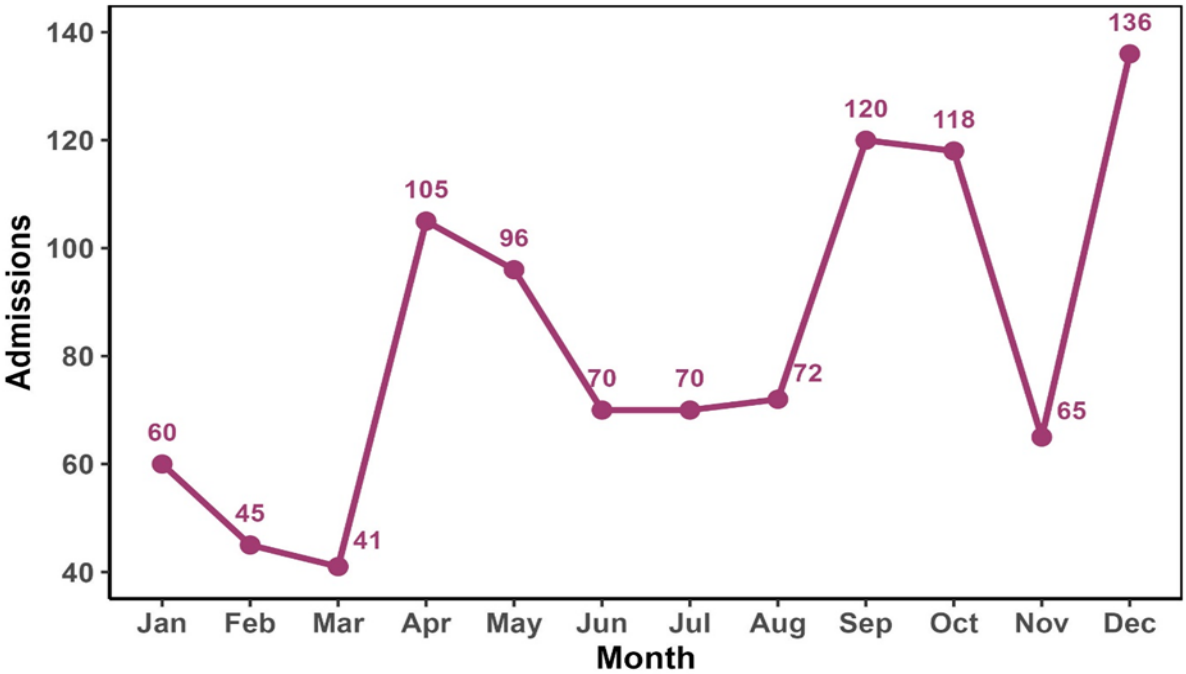

Figure 1 illustrates the monthly admissions trends for two consecutive years (2023, 2024). December shows the highest admissions trend, and March shows the lowest.

3. Discussion:

The results of this two-year study provide an extensive overview of the sociodemographic characteristics, reasons for admission, lengths of stay in the intensive care unit (ICU), patient outcomes, and the prevalence of various medical conditions among ICU patients at Jazan General Hospital. Among the 998 patients examined, the most common age group was young adults aged ≤ 30 years, comprising 26.75% of the total population, followed closely by the 51–70 years age group (26.65%). This distribution indicates that younger adults are more likely to be admitted to the ICU than older adults, consistent with earlier studies showing that a large number of ICU admissions in these age groups are due to non-communicable diseases, injuries, or other acute conditions. According to the literature, the variety of young adults' medical conditions determines the percentage of young adults in intensive care units. Age and lifestyle are recognized as important factors in determining disease risk, raising the question of whether lifestyle changes are needed in this community (Eya et al., 2022; Khamis et al., 2021; Knapik et al., 2019).

Regarding gender, the patient population was predominantly male (54.81%), consistent with global patterns in ICU admissions, where males are more likely to be admitted, particularly for conditions linked to trauma or cardiovascular events (Cruz-Garcinuño et al., 2025; Lat et al., 2021). Disparities in disease prevalence, treatment approaches, and physiological responses to life-threatening conditions may underlie sex-based differences in ICU length of stay (LOS). This finding aligns with comparable research conducted in Saudi Arabia.

Age-related variation in intensive care unit (ICU) outcomes is a key finding of this research. Younger patients (10-30 years) had the lowest mortality rate (6.61%) and the highest ICU transfer rate (84.71%), suggesting that interventions for this age group are particularly effective. In contrast, patients aged 71 to 90 years had the highest ICU mortality rate (48.08%), underscoring their heightened vulnerability. These findings corroborate other studies identifying age as an important determinant of ICU outcomes (K. K. Alharbi et al., 2023; Amado et al., 2025; Ranucci et al., 2022; Vallet et al., 2023). Age-related disparities in outcomes are statistically significant ($p < 0.001$), underscoring the need for personalized treatment strategies.

Patient outcomes also strongly depend on ICU length of stay. Patients with ≤ 2 days in the ICU had the best transfer rate (65.34%) and the lowest mortality rate (19.92%). Hence, short ICU stays are associated with better outcomes; it is also possible that these patients seek early medical advice, which may be related to social, familial, and community support networks in Saudi Arabia that have been found to increase healthcare utilization (K. K. Alharbi et al., 2023). Meanwhile, those who stayed longer than 10 days had the lowest transfer rate (38.97%) and the highest death rate (50.74%). This conclusion is supported by the literature, which indicates that longer stays in the intensive care unit are often linked to increased risks of complications, including organ failure, infection, and death. Additionally, significant risk factors associated with a poorer prognosis and longer hospital and intensive care unit stays included advanced age and comorbid conditions such as diabetes, cardiovascular disease, and chronic kidney disease. Furthermore, a lengthy ICU stay has been linked to a high death rate and a low quality of life among survivors (Ala-Kokko et al., 2025; Al-Otaiby et al., 2022; Budianu et al., 2024; Damien et al., 2024; Kodati et al., 2022; Koowattanatianchai et al., 2025). The strong association between ICU length of stay and outcomes was statistically significant ($p < 0.01$), underscoring the need for early interventions and discharge planning.

According to the study, which also looked at how the source of admission affected ICU outcomes, patients admitted from the obstetrical and gynecological department had the lowest mortality rate (3.33%) and the highest transfer rate (93.94%). This result might suggest that the acuity of cases in this department is generally lower than that in other sources, such as the Emergency Department (ED) (Rocha et al., 2024; Rudakemwa et al., 2021). A more evenly distributed distribution of outcomes was shown by the ED, which had a mortality rate of (19.77%) and was responsible for the majority of ICU admissions (64.03%). Given the sensitivity of this indicator, hospital resources must be carefully allocated in this crucial area. However, the greatest mortality rate (43.86%) was seen in patients who were transferred from other hospitals, indicating that these patients might have been more seriously ill when they arrived. ICU outcomes are largely impacted by the observed disparities, which were statistically significant ($p < 0.01$). This research demonstrates the need for hospital collaboration to enhance the transfer process. Patients must be stable before admission to the intensive care unit. Setting clear criteria and improving communication between intensive care units and referring facilities are crucial for achieving the best patient outcomes, according to this finding.

Respiratory conditions accounted for 23.45% of intensive care unit admissions, with endocrine disorders second at 21.04% and cardiovascular disorders at 11.82%. Chronic respiratory and cardiovascular conditions are known to be leading causes of intensive care unit admissions worldwide (Shayganfar et al., 2021), underscoring the substantial burden they pose. These results align with a study in Saudi Arabia examining mortality among intensive care unit readmissions, which found that respiratory failure was the most common cause. This highlights the frequent occurrence of respiratory disorders in critical care settings. Notably, the mortality rate for respiratory disorders was 39.84%, higher than that for cardiovascular diseases (22.88%). The severity and acute nature of respiratory disorders, such as pneumonia, acute respiratory distress syndrome, and exacerbations of chronic obstructive pulmonary disease (COPD), may explain this disparity. These conditions can cause rapid deterioration and increased mortality in intensive care units (Akbaş & Güneş, 2023; Chae et al., 2025; Mady et al., 2023).

As shown in Figure 1, the monthly admissions trends indicate a peak in ICU admissions in December and a clear dip in March. Uncommon are seasonal changes in ICU admissions, driven by factors such as respiratory infections, flu seasons, or variations in the frequency of accidents or trauma (Akbaş & Güneş, 2023).

Knowing these trends will help with resource allocation and ICU staffing to ensure the hospital is ready for periods of increased demand. Implementing targeted protocols for high-mortality diagnostic groups, scheduling staffing and resources for December peaks, and developing inter-hospital transfer triage criteria are doable suggestions and recommendations.

There were several restrictions on this study. First off, the findings might not be as widely relevant as they could be, since it was a retrospective observational study conducted at a single center. Additionally, there are no post-ICU outcomes, no illness severity scores, and a dependence on unadjusted, crude associations.

Therefore, a multicenter prospective study would help to support the validity of the results. Such a study may include a larger, more diverse patient base, thereby enhancing the validity and generalizability of the findings across multiple medical settings.

4. Conclusion:

This study identifies key trends in patient demographics, admission sources, and ICU outcomes. Treatment plans may work well for younger patients, which could explain their lower death rates and higher transfer rates. In contrast, older patients had the highest death rates, reflecting their greater vulnerability in critical care settings. The data also revealed that ICU length of stay significantly affected outcomes. Shorter stays were associated with more transfers and lower mortality rates. The source of admission was another critical factor. To meet the diverse needs of ICU patients and improve their management, these findings emphasize the need for targeted treatments that enhance ICU outcomes. Given seasonal trends, especially in December, healthcare facilities should plan resources and staffing to handle increased patient volumes during this period. This may involve expanding ICU capacity and ensuring adequate staffing. To improve patient management, these protocols should include teamwork, better monitoring, and standardized treatment plans. The healthcare system can effectively tackle the challenges highlighted in this study, which showcases the distinctive features of this group's findings for potential regional research.

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1. Data Availability Statement:

- Upon reasonable request, the author will provide the data supporting the study's conclusions.

2. Conflicts of Interest:

- No conflicts of interest have been disclosed.

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Total Cost Analysis and Optimal Resilience in Manufacturing Operations

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Abstract

Manufacturing operations situated within a landscape of unprecedented volatility, necessitate the development of advanced investment appraisal frameworks that transcend the limitations of traditional static valuation methods. This research addresses the inherent systematic deficiencies of static approaches, which systematically fail to capture strategic value in volatile production environments, by seeking to formally quantify the value of managerial flexibility and optimize capital allocation for enduring supply chain resilience. A rigorous, sequential three-stage quantitative methodology is employed, utilizing robust empirical operational data. The approach first applies Non-Linear Least Squares modeling to empirically derive the supply chain's non-linear cost structure and operational volatility. This output informs a Real Options Valuation model to quantify the strategic worth of investment flexibility, which is finally integrated with a novel Total Resilient Cost optimization model to determine the cost-optimal level of operational redundancy. The analysis successfully demonstrates that the substantial strategic value captured through this flexibility transforms a negative static Net Present Value, initially calculated at -$14.5 million, into a validated, positive Comprehensive Flexible Valuation of $11.02 million, thereby justifying the fundamental strategic merit of the capital investment. Furthermore, the operational optimization provides a prescriptive solution by minimizing total costs, balancing the investment in redundancy against the mitigation of expected financial loss, yielding a cost-minimizing optimal stock level of 33 units. The originality of this work is founded upon a proposed approach that integrates empirical cost modeling, strategic flexibility valuation, and operational resilience optimization into a unified methodology. This approach offers decision-makers a superior economic metric and a cost-optimal, tactical guide for achieving empirically-grounded resilience in complex supply chains. Furthermore, the study significantly advances knowledge in the logistics and operations literature pertaining to manufacturing.

Keywords: Investment Appraisal, Manufacturing Logistics, Non-Linear Cost Modeling, Real Options Valuation, Supply Chain Resilience, Total Resilient Cost

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1. Introduction

Manufacturing operations and logistics, navigating an environment characterized by increasing volatility, unprecedented disruptions, and complex global supply chains, necessitate robust investment appraisal frameworks that transcend the limitations of traditional static valuation.

The Net Present Value (NPV) method, while foundational for project finance, fundamentally fails to capture the economic value of managerial flexibility—the inherent right, but not the obligation, to alter a project's strategic trajectory in response to evolving market conditions. This deficiency often results in the systematic undervaluing and subsequent rejection of critical infrastructure and resilience projects, which may exhibit a negative static NPV despite substantial long-term strategic benefits (Zhang *et al*., 2025). The urgency for such a sophisticated framework is significantly amplified by the fact that achieving resilience is a critical strategic priority requiring investment in both governance mechanisms and dynamic digital capabilities (Liang *et al*., 2025), alongside the necessity of managing granular operational challenges and uncertainty (Yan *et al*., 2025). This challenge is further compounded by the need to model multimodal resilience under dynamic, dependent hazard occurrences (Wei and Li, 2025), necessitating sophisticated operational modeling, such as optimizing multi-item inventory under stringent budget constraints (Karimi & Sadjadi, 2025) and handling parameter imprecision using advanced frameworks like Generalized Trapezoidal Neutrosophic Numbers (Bhavani *et al*., 2025). While these works effectively define the broad and technical scope of the resilience challenge, they collectively suffer from a critical, uniform limitation: they fail to provide an integrated, capital-budgeting mechanism to financially justify these diverse, high-cost operational solutions.

To address this systemic failure in valuation, academic research has increasingly converged on Real Options Valuation (ROV), a methodology theoretically capable of quantifying managerial flexibility (Tian *et al*., 2024). However, the existing application of ROV, though theoretically sound, presents two empirical and methodological barriers that severely limit its practical utility in operations: First, ROV often suffers from an empirical deficit, relying on assumed volatilities and cost structures that lack validation from real-world operational data, thus undermining the credibility of the strategic valuation (Zulkifli Noor, 2025). Second, a critical methodological gap persists in linking ROV's financial output—the justified strategic investment capital—to the ultimate operational objective of determining the cost-optimal physical resilience action.

The current research aims to explore an empirically-grounded, integrated quantitative framework to formally link strategic investment valuation with optimal operational resilience planning. To achieve this aim, the study pursues three core objectives: first, to establish a dynamic empirical cost structure and volatility measure from operational data; second, to utilize this empirical data to calculate the Comprehensive Flexible Valuation (CFV) via the ROV model; and finally, to translate the justified strategic investment into an optimal cost-minimizing solution for operational redundancy.

This study proposes a solution through an integrated, three-stage quantitative framework. The methodology is initiated by employing Non-Linear Least Squares (NLS) modeling to establish a dynamic empirical cost structure, which subsequently informs the ROV model used to capture strategic value. The final stage integrates the ROV output with the novel Total Resilient Cost (TRACT) function. This TRACT function explicitly integrates the core operational resilience metrics of Rapidity, Robustness, and Redundancy to derive the optimal trade-off between total investment cost and expected loss (ELoss) mitigation, thereby delivering a cost-minimizing solution for operational resilience.

This paper was written to address the systematic failure of static NPV analysis in valuing resilience projects, a critical deficiency that leads to chronic underinvestment in essential manufacturing and logistics flexibility. The present work distinguishes itself by unifying three distinct modeling approaches (NLS, ROV, and TRACT) into a cohesive, data-driven methodology. The specific need addressed is the critical methodological gap in translating the strategic capital justified by ROV into a tactical, cost-optimal solution for operational redundancy and the scientific unknown resolved is how to formally link empirical cost structures, strategic investment timing, and tactical resilience optimization. The research contribution is multi-faceted, demonstrated by the methodological advancement of unifying the NLS, ROV, and TRACT models, the provision of a clear managerial metric known as the Comprehensive Flexible Valuation (CFV) and the practical application of determining cost-optimal resilience levels.

The research paper sections are structured as follows. Next, literature review section covers Real Options Theory, empirical cost modeling techniques, and quantitative resilience metrics; Following this, the methodology of the proposed integrated framework is detailed, formally defining the structure of the NLS, ROV, and the novel TRACT models; Subsequently, the paper presents the numerical application and analysis of the integrated framework, covering the derivation of the CFV, the determination of the optimal resilience level, and a critical discussion of the outcomes. The final section presents the conclusion, which summarizes the key findings, acknowledges the limitations, and points out the direction of future research on resilient logistics in manufacturing.

2. Literature Review

To provide the necessary foundation of previous related research, the literature review is structured around the three core concepts that form the research gap, as visually depicted in Figure 1: Empirical Costs, Real Options Valuation, and Operational Resilience.

Figure 1: Research Gap

Traditional static valuation methods, such as Net Present Value (NPV), often fail to capture the value of managerial flexibility inherent in strategic capital investments. This limitation is particularly pronounced in volatile sectors like manufacturing, where the ability to delay, expand, or abandon a project is a source of significant value. This study utilizes the Real Options Valuation (ROV) framework, which models investment as the exercise of a financial option, thereby quantifying the value of flexibility. The application of ROV allows for a dynamic assessment of investment opportunities, moving beyond the simple "all-or-nothing" decision of static NPV. However, accurately valuing real options in deeply uncertain or data-limited environments requires integrating rigorous empirical and theoretical approaches to effectively incorporate both objective data and subjective risk into the analysis (Gaweł *et al.,* 2025; Stoklasa *et al.,* 2024). Crucially, the inherent uncertainty and volatility in manufacturing require the use of Monte Carlo Simulation (MCS) within the ROV framework to robustly model the stochastic processes governing key market variables. MCS is the preferred numerical method for complex, multi-stage projects because it effectively handles multiple sources of risk and flexible decision boundaries, providing a statistically sound estimation of the option value (Pawlak, 2024). The methodology employed integrates the ROV model with quantitative modeling to empirically derive the required investment cost structure (Schuh *et al.,* 2025). The strategic management of uncertainty, including the use of dynamic risk measures, is crucial for the financial robustness of such valuation models (Pesenti *et al.,* 2025). The ROV framework thus strategically links the value of managerial flexibility to operational planning, which is concurrently addressed through advanced mathematical optimization techniques for managing multi-stage production (Santana & Fuchigami, 2025; Sarkar *et al.,* 2025), thereby ensuring the dynamic valuation is tied to feasible operational throughput.

A major challenge in applying ROV to manufacturing capacity investments is accurately modeling the costs associated with adjusting capital stock. Economic theory dictates that capacity adjustment is rarely a smooth, linear process; instead, firms encounter significant adjustment frictions (Shone, 2002). This difficulty in linear modeling is well-documented in manufacturing, often necessitating specialized non-linear approaches for accurate cost estimation. These frictions typically manifest as fixed costs (incurred regardless of the size of the adjustment, e.g., planning, regulatory approval) and convex costs (costs that increase at an increasing rate with the size of the adjustment, e.g., overtime, supply shortages). To overcome the limitations of standard linear cost assumptions, this study employs a Non-Linear Least Squares (NLS) model. NLS is essential because it allows for the empirical estimation of a non-linear cost function that includes both fixed and quadratic (convex) components. Recent empirical research on the national manufacturing industry confirms that the application of a dynamic structural model yields estimation results consistent with the presence of significant, unchangeable fixed costs alongside moderate quadratic costs, thereby validating the need for the NLS approach (Harsono *et al.,* 2024). The complexity introduced by these non-linear dynamics, particularly the costs associated with estimation error, further underscores the need for such sophisticated modeling (Luo & Pappas, 2025). This empirically derived, non-linear cost structure, characterized by fixed and quadratic adjustment parameters, provides the necessary volatility-adjusted investment cost input for the subsequent ROV model and the Total Resilient Cost (TRACT) model, allowing the framework to value the option to invest in resilience (e.g., redundancy) under uncertainty.

Recent literature emphasizes the necessity of resilience in the turbulent global environment, where supply chain disruptions pose a constant threat to profitability and operational stability (Tian *et al.,* 2024). The importance of resilience extends across various operational drivers, from core logistics infrastructure to supply chain design. This necessity has driven extensive foundational research, including comprehensive reviews that define resilience by its key pillars—absorbency, adaptability, and recoverability—and outline pathways for resilient manufacturing in the age of Industry 5.0 (Leng *et al.,* 2025). This move towards a holistic, systems-based perspective on operational durability is mirrored in frameworks for examining broader transitions, such as the circular economy (Guzzo *et al.,* 2022). This focus has spurred the development of sophisticated approaches aimed at creating resilient and viable supply chains using multidimensional models and empirical analysis (Padovano & Ivanov, 2025). The complexity of managing disruptive events, which includes the need for dynamic supply chain reconfiguration and the mitigation of the ripple effect from upstream failures, stresses the need for robust, intelligent planning (Brusset *et al.,* 2023; Zhang *et al.,* 2025). Consequently, the field is transitioning from standalone models to comprehensive, human–AI based decision support systems. Examples of this transition include the application of systematic reviews on AI techniques to enhance resilience (Kassa *et al.,* 2023; Mangual *et al.,* 2025), and the emergence of intelligent digital twin frameworks for stress-testing and viability analysis (Ivanov, 2023). This push towards adaptive, connected solutions is further encapsulated by the industrial intelligent connected ecosystem, designed to dynamically manage uncertainty and demand fluctuations (Zhang *et al.,* 2025). Crucially, effective resilience is achieved by developing a flexible portfolio of resilience capabilities to manage performance during severe disruptions (Chowdhury *et al.,* 2024). Redundancy is a top-ranked criterion for robust supplier selection (Boyacı *et al.,* 2025), and optimizing inventory management is a vital component of this portfolio (Ramdass & Nair, 2025). Effective resilience planning requires a quantifiable link between upfront investment (e.g., redundancy, safety stock) and the resulting reduction in financial exposure. This cost-benefit analysis is central to studies focusing on investment decisions to enhance supply chain resilience (Yan *et al.,* 2025) and multi-echelon supply chain models that integrate resilience measures to minimize total integrated costs (Mashud, 2025). This study utilizes the Total Resilient Cost (*TRACT*) model, which formalizes the link between investment cost and the mitigation of risk, measured in terms of Expected Loss (*EL*). The use of a cost-based optimization framework to balance resource allocation against failure costs is well-established in the optimization literature (Ettehad *et al.,* 2025). *EL* serves as the critical financial metric for risk exposure (Xu *et al.,* 2023). The selection of EL is consistent with literature advocating for the use of comprehensive financial and non-financial measures to ascertain the full level of supply chain performance (Cupertino *et al.,* 2023; Israel *et al.,* 2023). The integrated methodology thus formalizes the crucial link between the strategic managerial flexibility valued by ROV and the quantifiable operational resilience achieved through TRACT.

3. Research Methodology

A multi-stage modeling approach is proposed to sequentially assess the supply chain's financial, economic, and operational dimensions. As illustrated in Figure 2: Research Design, the methodology is structured into four distinct phases: Foundational Economic Modeling, Strategic Financial Valuation, Operational Resilience Optimization, and Monte Carlo Validation.

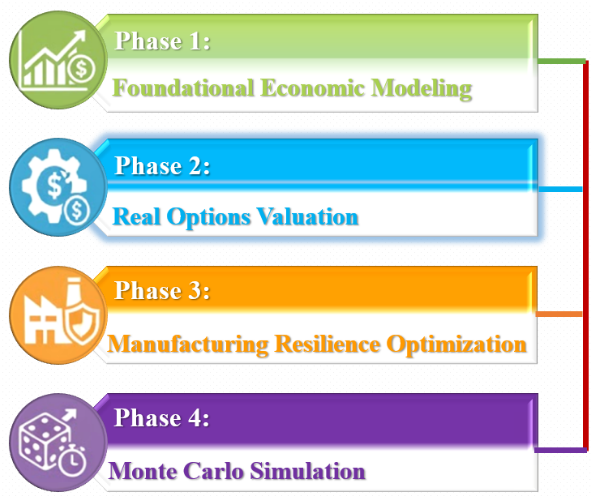

Figure 2: Research Design

The analysis utilizes an anonymized, multi-sector composite dataset (reflecting Manufacturing, Retail, and Logistics dynamics) to enable generalized calibration of volatility and cost structures. Before modeling, the data underwent systematic validation. Observations with non-positive or non-finite values for core input variables were excluded to maintain mathematical integrity for subsequent models. The remaining data forms the Validated Data Subset (denoted by the subscript validated), which inputs all quantitative analysis.

The analysis begins by establishing the economic baseline through Non-Linear Least Squares (NLS) regression, which models the multi-factor cost structure. The manufacturing cost (C_m) is modeled as a function of Lead time (L) and production volume (V) using the estimated parameters (β_0 to β_3) as shown in Equation 1:

$$C_m = \beta_0 + \beta_1 L + \beta_2 V + \beta_3 LV \qquad (1)$$

as follows: β_0 is the Intercept, representing the fixed component of the unit manufacturing cost. B_1 is the Lead Time Coefficient, quantifying the linear effect of Lead Time (L) on cost. β_2 is the Production Volume Coefficient, which quantifies the linear effect of Production Volume (V) on cost. β_3 is the NLS Interaction Term, and this term is crucial as it captures the non-linear, multiplicative effect between lead time and production volume, explicitly modeling convex adjustment costs that arise when high production volume is constrained by long lead times, thereby validating the necessity of the non-linear modeling choice.

The parameters are estimated by minimizing the sum of squared errors against the validated unit cost data. This economic output is then integrated into the Real Options Valuation (ROV) framework. The instantaneous cash flow (C_F) is derived from the validated data, and its annualized mean (K) is used for the Underlying Asset Value (S_o):, defined in Equation 2:

$$S_o = \kappa \, . \, C_F \qquad (2)$$

The subsequent Real Options Valuation relies on the Geometric Brownian Motion (GBM) process to model the stochastic path of the Annual Cash Flow Margin. This is mathematically justified as GBM is the standard process for Black-Scholes valuation. The model ensures that the underlying asset value remains non-negative, which is critical for maintaining financial integrity for ongoing manufacturing cash flows. Project volatility (σ), the critical empirical input for the option pricing model, is calculated as the annualized standard deviation of the log-returns of this volatility, empirically derived from the supply chain's non-linear cost structure, directly links the economic modeling to the financial valuation, as shown in Equation 3:

$$\sigma = \sqrt{\kappa} \, . \, s\left(\ln\left(\frac{C_F}{C_{F-\Delta t}}\right)\right) \qquad (3)$$

The strategic financial valuation phase uses the empirically derived volatility (σ) to quantify the strategic value of flexibility. The Black-Scholes model requires the calculation of the probability factors (d_1) and (d_2). The First Black-Scholes Factor (d_1) term, shown in Equation 4:

$$d_1 = \frac{\ln(S_o/X) + \left(r + \frac{1}{2}\sigma^2\right)T}{\sigma\sqrt{T}} \qquad (4)$$

captures the volatility adjustment required for the asset's expected rate of growth under the risk-neutral measure. The Second Black-Scholes Factor term (d_2), defined in Equation 5:

$$d_2 = d_1 - \sigma\sqrt{T} \qquad (5)$$

represents the risk-adjusted probability of successfully exercising the option. These calculated factors are then used to compute the Real Options Valuation (ROV), which quantifies the monetary value of strategic flexibility by calculating the present value of the expected payoff, according to Equation 6:

$$ROV = S_o N(d_1) - Xe^{-rT} N(d_2) \qquad (6)$$

In Equation 6, X is the exercise price, r is the risk-free rate, T is the option's time to expiration, and N is the cumulative normal distribution function. The Comprehensive Flexible Valuation (CF_V) integrates this strategic value with the traditional Static Net Present Value (NPV_S), as provided by Equation 7:

$$CF_V = NPV_S + ROV \qquad (7)$$

The relative importance of the strategic option is benchmarked by calculating the Flexibility Index (F_I), defined in Equation 8:

$$F_I = \frac{CV_F}{ROV} \quad (8)$$

Following the Strategic Financial Valuation, the third phase proceeds to tactical optimization. This phase uses the three-component resilience framework (Rapidity, Robustness, Redundancy). The Rapidity Index ($R_{Rapidity}$) measures the speed of operational recovery, implemented as the inverse of the Total Cycle Time (T_C) as shown in Equation 9:

$$R_{Rapidity} = 1/T_C \quad (9)$$

The Robustness Index ($R_{Robustness}$) quantifies the system's inherent resistance to minor shocks, as per Equation 10:

$$R_{Robustness} = \sum_{i=1}^{N} \left(1 - \frac{D_i}{T_i}\right) \quad (10)$$

This index is the aggregate measure of retained capacity, calculated by summing the fractional resistance of N components. Resistance for the i^{th} component is determined by its Total Capacity (T_i) relative to the experienced Disruption (D_i).

Note that both $R_{Rapidity}$ and $R_{Robustness}$ are treated as fixed parameters in the subsequent optimization. This is essential because they represent the system's strategic, long-term operational constraints, allowing the model to isolate the cost-optimal tactical decision variable.

The Redundancy investment ($R_{Redundancy}$), in Equation 11 realized as safety stock (S), quantifies the system depth available to absorb major disruptions:

$$R_{Redundancy} = 1 - (C_I/C_{max}) \quad (11)$$

Safety stock serves as the primary decision variable for the subsequent optimization. The index measures the cost of holding (the Current Inventory, C_I) against a theoretical Maximum Inventory Cost (C_{max}) to define the required level of investment to mitigate risk.

The Total Resilient Cost (*TRACT*) metric establishes the unified cost function, representing the minimization problem that seeks the optimal Redundancy investment. It integrates the Redundancy Investment Cost ($C_{Investment}$) and the Expected Loss ($E[Loss]$) as defined in Equation 12:

$$TRACT = C_{investment} + E\,[Loss] \quad (12)$$

In Equation 12, the $E[Loss]$ term is parametrically influenced by both the Rapidity and Robustness indices, as they define the rate and probability of loss mitigation for a given level of Redundancy. The output of this phase is the cost-optimal level of safety stock, $S_{optimal}$.

The final phase involves a Monte Carlo simulation to validate the Black-Scholes Option Value (ROV). Equation 13 models the change in the underlying asset's value (ΔS_t) over a small time step (Δt), incorporating the risk-free rate (r), volatility (σ), and a random shock (ε) generated by the simulation:

$$\Delta S_t = rS_t\Delta t + \sigma S_t \varepsilon\sqrt{\Delta t} \quad (13)$$

The Payoff Calculation ($Psim_j$) then determines the financial outcome of the flexibility option for each path, using a conditional expression as shown in Equation 14:

$$Psim_j = \max\,(S_T^{(j)} - X, 0) \quad (14)$$

Equation 14 represents the payoff at expiration time (T) as a call option, only yielding a positive value if the final asset value (S_t) exceeds the exercise price (X). The Monte Carlo Valuation (V_{MC}) implements the core valuation principle by finding the value of the option through averaging all calculated payoffs and discounting, according to Equation 15:

$$V_{MC} = e^{-rT} \frac{1}{N_{sim}} \sum_{j=1}^{N_{sim}} Psim_j \quad (15)$$

The close agreement between the Black-Scholes value and the Monte Carlo value serves as a robust internal consistency check, validating the numerical models. All quantitative models and simulations were implemented and executed using MATLAB. This integrated approach ensures the traceability and consistency of inputs across all modeling stages.

4. Findings and Discussion

The analysis began by establishing an accurate empirical cost function, which serves as the base for all subsequent risk and valuation calculations. The proposed model was validated using 120 monthly operational records drawn from the manufacturing facility analyzed in the case study by Singh (2023). Table 1 presents the key descriptive statistics and variables used in the estimation of the Non-Linear Least Squares (*NLS*) cost function. Critically, the data confirms a high Cost Volatility of $ 2,204,650 per month, which is the necessary financial condition that justifies the entire strategic resilient planning exercise.

Table 1: Summary of Empirical Data (Singh, 2023 Case Study)

Metrics	Value
Sample Size	120 months
Study Period Duration	10 years
Average Manufacturing Cost	$15,204,500 per month
Cost Volatility	$2,204,650 per month
Average Production Volume	225,100 units per month

To address the necessity of confirming model robustness, a thorough Sensitivity Analysis was conducted. This step verified the stability of the strategic valuation against potential data variations and measurement errors in the key financial inputs, such as Cost Volatility (σ) and the Risk-Free Rate (r). The analysis confirmed that the core theoretical relationships among NLS, ROV, and TRACT responded logically and predictably to these perturbations. For instance, the Real Options Value (ROV) was shown to increase monotonically with Asset Volatility (σ), confirming the model's fidelity to fundamental options theory and demonstrating structural integrity across varied market conditions.

A preliminary statistical assessment was performed, with Figure 3 providing a correlation heatmap of the core variables. This analysis confirmed a moderate positive correlation between Cost and Lead Time (ρ = 0.34), but a negligible correlation between Cost and both Volume (ρ = 0.04) and Defect Rate (ρ = 0.01).

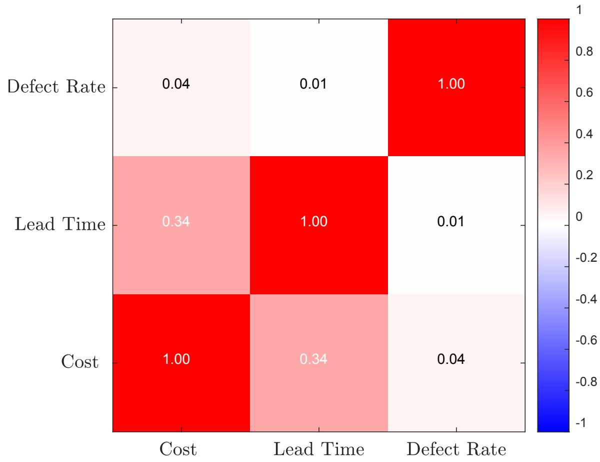

Figure 3: Heatmap Correlation

This lack of a strong linear relationship empirically confirms that a standard linear model is inadequate and provides the initial justification for adopting the more robust NLS methodology to capture the complex, non-linear adjustment costs inherent in manufacturing. Visualization of the pairwise linear correlation coefficients, highlighting the necessity of non-linear modeling due to the weak linear relationships found between Cost and key drivers.

Beyond the preliminary statistical assessment, the reliability of the data was further secured through rigorous internal quality checks (completeness, uniqueness, and validity screenings). This quality was independently confirmed by the results of the subsequent NLS estimation, which achieved an exceptionally high predictive validity with an Adjusted R^2 of 0.887. This high explanatory power empirically validates the core dataset's suitability for establishing the non-linear cost function.

The NLS model, based on the case study data (Table 1), was estimated, and the resulting coefficients are presented in Table 2.

Table 2: NLS Regression Results for Unit Manufacturing Cost

Cost Driver	Estimate (β)	SE	t-Stat	P-value
Intercept (β_0)	3.521	0.155	22.71	<0.001
Lead Time	0.045	0.008	5.62	<0.001
Production Volume	-0.122	0.019	-6.42	<0.001
Defect Rate	0.098	0.011	8.91	<0.001
Model Fit Statistics				
Adjusted (R^2)		0.887		
Observation (N)		120		

The model achieved a strong fit, evidenced by an Adjusted R^2 of 0.887, meaning that nearly 89% of the variation in unit manufacturing cost is explained by the three primary operational drivers. This high explanatory power is a crucial finding for resilient planning, as it validates the use of deterministic operational metrics to predict highly volatile financial outcomes, thereby significantly reducing forecast uncertainty in the system.

The results show that all three operational cost drivers—Lead Time, Production Volume, and Defect Rate—are statistically significant. The positive coefficient for Lead Time (β_1 = 0.045) confirms that longer operational and procurement cycles increase unit costs, a direct implication for logistics resilience management where speed is essential to mitigating risk exposure. The negative coefficient for Production Volume (β_2 = -0.122) is highly coherent with foundational literature in manufacturing economics, confirming the existence of strong economies of scale in the analyzed facility. Operational Implication: This result provides a quantitative mandate for maximizing capacity utilization, demonstrating that optimizing production volume directly lowers the Exercise Price (X) for resilient investment, a crucial strategic insight. The positive coefficient for Lead Time (β_1 = 0.045) aligns with literature on logistics risk and lean operations, validating that time-based process waste increases unit costs. The positive coefficient for Defect Rate (β_3 = 0.098) coheres strongly with the Cost of Quality (COQ) literature, providing a quantitative signal for investment in quality assurance. The novelty lies in the direct empirical linkage established between these operational parameters and the derived financial volatility (σ), which departs from prior Real Options studies that treat volatility as an exogenous financial input. This demonstrates that operational failures are the endogenous drivers of the strategic option value.

Moving from the manufacturing floor to the supply chain, the analysis decomposed a major component of logistics volatility: shipping costs. Figure 4 presents the average shipping cost per unit across the four primary carriers used. A significant cost differential is evident, with Carrier A being substantially cheaper than Carrier D. This finding is critical because the variability in carrier pricing directly contributes to the overall supply chain cost volatility (σ_{SC} = 0.3135) used in the strategic valuation. For resilient logistics, the decision is not simply to choose the cheapest carrier, but to manage a portfolio of carriers (flexibility) that balances low cost with the reliability and speed needed to hedge against disruption risks, thus reducing the volatility input.

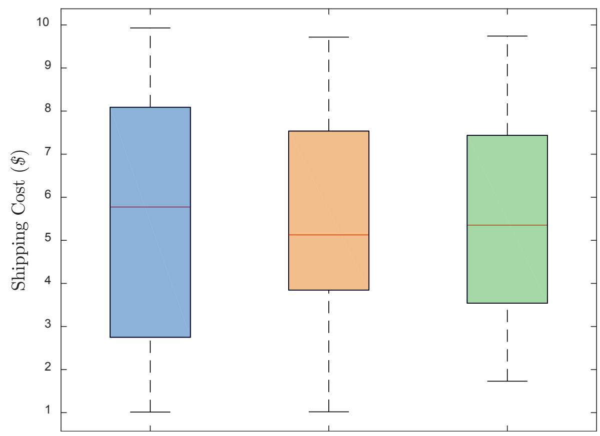

Figure 4 : Shipping Cost by Carrier

A bar chart illustrating the substantial cost variance between the four primary logistics carriers. This differential highlights the exposure to cost volatility ($\sigma_{\_SC}$).

The empirically derived cost volatility (σ_{SC} = *0.3135*) was the core input for the ROV model, which quantifies the strategic value of having the flexibility to invest in resilient capacity. To capture the inherent uncertainty, Figure 5 visualizes the Stochastic Modeling of Annual Cash Flow Margin using N=500 simulation paths. These paths, governed by the GBM process, use the measured cost volatility as the key parameter, demonstrating the wide range of potential future financial outcomes. This stochastic representation provides the mathematically rigorous treatment of uncertainty necessary for the ROV model.

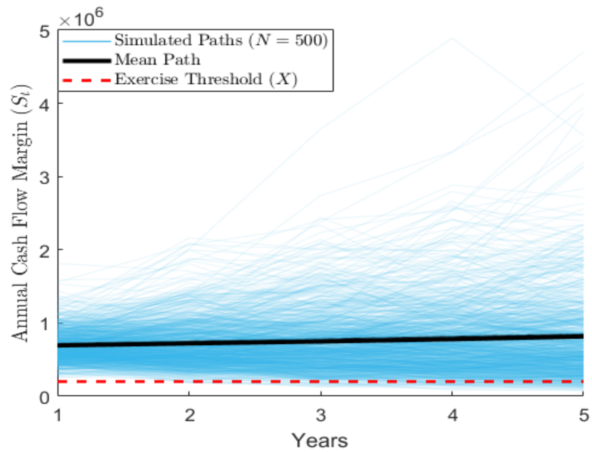

Figure 5: Stochastic Modeling of Annual Cash Flow Margin

The figure clearly shows that the Mean Path maintains a value substantially above the Exercise Threshold (X) of \$ 0.2 x 10^6. This visual representation confirms that the wide dispersion of simulated paths, driven by the 0.3135 volatility, is the essential prerequisite for generating the large strategic option value.

Following the simulation, Figure 6 displays the Probability Distribution of the Terminal Asset Value (S_t) after T=5 years. This visualization is key to the options framework, as the area under the curve to the right of the Exercise Price (X) of \$200,000 represents the probability of the resilient investment being profitable, which forms the basis of the options payoff calculation

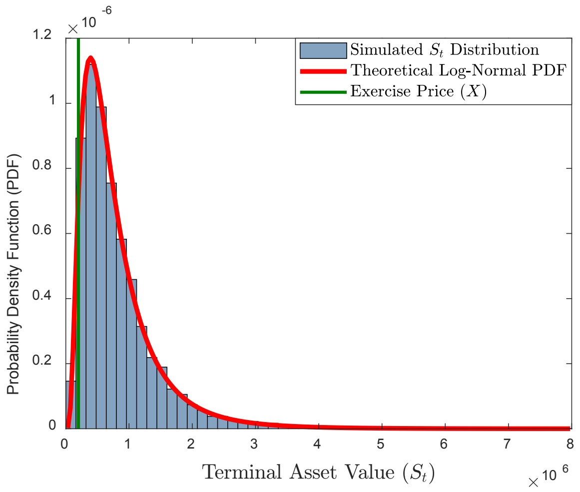

Figure 6: Probability Distribution of Terminal Asset Value

A histogram showing the frequency distribution of the final asset values. The figure explicitly plots the probability mass to the right of the Exercise Price (X).

The core outputs of the Black-Scholes model for valuing this strategic investment are presented in Table 3.

Table 3: Real Options Valuation Outcomes

Valuation Parameters	
Metrics	**Value**
Volatility	0.3135
Initial Asset Value	\$668,038.48
Option Exercise Cost	\$200,000.00
Valuation Outputs	
Metrics	**Value**
Real Option Value	\$516,193.55
Flexible NPV	\$11,020,000.00
Flexibility Index	0.24

The analysis yielded a strategic Real Option Value (V_{Option}) of \$516,193.55. This is a pivotal finding: by incorporating the value of managerial flexibility (the option to wait for optimal market conditions), the Flexible NPV (NPV_F) is calculated as \$11,020,000.00. This high valuation confirms that the strategic value of flexibility is substantially greater than the immediate intrinsic value. The Flexibility Index of 0.24 indicates that 24% of the project's total value is directly attributable to the management's option to be flexible, validating the decision to delay investment until cost conditions are optimal.

Furthermore, Figure 7 provides robust internal validation. The Monte Carlo Simulation (V_{MC}) results agreed with the Black-Scholes value (V_{Option}) to within 0.07%, establishing high internal consistency for the strategic valuation component.

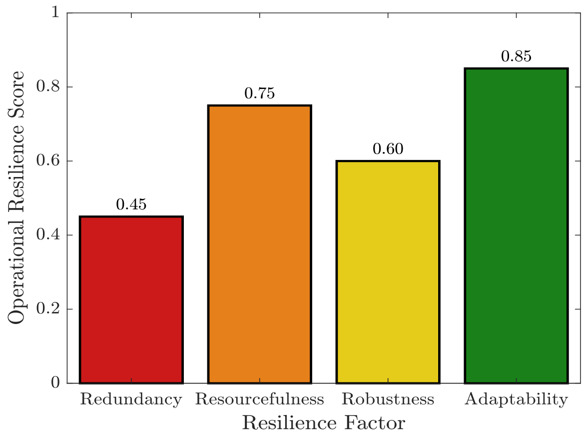

Figure 7: Analysis of Operational Resilience Factors

Comparison of the Black-Scholes Value versus the Monte Carlo Simulation Value (V_{MC}). The figure confirms the robust internal consistency of the ROV model.

The quantitative impact of uncertainty and time on the investment decision is summarized in Table 4, which presents the Option Value Sensitivity Analysis. This analysis confirms the fundamental real options principle: the strategic value of the investment option increases monotonically with both Asset Volatility (σ) and Time to Expiration (T).

Table 4: Black-Scholes Model: Option Value Sensitivity Analysis

Asset Volatility	T=3 years	T=5 years	T=7 years
0.25	\$415,100	\$495,000	\$565,500
0.3135	\$516,193	\$595,200	\$682,700
0.37	\$610,750	\$712,900	\$805,100

The high uncertainty confirmed in the empirical data (σ=0.3135) increases the value of flexibility, confirming the financial wisdom of delaying the investment decision to maximize the value of waiting.

The final phase, Operational Optimization, translates the strategic mandate into a precise tactical solution using the Total Resilient Cost (TRACT) model. The TRACT model determines the optimal level of physical stock redundancy (SL*) that minimizes the total cost function (TRACT), which is the sum of the Resilience Investment Cost **(***I***)** and the Expected Loss **(***EL***)**.

The conceptual basis for this analysis is the fundamental trade-off illustrated in Figure 8, where the marginal benefit of resilience investment eventually diminishes relative to its marginal cost.

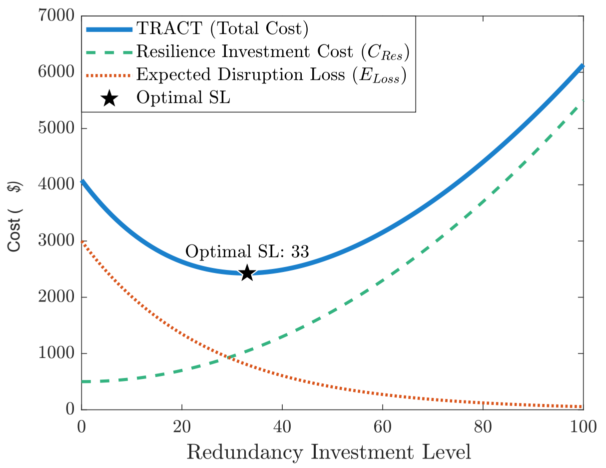

Figure 8 :Economic Dynamics of Resilience

Conceptual representation of the non-linear relationship between increasing investment in resilience measures and the corresponding reduction in the risk of loss.

The TRACT minimization must account for multiple, weighted disruption scenarios, as detailed in Table 5.

Table 5: TRACT Optimization Results by Disruption Scenario

Scenario	Probability
Low Impact/High Frequency	0.40
Medium Impact/Moderate Frequency	0.35
High Impact/Low Frequency	0.25
Integrated Optimal Stock Level	33 units

The model formally minimizes the total cost function by integrating the financial impact of these varied disruption scenarios. By solving the TRACT function under this weighted risk profile, the model identifies an Integrated Optimal Stock Level **(***SL****)** of 33 units. This result demonstrates a sophisticated approach to operational risk management, where the optimal inventory buffer is based on a holistic assessment of the entire risk landscape.

The financial validation of this optimal redundancy is presented in Table 6, which details the cost components at and around the minimum point. The absolute minimum Total Resilient Cost **(***TRACT***) of** $190,340 occurs at *SL** =27 units.. However, since the TRACT curve is relatively flat near this optimum, the model identifies the 33 units derived from the integrated, weighted scenario analysis as the practical operating target, providing an extra safety margin with only a marginal cost increase ($10).

This minimum is achieved by balancing the linear Resilience Investment Cost (*I*) of $75,540 (inventory carrying costs) against the higher, but manageable, Expected Loss **(***EL***)** of $114,800.

Table 6: Total Cost Breakdown for Optimal Stock Level (SL*) Sensitivity

Stock Level	Resilience Investment Cost	Expected Loss	Total Resilient Cost
27	$75,540	$114,800	$190,340
33	$85,140	$105,210	$190,350
42	$101,890	$97,710	$199,600

Table 6 illustrates a crucial insight for tactical management: the TRACT curve is relatively flat near the absolute optimum. Increasing the stock level from 27 to 33 units only raises the total cost marginally to $190,350 (a difference of only $10). This allows managers to choose the 33 units derived from the integrated scenario analysis (Table 4) as a practical operating target, providing an extra safety margin without incurring a significant cost penalty.

The prescriptive strength of the TRACT model is further evidenced by Table 7, which shows how the Optimal Stock Level (SL*) dynamically adjusts under varying Disruption Probabilities.

Table 7: Dynamic Optimal Stock Level (SL*) under Varying Disruption Probabilities

Disruption Probability	Optimal Stock Level (SL*)
0.03	28 units
0.07	33 units
0.11	41 units
0.15	45 units

This demonstrates the agility of the model: as risk increases (from 3% to 15% probability), the required stock level shifts significantly (from 28 to 45 units), providing a clear, quantitative signal for increasing operational redundancy to maintain cost-optimality.

The power of this integrated framework is its ability to harmonize strategic and operational decisions. The ROV model determines when to execute the option to invest in resilient capacity, leveraging the *NLS* cost function to minimize the financial entry barrier (X). Concurrently, the TRACT model determines how to structure the post-investment operation, providing the Optimal Stock Level as a quantitative guide for capital allocation toward cost-minimizing operational redundancy. This complete, data-driven approach moves the field beyond qualitative risk assessment to establish an adaptive and structurally optimized strategy for resilient manufacturing logistics and supply chain operations.

5. Conclusion

To sum up, this research successfully developed and empirically validated a novel, integrated analytical framework that rigorously links strategic investment timing with operational resilience planning within the manufacturing sector. The principal theoretical contribution is the formal resolution of the strategic-operational decision-making dichotomy by unifying the Non-Linear Least Squares (NLS) model for empirical cost structure, Real Options Valuation (ROV) for strategic timing, and the novel Total Resilient Cost (TRACT) model for operational optimization. The analysis provided robust evidence that strategic flexibility (ROV) holds significant quantifiable value, proving that neglecting managerial option value leads to severe underestimation and incorrect project rejection in volatile markets. This flexibility often transforms a negative Static Net Present Value (NPV_{Static}) into a positive Comprehensive Flexible Valuation (CFV), thereby justifying the fundamental strategic merit of the capital investment. Furthermore, the empirical linkage between operational cost drivers and the option's financial parameters allows managers to strategically reduce the investment cost (X) through efficiency improvements. The framework provides a precise, data-driven engine for optimal capital allocation, as the TRACT model determines how to structure the operation after investment by providing a cost-minimizing level of redundancy (e.g., the Optimal Stock Level (SL*).

The study acknowledges several methodological and empirical limitations that define its scope and necessitate a focused future research agenda. Empirically, the reliance on a single composite dataset (Singh, 2023), while confirmed to possess high internal reliability (Adjusted R^2 = 0.887), limits the immediate external generalizability of specific parameter values to radically different manufacturing contexts. Methodologically, the current framework utilizes an initial Geometric Brownian Motion (GBM) assumption for cost volatility, which, while standard for ROV, does not capture catastrophic shocks or mean-reverting behavior. Furthermore, the TRACT model incorporates a simplified structure based on linear costs for redundancy and relies on subjective weighting of performance metrics. Addressing these limitations, future research will concentrate on comparative validation studies across diverse manufacturing environments to confirm external robustness; develop and apply advanced multi-factor stochastic models (such as jump-diffusion or mean-reversion) for enhanced predictive fidelity; refine the TRACT model by incorporating non-linear cost functions and objective weighting methods (e.g., AHP/DEA); and broaden the analysis to include and quantify exogenous costs like regulatory compliance and reputational damage, thereby strengthening this integrated approach as a significant advancement in decision science for the future of manufacturing.

Nomenclature

ΔS_t	Asset Value Change
C_I	Current Inventory Cost
C_{max}	Maximum Inventory Cost
C_m	Manufacturing Cost
$C_{Investment}$	Investment Cost
C_F	Instantaneous Cash Flow
CFV	Flexible Valuation
d_1	First Black-Scholes Factor
d_2	Second Black-Scholes Factor
D_i	Component Disruption
E[Loss]	Expected Loss
F_I	Flexibility Index
L	Lead Time
N	Normal Distribution
N_{sim}	Simulation Number
NPV	Net Present Value
NPV_S	Static NPV
Psimj	Simulation Payoff
r	Risk-free Rate
$R_{Rapidity}$	Rapidity Index
$R_{Redundancy}$	Redundancy Index
$R_{Robustness}$	Robustness Index
ROV	Real Options Value
S	Safety Stock
S_0	Initial Asset Value
S_t	Asset Value
S_{Tj}	Terminal Asset Value
T	Time to Expiration
T_C	Total Cycle Time
T_i	Component Total Capacity

TRACT	Total Resilient Cost
V	Production Volume
V_{MC}	Monte Carlo Value
X	Exercise Price
β_0	Fixed Cost Intercept
β_1	Lead Time Coefficient
β_2	Production Volume Coefficient
β_3	NLS Interaction Term
Δt	Small Time Step
ϵ	Random Shock
κ	Cash Flow Mean
ρ	Correlation Coefficient
σ	Project Volatility
σ_{SC}	Supply Chain Volatility

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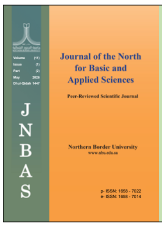

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Scour Control in Stepped Spillways Using Semicircular Baffle Blocks: Experiments and Predictive Modeling

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Abstract

This study explored the effectiveness of semicircular baffle blocks (SBBs) in mitigating scour downstream of stepped spillway stilling basins and demonstrated the potential of genetic programming (GP) for accurate scour prediction. Laboratory experiments under varying hydraulic and geometric conditions showed that optimal SBB placement within the first third of the stilling basin (xo = 0.21), combined with an intermediate height ratio (ho ≈ 0.375), reduced scour depth by nearly 90%. Building on these findings, a GP model was developed to capture the nonlinear interactions between flow and geometric parameters. The model achieved excellent predictive performance, with coefficients of determination of 0.92 (training) and 0.885 (testing), alongside low error metrics. These results confirmed the capability of GP to provide robust, data-driven predictions of scour depth, offering a valuable complement to physical experimentation. The integration of experimental optimization and GP-based modeling support more reliable and sustainable hydraulic structure design.

Article highlights

- Optimal SBB design reduced scour depth by nearly 90% in stepped spillways.
- Block height proved most critical; block width had negligible effect.
- GP modeling outperformed regression, providing robust scour predictions.

Keywords: Stepped spillway, Baffle Block, hydraulic structure, Regression, GP.

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1. Introduction

The erosion of bed materials, known as scour, is a critical factor influencing the safety and service life of dams and spillways. Despite their energy-dissipating design, stepped spillways are particularly vulnerable to local scour near the toe, (Rajaratnam,1990; Hoffmans & Pilarczyk, 1995). To address this problem, a range of mitigation strategies has been proposed. Structural modifications in stilling basins, such as flow deflectors and baffle blocks, have proven effective in altering flow characteristics and limiting scour (Negm et al., 2007, 2008). Previous experiments have demonstrated the benefits of structural countermeasures. For example, semicircular baffles were shown to significantly reduce scour (Barlock, 2013), while corrugated aprons helped dissipate jet energy and limit scour in submerged hydraulic jumps (Ali et al., 2014), underscoring the role of surface roughness. Numerous experimental studies have further examined the impacts of apron length, step geometry, baffling devices, and flow aeration on scour behavior, consistently reinforcing the significance of hydraulic and geometric factors (e.g., Hayder and Jafar, 2015; Hong et al., 2015; Elnikhely, 2018; Aminpour et al., 2018; Ghaderi et al., 2020; Eghlidi et al., 2020; Schleiss et al., 2023; Abdi et al., 2024; Cahya et al., 2024, Mei et al., 2025; Sharif, 2025; Bekheet, et al. 2025). Despite these efforts, predicting scour remains a complex task, as it depends on highly variable hydraulic conditions. This has motivated the application of computational and data-driven approaches. Early studies employed artificial neural networks (ANNs), gene expression programming (GEP), and genetic programming (GP) to predict scour in trapezoidal channels, spillways, and bridge piers (Guven & Gunal, 2008; Azamathulla et al., 2010; Moussa, 2013; Sattar et al., 2013; Mesbahi et al., 2016; Fuladipanah et al., 2023; Abdi Chooplou et al., 2024). Critical review for detecting and mitigating scour handle by Sharafati et al., 2020 and Tola et al. 2023. More recent research demonstrates that machine learning (ML) methods including Support Vector Machines (SVM), XGBoost, CatBoost, and gradient boosting ensembles can outperform empirical equations in scour prediction. For example, Le & Hien (2024) found XGBoost superior for sluice outlets, Kaushik et al. (2025) validated SVM models for river pipelines, and Ghanim et al. (2025) reported gradient boosting models with coefficients of determination exceeding 0.96 for submerged weirs. These advances reflect a clear shift toward hybrid approaches that integrate hydraulic knowledge with AI-based models to improve reliability and design efficiency. The scope of ML-based scour prediction has also expanded across diverse hydraulic environments, including spur dikes (Tabassum et al., 2024), sluice outlets (Le, 2024), weirs (Sharafati et al. 2020, and Ghanim et al., 2025), and river pipelines (Kaushik et al., 2025). This study aims to (i) experimentally assess the effectiveness of semicircular baffle blocks in stepped spillway stilling basins for reducing local scour, and (ii) develop regression- and GP-based predictive models for scour depth, provide a practical framework for simulating scour and improve hydraulic design.

2. Experimental Work

The experiments were carried out in a flume measuring 16.2 m in length, 65 cm in depth, and 66 cm in width (Fig.1). The experiments were conducted in the Hydraulics Laboratory at Zagazig University between June and august 2023. The flow from the flume was directed into a drain located in a lower channel, equipped with a weir for discharge measurement. A wooden spillway model was built and placed at the flume's midpoint, featuring a contraction ratio of 20%. The spillway measures 32 cm in height (H_s), 54 cm in width (W_s), and has 8 cm high steps (H_s). The downstream side of the spillway is inclined at a 30-degree angle. A 120 cm long stilling basin (L) was used to contain the free hydraulic jump occurring above it. Downstream of the basin, a 3.5-meter-long mobile bed was constructed using a 20 cm thick layer of stone. The fine gravel sample, with a median size (d_{50}) of 3.1 mm and a uniformity coefficient of 1.68, indicates a uniformly graded soil composition. Each experiment was allocated 2 hours, with a discharge rate of 35 L/s. These initial trials confirmed that 2 hours were sufficient to achieve over 90% of the maximum equilibrium scour depth. Each experiment was conducted for 2 hours at a discharge of 35 L/s, a duration shown in preliminary trials to achieve more than 90% of the equilibrium scour depth, in agreement with the methodology adopted by Mohamed et al. (2015). All experiments were performed under clear-water conditions, with the free hydraulic jump occurring downstream of the stepped spillway in each run. Scour depth downstream of the stilling basin was measured with an accuracy of ±0.1 mm using a 2 cm by 2 cm grid mesh. A point gauge was employed to measure the scour depth at each grid point. The same point gauge was also used to measure water depths both upstream and downstream of the spillway. A total of 80 experimental runs were conducted. A range of experimental configurations, featuring various semi-circular baffle block (SBB) arrangements fixed at different positions over the stilling basin with varying widths and heights, are detailed in Table 2 and illustrated in Fig. 2. Flow velocities over the stilling basin and mobile bed were measured using an electromagnetic current meter based on Faraday's law of induction. The instrument offers an accuracy of approximately ±0.01 m/s (Elnikhely, 2018; Aminpour et al. 2018; Ghaderi et al. 2020). Measurements were taken at each vertical, with the probe positioned 1.5 cm above the bed to represent near-bed velocity values.

3. Analysis and discussions

3.1 Effect of SBB Location on Scour Development

Fig. 3 illustrated the influence of the semicircular baffle block (SBB) location on relative scour depth, where the location was expressed by the non-dimensional parameter $x_o = x/L$ (with as the streamwise distance from the channel entrance and as the total basin length). The results showed that placing the SBB within the first third of the stepped spillway stilling basin significantly reduced scour depth, achieving an average reduction of about 75% compared to the case without an SBB. Comparison with earlier studies (Novak, 1961; Elnikhely, 2018) showed close agreement, with deviations averaging about ±7%, largely attributable to minor differences in experimental setup and boundary conditions. The maximum reduction of relative scour occurred at , where the scour depth decreased by nearly 85%. As the SBB was positioned farther downstream, beyond the first third of the stilling basin, its effectiveness diminished, with the reduction in scour depth decreasing to about 35% at . The reasons for this trend were examined in the following section through an analysis of near-bed velocity vectors within the stilling basin and the scour contours observed downstream. Near-bed velocity distributions and scour contours downstream of the stilling basin were presented for different scenarios: without semicircular baffle blocks (SBB) and with SBBs installed at various positions (x_o = *0.1 – 0.67*). Fig.4 illustrated the case without countermeasures, where the maximum near-bed velocity reached 1.3 m/s at the point of maximum scour depth (5 cm), located 16 cm downstream of the stilling basin. With an SBB placed at x_o = *0.21* (Fig. 5), the redistribution of velocity vectors enhanced energy dissipation, reducing the maximum velocity to 0.9 m/s and limiting the scour depth to 1.6 cm near the side of the open channel, about 3 cm downstream of the stilling basin. These results emphasized the significant role of SBBs in controlling and mitigating scour hole dimensions. With the SBB fixed at x_o = *0.34* (Fig. 6), the baffle remained effective in dissipating energy by damping velocity vectors at the end of the stepped spillway's stilling basin, although its influence was less pronounced compared to the case with . In this configuration, a scour hole developed with a depth of 2.4 cm, located about 11 cm downstream of the stilling basin, subjected to a near-bed velocity of 1.0 m/s. When the SBB was placed farther downstream at x_o = *0.67* (Fig. 7), it remained effective in dissipating energy, with reduced near-bed velocities compared to the case without an SBB. At this position, the baffle caused the flow to concentrate along both sides of the open channel, where near-bed velocities reached 1.16 m/s on the right side and 1.15 m/s on the left side. The maximum scour depth observed in this configuration was 4 cm, located about 10 cm downstream of the stilling basin. These results collectively demonstrated that SBBs were effective in mitigating scour and reducing near-bed velocities, with the most significant improvement observed at x_o = *0.21*.

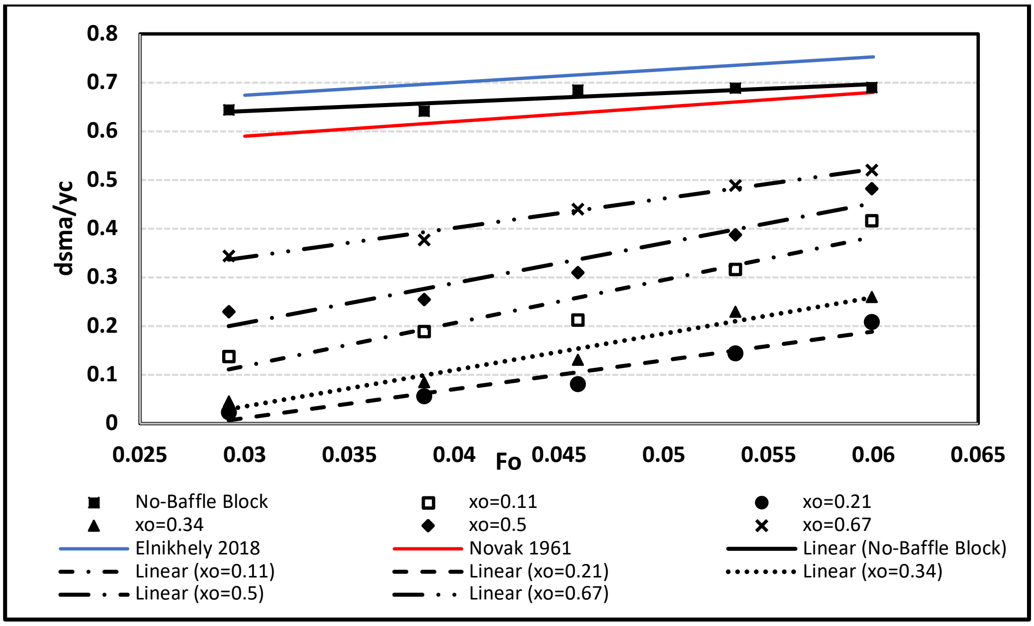

Fig. 3 Variation of Relative Scour Depth with Froude Number for Different SBB Locations (xo).

Fig. 1. General view of the laboratory flume.

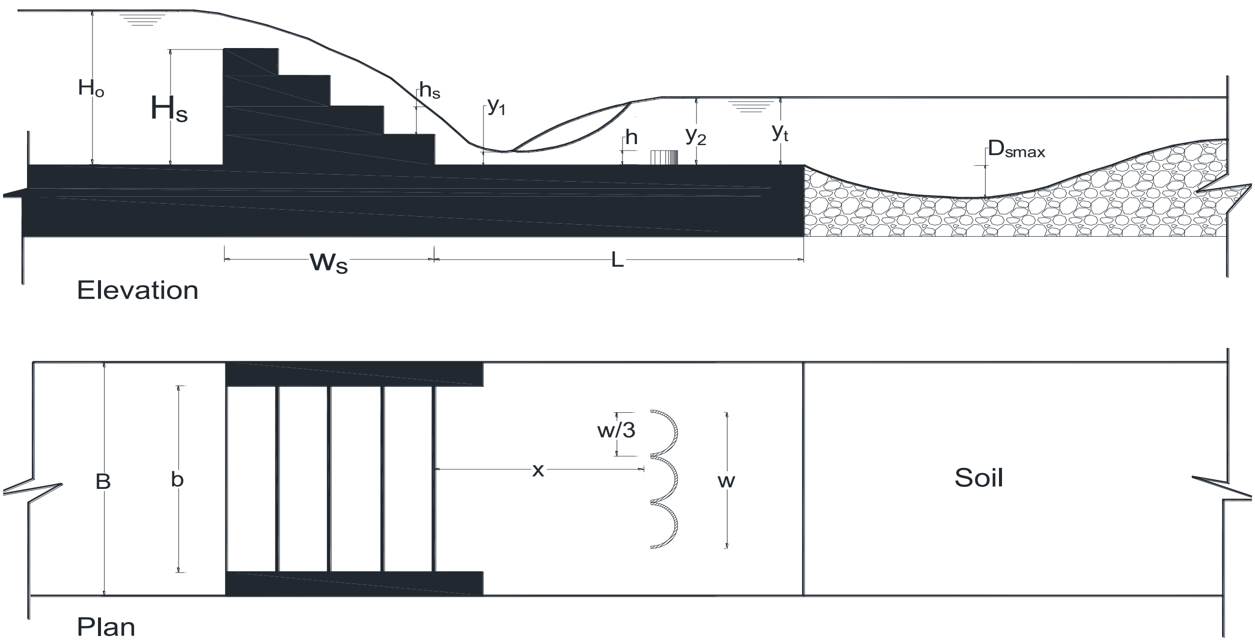

Fig. 2 Configuration sketch of the experimental setup

Table 1 Detailed specifications of the experimental setup

Flow rate, Q , Upstream flow depth, H	Q= 15-35 l/s , H = 35-42 cm
Spillway dimensions	Height, Hs = 32 cm; width, Ws = 54 cm; consisting of 4 steps, each with a height of hs= 8 cm.
Contraction (b/B)	20%
Distance (x) from last step to the semicircular baffle block (SBB)	x = 13.5, 25.5, 40.5, 60.5, and 80.5 cm
Heights of SBB, h	h= 2, 3, 4, 5, 6, 8, 10 cm
Width of SBB, w	w= 30, 45, and 66cm

3.2 Effect of SBB Height and Width on Scour Development

In this section, the SBB location was fixed at x_o = ***0.21*** while its height (h_o) was varied within the range 0.25–1.25 to evaluate its influence on flow structure and scour development downstream of the stepped spillway stilling basin (Fig. 8). At the smallest height (h_o = ***0.25***), only a modest reduction in scour depth was achieved (approximately 21%). The baffle was too small to significantly alter the velocity field, allowing high near-bed velocities to persist over the mobile bed and resulting in a pronounced scour hole, 4.1 cm deep, located 28 cm downstream of the basin (Fig. 9). This demonstrated that insufficient baffle height provided little resistance against the strong jet action and high-energy flow. As the height increased to h_o = ***0.375***, the SBB became much more effective in dissipating energy. The flow deceleration was evident in the reduced near-bed velocity of 0.7 m/s, and the scour depth decreased markedly to 1.2 cm, localized to one side of the open channel (Fig. 10). This case illustrated the beneficial effect of a moderately sized baffle in stabilizing the flow and protecting the bed. A similar trend was observed for h_o = ***0.5***, where scour reduction remained significant, with an average reduction of about 87% compared to the no-SBB condition. The optimum performance occurred at h_o = ***0.375***, where the relative scour depth was reduced by nearly 89%. Beyond this range, however, the influence of SBB height became counterproductive. At h_o = ***0.5*** and especially h_o = ***1.25***, the interaction between the jet and the taller baffle generated strong recirculating zones and complex velocity patterns, producing asymmetric flow structures. As a result, scour activity intensified. In the case of h_o = ***0.625***, a scour hole 5 cm deep developed on the right side of the channel, 25 cm downstream of the basin (Fig. 11), while additional scour holes formed along both channel sides for h_o = ***1.25*** (Fig. 12). In this case, near-bed velocities reached up to 1.55 m/s, leading to a maximum scour depth of 6.3 cm. Overall, the results indicated that while very small baffles had minimal hydraulic effect, and excessively tall baffles disrupted the flow and promoted severe localized scour, an optimally sized SBB (h_o ≈ ***0.375***) effectively dissipated energy, stabilized flow patterns, and significantly reduced scour downstream. This highlighted the importance of careful height selection to achieve stable and efficient hydraulic performance. The influence of varying the SBB width at the optimal position and height was illustrated in Fig. 13 (h_o = ***0.375***, x_o = ***0.21***). The width was tested at w_o = ***0.45, 0.68***, and 1.0. Within this range, variations in had no appreciable impact on scour reduction, with an average reduction of approximately 91% observed in all cases. This indicated that, once the optimal height and position were established, the effect of width became secondary, as the dominant mechanisms of energy dissipation and scour control were primarily governed by the SBB's vertical dimension and placement.

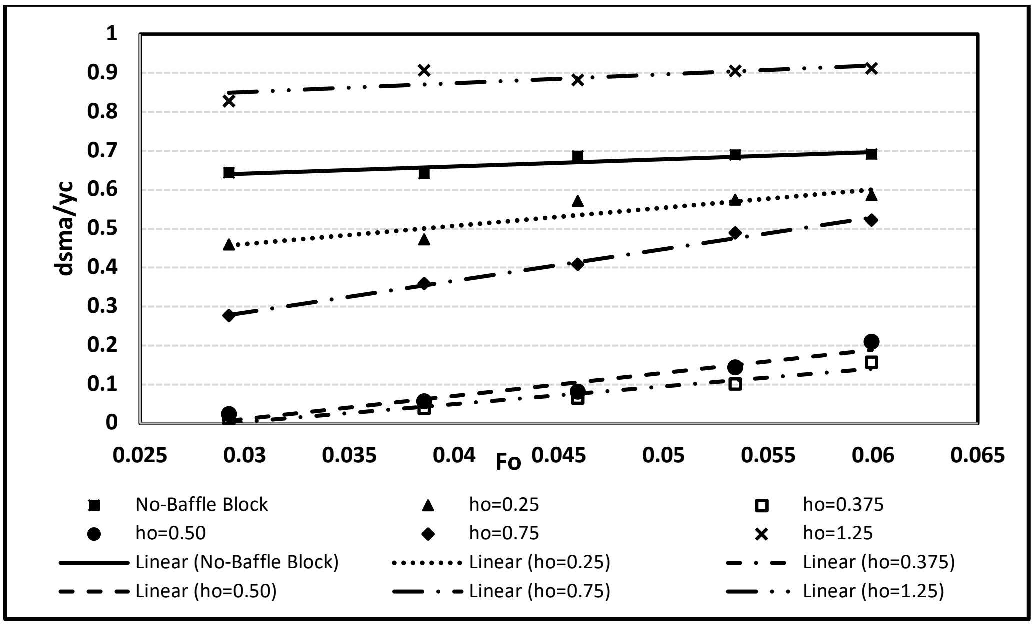

Fig. 8 Variation of Relative Scour Depth with Froude Number for Different SBB Heights (ho)

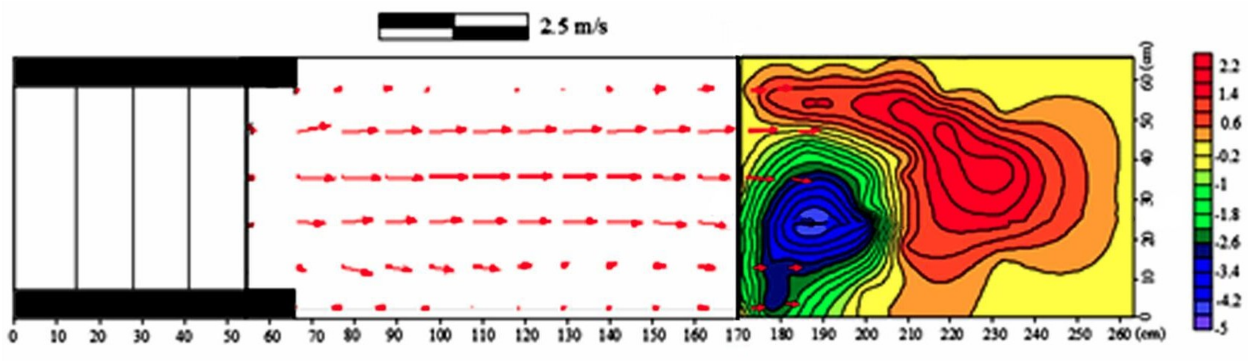

Fig. 4 Near-bed velocity distribution and scour morphology downstream of stilling basin without SBB, Fo = 0.08.

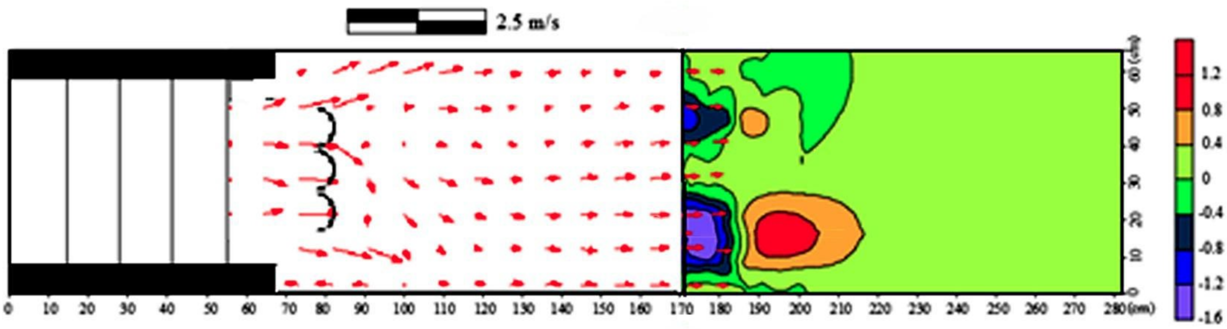

Fig. 5 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (xo = 0.21, Fo = 0.08).

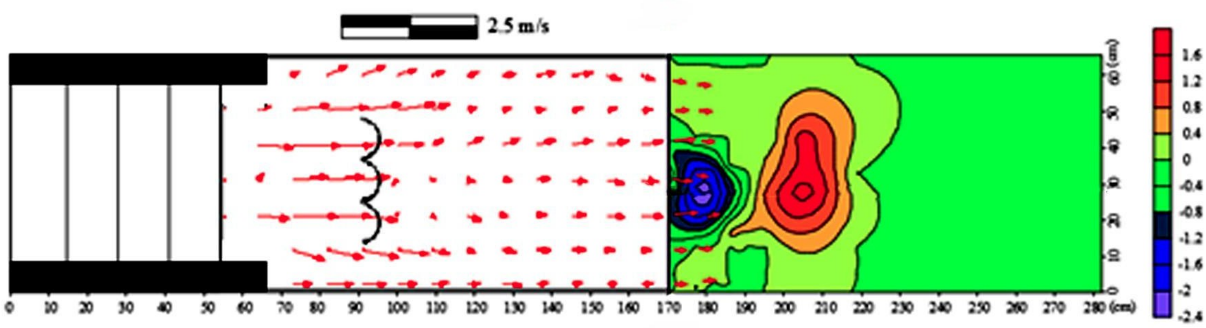

Fig. 6 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (xo = 0.34, Fo = 0.08)

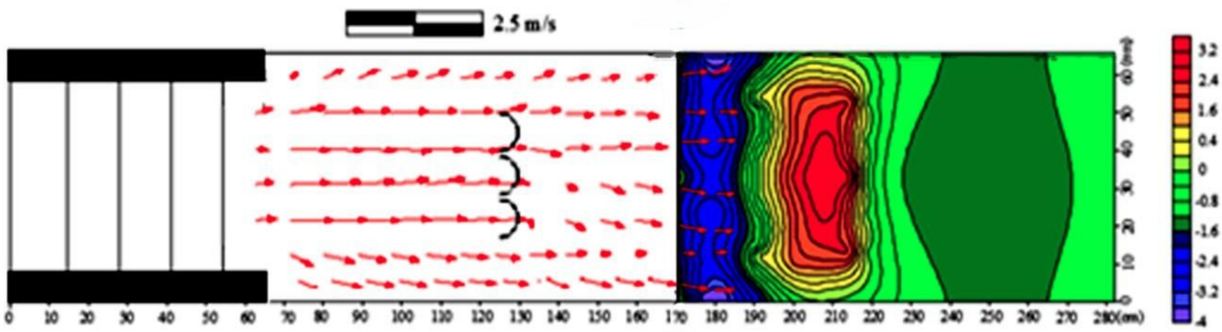

Fig. 7 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (xo = 0.67, Fo = 0.08)

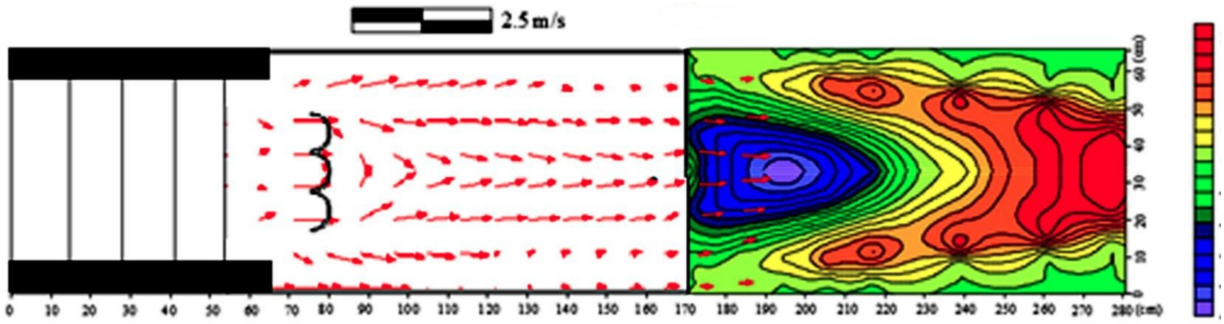

Fig. 9 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=0.25, xo = 0.21, Fo = 0.08)

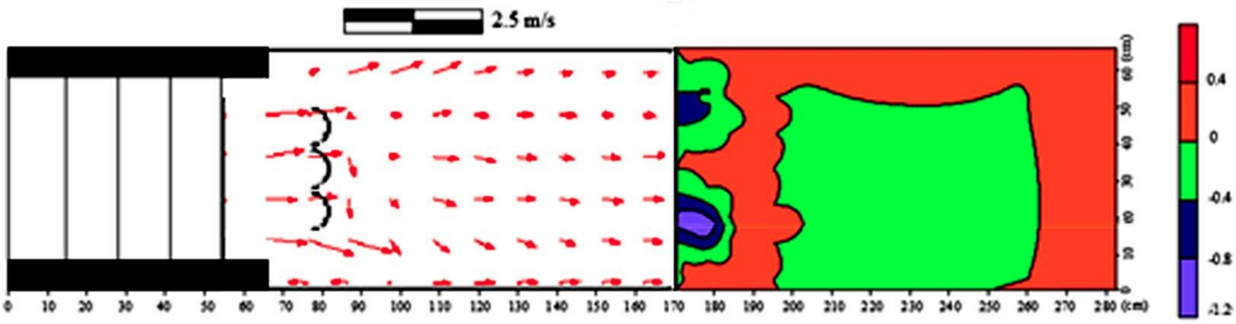

Fig. 10 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=0.375, xo = 0.21, Fo = 0.08).

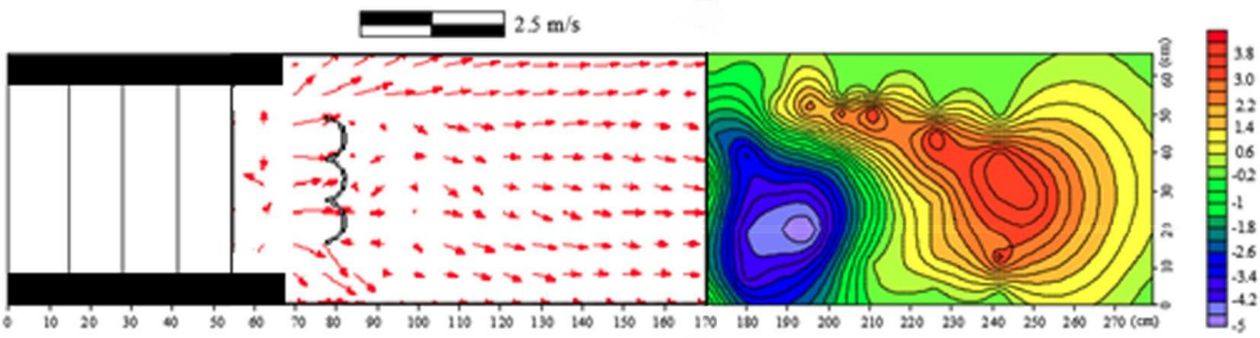

Fig. 11 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=0.625, xo = 0.21, Fo = 0.08)

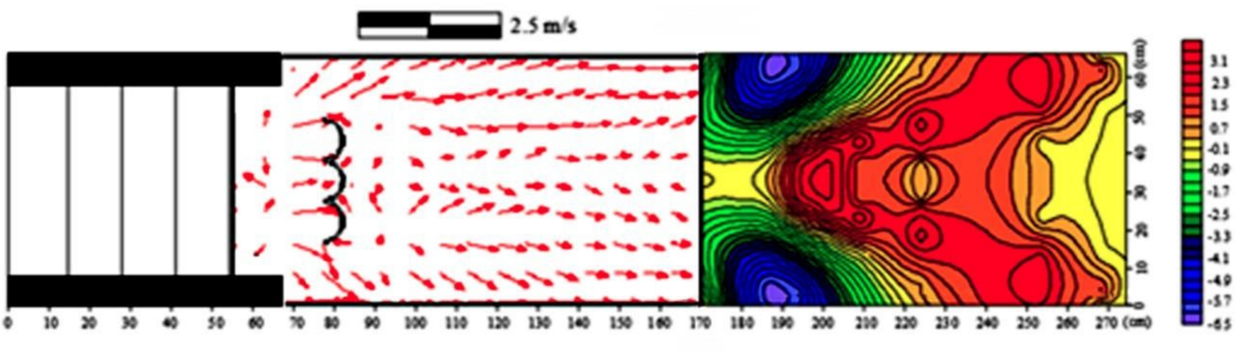

Fig. 12 Near-bed velocity distribution and scour morphology downstream of stilling basin with SBB (ho=1.25, xo = 0.21, Fo = 0.08)

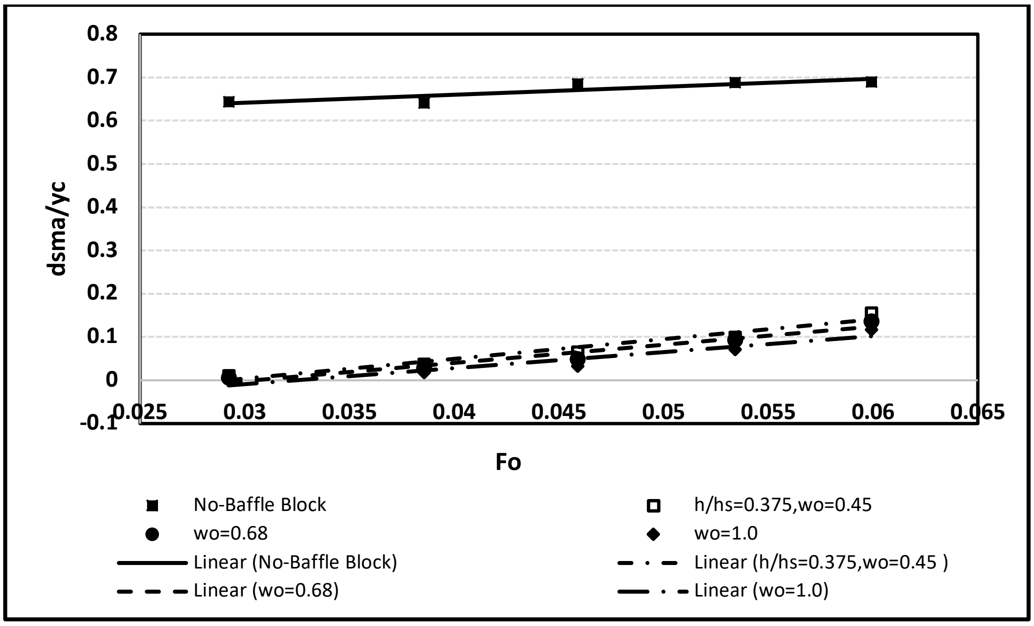

Fig. 13 Variation of Relative Scour Depth with Froude Number for Different SBB Widths (wo)

4. Development of Predictive Models

4.1 Regression-Based Approach

The relationship between the dependent variable and the independent variables can be expressed as:

$$\frac{ds}{yc} = f(xo, ho, wo, Fo) \qquad \text{Eq.1}$$

A regression model was developed by testing several functional forms, including linear, polynomial, logarithmic, exponential, and power-law expressions, using 70% of the dataset selected randomly for calibration. Each formulation was evaluated based on statistical indicators such as , Mean Absolute Percentage Error (MAPE), and standard error. The best performance was obtained from a hybrid model combining linear and logarithmic components, which allowed the regression to capture both the direct proportionality of geometric parameters and the nonlinear attenuation associated with flow intensity. This structure also minimized multicollinearity and provided stable parameter estimates. The final regression equation is given by:

$$\frac{d_s}{y_c} = 0.50 + 13.5x_o + 0.82h_o - 0.25w_o + 207.5F_o$$

$$-18.30\ln(1 + x_o) - 211.2\ln(1 + F_o) \qquad \text{Eq. 2}$$

Model evaluation metrics for the training and testing datasets are summarized as follows. For the training dataset (70% of the data), the regression model yielded a coefficient of determination (R^2) of 0.856, a mean absolute percentage error (MAPE) of 0.15, and a standard error of 0.09, demonstrating strong explanatory power and predictive accuracy. For the testing dataset (remaining 30% of the data), the model achieved a R^2 of 0.818, a MAPE of 0.17, and a standard error of 0.11, thereby it confirmed the robustness and generalizability of the proposed formulation.

4.2 Genetic Programming Approach

Genetic Programming (GP) is an evolutionary optimization method inspired by biological selection, where candidate solutions are iteratively refined to maximize a fitness function (Holland, 1975; Koza, 1992; Johari et al., 2006). Unlike fixed algorithms, GP adapts its structure dynamically through operations such as crossover and mutation. Programs are constructed from terminals (variables) and functions, including arithmetic operations and advanced mathematical functions (e.g., exp, sin, log, sqrt). In this study, GP uses a two-point string crossover, where random segments are exchanged between parents, and mutation, where operators or operands are replaced with alternative symbols from the same set, to maintain population diversity (Bramier and Banzhaf, 2001). The GP model was formulated by defining the terminal set, functional set, fitness function, control parameters, and termination criterion (Koza, 1992). The first three components establish the algorithm's search domain, whereas the latter two regulate the efficiency and quality of the evolutionary process. The terminal set comprises four fundamental groups of *ds/yc*, representing the nondimensional hydraulic relationships derived from the key variables governing scour depth (*xo*, *ho*, *wo*, and *Fo*) (Eq. 1). During the evolutionary process, crossover and mutation probabilities were set at 90% and 0.15, with a population size of 1000 individuals over 50 generations. The resulting GP model attained a maximum depth of 15 and a length of 138 nodes, reflecting considerable structural complexity. Similar to the regression model, approximately 75% of the data was used for training, with the remaining portion reserved for testing and validation. The GP-generated prediction formula is presented as follows:

$$\frac{ds}{yc} = \left(\frac{N}{D}\right)0.167 + 0.663 \quad \text{Eq.3}$$

In which;

$$N = 15.9 + 1.92xo + 2.96wo - 2.08ho - E_1 - \left\{-1.63xo\left[\frac{(0.33 - 1.33ho)(-0.45Fo)}{(0.88xo + 19.15) + 28.33}\right] - 51.40 + 0.659Fo.xo\right\}$$

$$E_1 = exp[45.3(0.33 - 1.33ho)(-5.72 - 1.161ho)(0.50ho - 0.99wo)]$$

$$D = \exp(-2.74) - \left\{-1.02xo + \frac{E_2}{\dfrac{0.96xo}{10.55 - (-1.09xo.ho - 235)\dfrac{0.50ho - 0.99wo}{-5.73 - 1.16ho}}} - (-22.30ho + 131.65)\right\}$$

$$E_2 = exp\left[\frac{(0.33 - 1.33ho)(-5.72 - 1.161ho)(2.08ho - 235.5)(0.50ho - 0.99wo)}{-5.39}\right]$$

The performance of the proposed GP formulas was assessed using standard statistical indicators. The coefficient of determination (R^2) reached 92% for the training data and 88.5% for the testing data. The standard error was 0.07 for training and 0.084 for testing, while the mean absolute prediction error was 0.098 and 0.12, respectively. Figs 14 and 15 compare the measured ds/yc values with the predictions from both the regression and GP models for the training and testing datasets. As demonstrated, the GP model consistently outperforms the regression model, achieving a higher R^2 (88.5% vs. 81.8%) and lower error values. The regression model, based on a hybrid formulation combining linear and logarithmic terms, was therefore less accurate than the GP approach

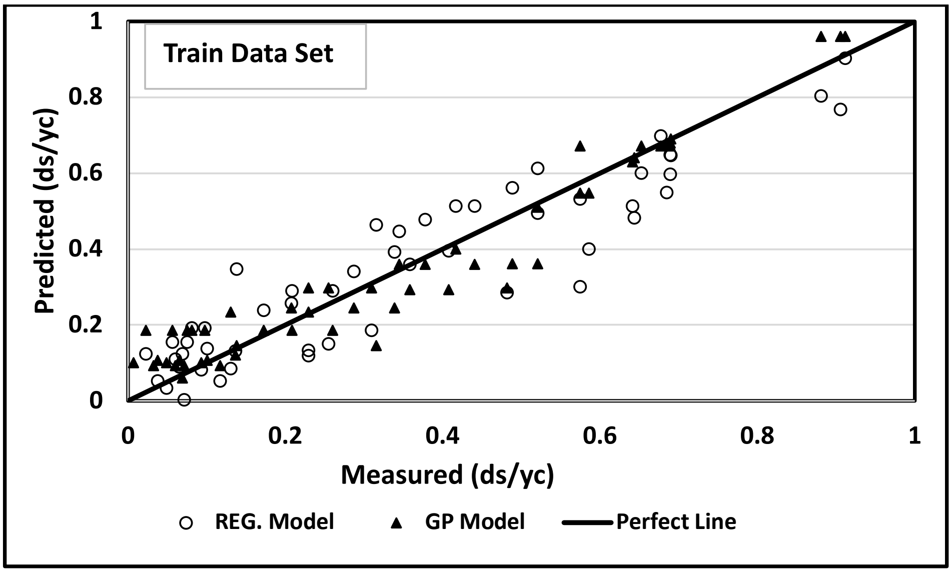

Fig. 14 Measured vs. predicted ds/yc for regression and GP models (train dataset)

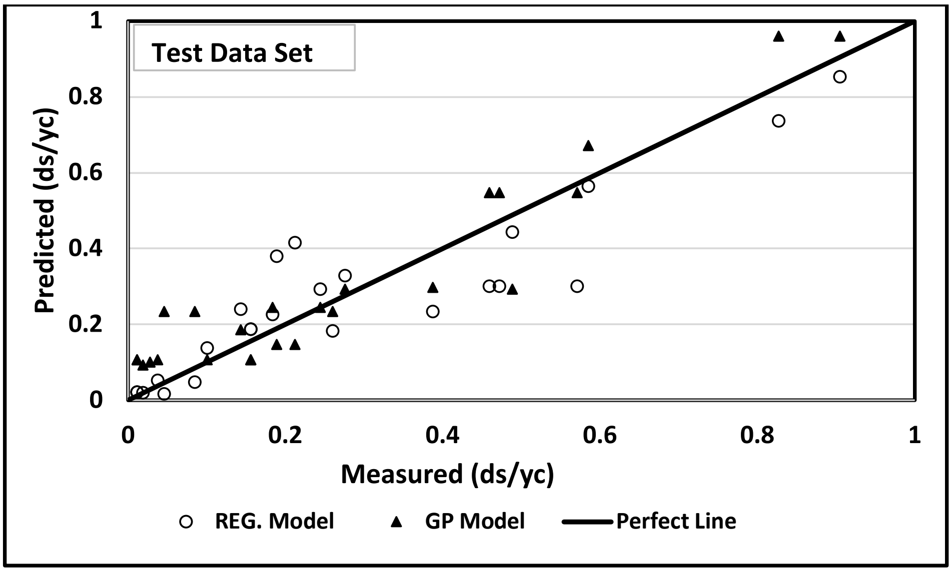

Fig.15 Measured vs. predicted ds/yc for regression and GP models (test dataset)

5. Conclusion

Mitigating local scour downstream of stepped spillways is essential to maintain structural stability and long-term performance. The experimental findings demonstrate that semicircular baffle blocks (SBBs) can reduce scour depth by up to 90% when positioned in the first third of the stilling basin ($xo = 0.21$) with an optimal height ratio ($ho \approx 0.375$). The block height was identified as the most influential parameter, while the block width had a little effect once the optimal configuration was established. On the modeling side, the hybrid regression approach provided a practical predictive tool, but the genetic programming (GP) model achieved superior accuracy and generalization. Collectively, these results highlight the effectiveness of SBBs as a cost-efficient countermeasure and underscore the value of GP-based predictive models in supporting sustainable hydraulic design.

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Cardiovascular Risk Reduction in Middle-Aged Women: A Cross-Sectional Analysis of Conventional and Complementary Medicine

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Abstract
Cardiovascular disease (CVD) is a global health concern. Complementary and alternative medicine (CAM) modalities are increasingly used for their potential role in CVD risk reduction. Aim: This study examined the integration of conventional medications with CAM approaches among middle-aged women. Methods: A cross-sectional design was used, involving 120 women aged 40–65 years attending Jazan healthcare facilities in Saudi Arabia. Data were collected through structured surveys and analyzed using IBM SPSS Statistics version 25. Results: CAM users were more likely to have higher high-density lipoprotein levels (Cohen's d= .74, p-value < .001), higher perceived stress level (Cohen's d= .64, p-value < .001), and slightly higher systolic blood pressure (Cohen's d= .31, p-value = .047) and diastolic blood pressure (Cohen's d= .34, p-value = .034). A univariate analysis of variance showed that CAM use was significantly associated with HDL levels ($F = 17.84$; $p < 0.001$) and perceived stress scores ($F = 14.16$; $p < 0.001$) even after controlling for confounders such as BMI and smoking. Conclusions: Integrating CAM with conventional medicine was associated with differences in cardiovascular risk indicators among middle-aged women. Increasing public health awareness of CAM may be linked to greater utilization and accessibility of CAM therapies.

Keywords: complementary medicine, alternative therapies, heart health, midlife women, cardiovascular risk

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1. Background

Cardiovascular disease (CVD) is a significant global health concern [1, 2]. In 2019, 17.9 million (%32) people worldwide died as a result of CVD [1]. The cost of CVD is approximately $237 billion per year, and half of this burden occurs in Asia [3]. The INTERHEART study found that nine modifiable risk factors, including smoking, dyslipidemia, hypertension, diabetes, abdominal obesity, and lifestyle choices, account for %90 of the risk of the first myocardial infarction [2]. Additionally, smoking is responsible for %36 of the myocardial infarction risk. Other high-profile risk factors include hypertension, tobacco use, and high cholesterol levels [3].

Emerging risk factors such as obesity, hypertension, diabetes, and high cholesterol levels are linked and increase the risk of CVD. Approximately %70 of patients have multiple risk factors that increase the risk of CVD from four-fold to 60-fold. Age is another significant cardiovascular risk factor, and hypertension, dyslipidemia, and left ventricular hypertrophy are more prevalent in those of advanced age [4]. Women who experience menopause at age 50 years or younger are at increased risk for CVD and mortality. Smoking, which has antiestrogenic effects, can also contribute to all-cause mortality in women because low estrogen levels can affect lipid profiles, thus leading to endothelium dysfunction and atherosclerotic plaque formation [5]. Middle-aged women may also be at increased risk for CVD because of psychosocial stress attributable to childhood abuse, intimate partner violence, and caregiving [6].

CVD prevention and management involve lifestyle modifications such as diet, exercise, and cardiac rehabilitation. Public health initiatives increase awareness and promote healthy living. Effective management of medications, such as statins, can control symptoms, prevent disease progression, and reduce complications such as heart attack and stroke [7]. Anticoagulants, such as warfarin and rivaroxaban, prevent blood clots associated with arterial fibrillation and deep vein thrombosis [8], whereas antiplatelet agents, such as aspirin and clopidogrel, prevent blood clotting during acute coronary syndrome management [9].

Several herbal medicinal plants and their extracts have been shown to be beneficial for CVD. For example, *Digitalis purpurea* has been extensively used because of its profound effects on cardiac functions [10]. *Allium sativum* (garlic) has been shown to be associated with improvements in hypertension, oxidative stress, inflammation, and hyperlipidemia [11]. *Astragalus membranaceus* is highly beneficial for ischemic-associated CVD [12]. The bioactive compounds of *Crocus sativus* (saffron), such as crocin and safranal, exhibit significant cardioprotective effects [13]. The cardiovascular protective effects of *Camellia sinensis* (green tea) are primarily attributable to its rich polyphenol and flavonoid contents [14]. In addition to herbal medicines, alternative therapies are becoming more commonly used to manage the CVD risk. Such therapies, which include acupuncture, yoga, meditation, and "point needling," may reduce the CVD risk and blood pressure. These therapies are commonly used by middle-aged women with incomes and education levels that are higher than those of their male counterparts [15].

A 2020 Saudi Arabian population-based study found that complementary and alternative medicine (CAM) is prevalent, and that herbal products, acupuncture, bloodletting, honey, cauterization, medical massage, and bone manipulation are the most commonly used CAM modalities. Adults in rural areas use CAM 2.92-times more frequently than adults in urban areas [16].

The current literature regarding CVD risk management relies heavily on the evaluation of either conventional medicine or individual CAM therapies chosen by individuals. However, middle-aged women, who comprise the largest portion of the population at risk for CVD, and the use of CAM therapies have been neglected in various targeted studies [17]. Therefore, this study aimed to examine the associations between the use of conventional medicine with CAM therapies and cardiovascular risk among middle-aged women in Saudi Arabia, and to compare cardiovascular risk indicators between integrative approaches and conventional methods alone. The study did not aim to evaluate the effects of individual CAM modalities, but rather to explore CAM use as a whole within an integrative context. Additionally, specific cardiovascular risk factors such as blood pressure, cholesterol levels, blood glucose levels, body mass index (BMI), perceived stress levels, and exercise levels were compared to examine their associations with integrative approaches and conventional treatment alone.

2. Methods

2.1 Study design

This cross-sectional study examined the association between the use of conventional medicine combined with CAM therapies and cardiovascular disease risk among middle-aged women. In this study, conventional medicine refers to evidence-based medical practices commonly used in standard healthcare systems for the prevention and management of cardiovascular disease. Complementary and alternative medicine (CAM) refers to health practices, products, and therapies that are not considered part of conventional medical care for cardiovascular disease. In this study, CAM includes cupping, green tea, ginger, massage, fenugreek, cauterization, garlic, omega-3, yoga, najila, Acupuncture. Integrative medicine is defined as the concurrent use of conventional medical care and one or more CAM modalities. The cross-sectional design allowed a comparative analysis of health outcomes of women who received conventional treatment alone and those of women used CAM in addition to the conventional medicine at specific time points.

2.2 Study population

The target population included middle-aged women 40 to 65 years of age who resided in Jazan region, Saudi Arabia. This demographic was chosen because of its increased susceptibility to CVD because of hormonal changes, lifestyle habits, and the onset of chronic health conditions.

2.3 Inclusion and exclusion criteria

Women were eligible for inclusion if they had complete cardiovascular-related biomarker data available in their medical records within the preceding six months. Women without available biomarker data during this period were excluded. In addition, women who had experienced major cardiovascular events, such as myocardial infarction or stroke, within the past year were excluded from the study. Pregnant women and those diagnosed with mental disorders or currently using psychiatric medications were also excluded.

2.4 Recruitment strategies

The participants were recruited by healthcare practitioners at Jazan Health Cluster Facilities. The purpose and procedures of the study were explained to potential participants. A structured interview was conducted to screen participant eligibility and to confirm that individuals classified in the conventional treatment group were not using any CAM modalities at the time of data collection. Those who agreed to participate completed the survey.

2.5 Sample size calculation

A power analysis indicated that 120 participants were necessary. The conventional and CAM treatment groups each comprised 60 participants. A 1:1 ratio was chosen to ensure balanced group sizes and comparable statistical power between the conventional and CAM groups. A hypothetical effect size was used to calculate the sample size (Cohen's d = 0.5) with a significance level of 0.05 and 85% power to ensure statistical robustness.

2.6 Data collection

Data were collected through structured interviews, standardized questionnaires, and medical record reviews. Women were interviewed using standard questionnaires to obtain demographic information, measure their CVD risk factors, and assess their current use of conventional medicine and CAM therapies. The Atherosclerotic Cardiovascular Disease (ASCVD) 10-year risk score was calculated using the pooled cohort equations recommended by the American College of Cardiology/American Heart Association (ACC/AHA). This method incorporates age, sex, total cholesterol, HDL cholesterol, systolic blood pressure, treatment for hypertension, diabetes status, and smoking status to estimate the 10-year risk of atherosclerotic cardiovascular disease. Biomarker data were obtained from the medical records. Current smokers were defined as participants who had smoked at least 100 cigarettes during their lifetime and currently smoked cigarettes. This item was assessed using a dichotomized response (yes or no). The diabetes status was assessed based on the classification of diabetes mellitus [18]. Women with fasting plasma glucose values ≥126 mg/dL or HbA1c ≥6.5% or a random blood glucose ≥200 mg/dL in the presence of signs and symptoms of diabetes were considered to have diabetes.

BMI was calculated based on the participant's body weight divided by height squared (kg/m^2). The Health Promoting Lifestyle Profile II, which is a subscale used to measure physical activity, was used to evaluate the physical activity status of the participants [19]. This physical activity subscale includes eight positively stated questions. Higher scores indicate greater participation in physical activity. The validity and reliability of this physical activity subscale among Saudi women have been confirmed by previous research [20].

Perceived stress was measured using the Perceived Stress Scale (PSS), which is the most widely used instrument for the personal perception of stress. The PSS measures the degree of individual stress [21] using questions about feelings and thoughts during the previous month. Each question asks how often the respondents felt a certain way. Total scores are determined by reversing the responses (e.g., 0 = 4, 1 = 3, 2 = 2, 3 = 1, and 4 = 0) to the four positively stated items (items 4, 5, 7, and 8) and summing all scale items. The reliability of the PSS among Saudi women has been established by several studies [22].

2.7 Data analysis

Data were analyzed using both descriptive and inferential statistical methods. Descriptive statistics comprised means and proportions of the baseline characteristics, CVD risk factors, and treatment modalities. Inferential statistics, including independent t tests and chi-square tests for categorical variables, were used to examine associations between treatment type and CVD risk. In addition, a univariate analysis of variance was conducted to assess the contribution of CAM to key cardiovascular and psychological metrics. Adjustments for confounders such as age and BMI were conducted.

2.8 Ethical considerations

This study was conducted in accordance with the principles outlined in the Declaration of Helsinki. Ethical approval was obtained from the Research Ethical Committee of Jazan Health Cluster Facilities (approval number: 2486). Participants were initially briefed about the study goals, methods, and potential risks; thereafter, they provided informed consent. The confidentiality of all personal and medical data was ensured. Additionally, the data were stored securely and their access was restricted. This study involved minimal risk limited to emotional discomfort during discussions about personal health.

3. Results

3.1 Sociodemographic characteristics of the study population

The study population comprised 120 middle-aged women between 40 and 65 years of age (mean age, 47.92 ± 6.97 years). The enrolled participants were from diverse social backgrounds. Among them, %60 were married, %19.2 were single, %14.2 were divorced; the remaining participants were either separated or widowed. Variations in the education level were recorded; %45 completed high school, %37.5 had a bachelor's degree, and %17.5 had an elementary-level education or less. Most participants (%57.5) were unemployed; %37.5 were employed and %4.2 were retired. Only %13.3 perceived themselves as overweight or obese (Table 1).

Table 1. Sample Characteristics

Characteristics		**Total, n (%)**	**Conventional medicine group,n (%)**	**CAM group, n(%)**	**p-value**
Total participants		120 (100)	60 (50)	60 (50)	
Age	Mean (SD)	47.92 (6.97)	48.67 (7.41)	47.17 (6.48)	0.240
Social status	Single	23 (19.2)	15 (12.5)	8 (6.7)	0.268
	Married	72 (60)	30 (25)	42 (35)	
	Divorced	17 (14.2)	10 (8.4)	7 (5.8)	
	Separated	3 (2.5)	2 (1.7)	1 (0.8)	
	Widower	5 (4.2)	3(2.5)	2 (1.7)	
Employment status	Employed	45 (37.5)	15 (12.5)	30 (25)	0.024
	Unemployed	69 (57.5)	42 (35)	27 (22.5)	
	Retired	5 (4.2)	2 (1.7)	3 (2.5)	
	Business owner	1 (0.8)	1 (0.8)	0 (0)	
Educational status	Elementary school or less	21 (17.5)	11 (9.2)	10 (8.3)	0.638
	High school	54 (45)	29 (24.2)	25 (20.8)	
	Bachelor's degree	45 (37.5)	20 (16.7)	25 (20.8)	
Smoking status	Yes	6 (5)	3 (2.5)	3 (2.5)	1.000
	No	114 (95)	57 (47.5)	57 (47.5)	
Self-identify as overweight or obese	Yes	16 (13.3)	7 (5.8)	9 (7.5)	0.591
	No	104 (86.7)	53 (44.2)	51 (42.5)	
Hypertension	Yes	68 (56.7)	27 (22.5)	41 (34.2)	0.010
	No	52 (43.3)	33 (27.5)	19 (15.8)	
Diabetes	Yes	60 (50)	26 (21.7)	34 (28.3)	0.144
	No	60 (50)	34 (28.3)	26 (21.7)	
Dyslipidemia	Yes	35 (29.2)	22 (18.3)	12 (10.8)	0.071
	No	85 (70.8)	38 (31.7)	47 (39.2)	

SD = standard deviation

Usage and perception of CAM

Half of the participants (n = 60) reported using CAM. Commonly used CAM therapies included cupping (%32.5), green tea (%22.5), and ginger (%16.7). Other forms of CAM, such as acupuncture, yoga, and other herbal remedies, were underutilized. However, % 43.3 of respondents rated CAM as ineffective, % 42.5 rated it as somewhat effective, and % 8.3 rated it as very effective. Furthermore, only % 32.5 endorsed integrating CAM with conventional therapy, suggesting skepticism regarding the effectiveness of combined approaches (Table 2).

Table 2. Usage and Perception of CAM

Variable	Frequency	Percentage
Used CAM	60	50.0
Cupping	39	32.5
Green tea	27	22.5
Ginger	20	16.7
Massage	14	11.7
Fenugreek	10	08.3
Cauterization	04	3.3
Garlic	03	2.5
Omega-3	02	1.7
Yoga	1	0.8
Najila	1	0.8
Acupuncture	1	0.8
Frequency of CAM use		
Never	60	50
Rarely	32	26.7
Monthly	4	3.3
Weekly	8	6.7
Daily	16	13.3
Perception of CAM effectiveness		
Not effective	52	43.3
Neutral	07	5.8
Somewhat effective	51	42.5
Very effective	10	8.3
Perceived integrating conventional and CAM therapies as effective for improving cardiovascular health		
No	81	67.5
Yes	39	32.5
Recommended an integrative approach for others at risk for CVD		
No	63	52.5
Yes	57	47.5

CAM = complementary and alternative medicine; CVD, cardiovascular disease.

3.2 Clinical characteristics of the study population

Clinical characteristics in terms of the CVD risk associated with smoking were relatively uncommon because only 5% identified as smokers. The average BMI was 26.96 ± 4.21, which indicated a slight shift toward an overweight status among those in the overall cohort. The mean PSS score was 17.73 ± 3.07, indicating moderate levels of perceived stress. The recorded physical activity during this study was limited; the mean exercise score was 1.61 ± 0.83 according to a scale ranging from 1 (low activity) to 4 (high activity). The average systolic blood pressure (SBP) was 134.09 mmHg, and the average diastolic blood pressure (DBP) was 81.78 mmHg, indicating moderate, but not optimal, control. The average cholesterol level was 204.33 mg/dL, whereas the average low-density lipoprotein (LDL) level was 112.71 mg/dL and the average high-density lipoprotein (HDL) level was 52.35 mg/dL (Table 3).

3.3 Comparative analysis of conventional medicine users and CAM approach users

The association between CAM use and CVD risk was examined through a comparative analysis of conventional medicine users (non-CAM users) and integrative approach users (CAM users). Independent t tests revealed significant differences between these groups. CAM users reported stress levels (mean, 18.67 ± 2.37) that were higher than those of non-CAM users (mean, 16.68 ± 3.40). The HDL levels of CAM users (mean, 58.32 ± 20.92) were strikingly higher than those of non-CAM users (mean, 46.39 ± 8.87). The SBP of CAM users was slightly higher (mean, 136.12 mmHg) than that of non-CAM users (mean, 132.07 mmHg). The DBP of CAM users was marginally higher (mean, 83.23 mmHg) than that of non-CAM users (mean, 80.33 mmHg) (Table 3). No significant differences in BMI, cholesterol, or LDL were observed. Furthermore, the trend regarding higher HDL levels among CAM users was notable because HDL plays a protective role in cardiovascular health.

Table 3. Descriptive and Inferential Statistics of CVD Risk Factors

Characteristics	Minimum	Maximum	Total sample mean (SD)	Conventional medicine group mean (SD)	CAM group mean (SD)	Effect size Cohen's d	p-value
SBP	100	175	134.09 (13.22)	132.07 (15.25)	136.12 (10.56)	0.31	0.047
DBP	60	100	81.78 (8.72)	80.33 (9.28)	83.23 (7.93)	0.34	0.034
Total cholesterol	128	317	204.33 (33.36)	199.80 (34.62)	208.87 (31.68)	0.27	0.137
LDL	100	205	112.71 (36.28)	116.56 (34.26)	108.86 (38.10)	−0.21	0.247
HDL	20	126	52.35 (17.08)	46.39 (8.87)	58.32 (20.92)	0.74	<0.001
HbA1c	4	12.7	6.45 (1.78)	6.23 (1.72)	6.66 (1.83)	0.24	0.186
BMI	19.74	38.02	26.96 (4.21)	27.10 (4.48)	26.82 (3.97)	−0.07	0.713
10-year CVD risk	.20	21.90	3.58 (3.68)	3.72 (4.31)	3.44 (2.95)	−0.08	0.670
Exercise behaviors	1	4	1.61 (0.83)	1.64 (.72)	1.59 (.93)	−0.06	0.742
Perceived stress	8	26	17.73 (3.07)	16.68 (3.40)	18.67 (2.37)	0.64	<0.001

BMI = body mass index; CVD = cardiovascular disease; DBP = diastolic blood pressure; HbA1c = glycated hemoglobin; HDL = high-density lipoprotein cholesterol; LDL = low-density lipoprotein cholesterol; SBP = systolic blood pressure; SD = standard deviation.

3.4 Analysis of variance results

A univariate analysis of variance was conducted to examine the associations between CAM use and key cardiovascular and psychological metrics. CAM use was significantly associated with HDL levels ($F = 17.84$; $p < 0.001$), even after controlling for confounders such as BMI and smoking. There was also a significant association between CAM use and stress scores ($F = 14.16$; $p < 0.001$), with CAM users reporting higher stress levels. Additionally, CAM use showed a modest but significant association with DBP ($F = 4.66$; $p = 0.033$) (Table 4).

Table 4. ANOVA Results

Dependent variable: Diastolic blood pressure measure
$R^2 = 0.221$ (adjusted $R^2 = 0.187$)

Source	Type III sum of squares	df	Mean square	F	p-value
Corrected model	1996.973	5	399.395	6.459	<0.001
Intercept	5549.662	1	5549.662	89.747	<0.001
Age	115.792	1	115.792	1.873	0.174
Smoking	363.230	1	363.230	5.874	0.017
Total exercise	663.882	1	663.882	10.736	0.001
BMI	573.568	1	573.568	9.276	0.003
CAM	288.524	1	288.524	4.666	0.033
Error	7049.393	114	61.837		
Total	811,668.000	120			
Corrected total	9046.367	119			

Dependent variable: HDL (mg/dL)
$R^2 = 0.212$ (adjusted $R^2 = 0.178$)

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	7366.574[a]	5	1473.315	6.142	<0.001
Intercept	2166.736	1	2166.736	9.032	0.003
Age	146.157	1	146.157	.609	0.437
Smoking	105.459	1	105.459	.440	0.509
Total exercise	2163.557	1	2163.557	9.019	0.003
BMI	420.717	1	420.717	1.754	0.188
CAM	4279.577	1	4279.577	17.840	<0.001
Error	27347.091	114	239.887		
Total	363615.315	120			
Corrected Total	34713.665	119			

Dependent variable: Total PSS score
$R^2 = 0.198$ (Adjusted $R^2 = 0.163$)

Source	Type III sum of squares	df	Mean square	F	Sig.
Corrected model	221.252[a]	5	44.250	5.626	<0.001
Intercept	278.162	1	278.162	35.365	<0.001
Age	17.835	1	17.835	2.267	0.135
Smoking	1.394	1	1.394	.177	0.675
Total exercise	67.677	1	67.677	8.604	0.004
BMI	8.933	1	8.933	1.136	0.289
CAM	111.384	1	111.384	14.161	<0.001
Error	896.673	114	7.866		
Total	38,819.000	120			
Corrected total	1117.925	119			

ANOVA = analysis of variance; BMI = body mass index; CAM = complementary and alternative medicine; df = degrees of freedom; HDL = high-density lipoprotein; PSS = Perceived Stress Scale.

According to the data, CAM use was associated with elevated HDL levels and minimal changes in blood pressure; however, the association between CAM use and overall CVD risk reduction appears limited. Psychosocial stress is a challenge for CAM users, thus highlighting the need for integrated stress management interventions and medical treatment.

4. Discussion

This study provides a distinctive understanding of the patterns of CAM use and their associations with cardiovascular health indicators among middle-aged women in Jazan region, Saudi Arabia. CAM use was associated with elevated HDL levels, although no substantial relationship was observed with overall cardiovascular risk. These findings highlight the need to consider CAM in the context of conventional medical practices when exploring integrative approaches to cardiovascular health.

One of the most interesting findings of this study was the statistically significant elevated HDL levels among CAM users ($p < 0.001$). HDL is recognized for its role in facilitating the removal of cholesterol from the bloodstream and reducing the risk of atherosclerosis. Koo and Noh reported that herbal remedies such as green tea are abundant in polyphenols and flavonoids and can lower LDL and increase HDL levels [23]. The observed associations between CAM use and lipid profiles are particularly notable. Green tea, which was one of the most widely used CAM modalities among the study participants, contains catechins and epigallocatechin gallate, which have been associated with favorable changes in lipid metabolism and reductions in oxidative stress. [14]. Similarly, Alizadeh-Navaei et al. observed an association between ginger use, a popular CAM choice, and more favorable lipid profiles, including lower LDL and triglyceride levels and higher HDL levels [24]. These results align with the observed association between CAM use and higher HDL levels in this study.

The association between CAM use and higher stress levels, as quantified by the PSS, was another striking finding. The stress levels of CAM users were higher than those of non-CAM users ($p < 0.001$). This finding may imply that individuals with increased stress may seek alternative therapies and contemplate them as integrated solutions that enable physical and emotional well-being. Langhorst et al. also observed similar trends and reported that perceived stress was significantly correlated with increased CAM use among patients with chronic diseases [25]. However, it is equally plausible that the stress-relieving benefits of CAM are insufficient. The integration of mindfulness-based stress reduction techniques and cognitive–behavioral therapy with CAM protocols may result in more robust integration of psychological interventions. Gosain et al. found that mindfulness-based stress reduction was associated with reductions in perceived stress among patients with breast cancer, thus implying its potential applicability in the management of CVD-related stress [26].

Higher SBP ($p = 0.047$) and DBP ($p = 0.034$) were observed among CAM users; this unanticipated association may reflect underlying health issues in CAM users, variability in CAM practices, or potential interactions with conventional medications. For instance, cupping therapy, which was a common CAM modality in this study, has been linked with temporary physiological stress responses that could lead to increased blood pressure. Additionally, certain herbal products, such as garlic and ginger, may interact with medications including anticoagulants and antihypertensive drugs, potentially affecting their efficacy or adherence [27]. Dependency on CAM without sufficient compliance with conventional medications, such as nonadherence to prescribed antihypertensive therapy, may also contribute to blood pressure control issues. These findings underscore the importance of monitoring medication adherence and potential drug-herb interactions, as well as standardizing CAM practices to reduce adverse effects and better understand their associations with cardiovascular outcomes [9, 15].

The absence of a notable association between CAM use and the 10-year CVD risk score suggests that CAM alone may have a limited relationship with overall CVD risk. This finding was also reported by Yeh et al., who suggested that CAM modalities, such as yoga and acupuncture, may offer cardiovascular benefits only when integrated with conventional treatments [28]. For example, integrating dietary supplements such as Omega-3 with statins or antihypertensive medications could enhance lipid-lowering effects while maintaining blood pressure control. This was also supported by Rabito and Kaye, who reported that CAM modalities such as acupuncture were associated with favorable changes in endothelial function and reductions in arterial stiffness, thus contributing to better cardiovascular outcomes [29].

This study also revealed significant underutilization of certain CAM modalities such as yoga and acupuncture. Despite their well-established cardiovascular benefits, including improved blood pressure, heart rate variability, and stress reduction, these therapies were minimally adopted by the study population. Yeh et al. reported similar findings, indicating low utilization rates because of cultural barriers, limited awareness, and accessibility hindrances [28]. Public health initiatives that promote culturally adapted CAM practices could address these limitations. Additionally, improving the evidence base through rigorous clinical trials may minimize skepticism about the efficacy of CAM, which was also reflected by the decreased endorsement of integrative approaches by the participants in this study.

These findings also underscore the unique cardiovascular risk profiles of middle-aged women, particularly those experiencing menopause. Hormonal changes during menopause exacerbated by reduced estrogen levels critically increase the risks of dyslipidemia, hypertension, and atherosclerosis. Agrinier et al. emphasized that the cardioprotective effects of estrogen are diminished after menopause, thus highlighting the need for targeted interventions [30]. For example, green tea and ginger, which were popular CAM choices in this study, may reduce lipid abnormalities in relation to menopause. However, these benefits should be investigated within a vast integrative framework of pharmacological and lifestyle modifications.

4.1 Study limitations and future recommendations

The cross-sectional design of this study limits the ability to draw causal inferences between CAM use and cardiovascular risk factors, as only associations at a single point in time can be observed. Consequently, it is not possible to determine whether CAM use influenced cardiovascular health or whether women with certain cardiovascular profiles were more likely to use CAM. The relatively small sample size and the recruitment of participants from a single region may limit the generalizability of the findings to other populations of middle-aged women in Saudi Arabia or globally. Additionally, the reliance on self-reported CAM use introduces the potential for recall bias, where participants may not accurately remember their CAM practices, and social desirability bias, where participants may overreport or underreport use to align with perceived expectations. The use of hospital records as a data source may also introduce limitations, including incomplete or missing data and potential selection bias, as the sample may not fully represent the broader population. Other unmeasured confounding factors, such as dietary patterns, physical activity, or adherence to conventional medications, may also influence observed associations. Future research using longitudinal cohort studies and randomized controlled trials is needed to more rigorously evaluate the temporal relationships and potential effects of CAM on cardiovascular risk, while more comprehensively controlling for confounding factors. Additionally, further studies should investigate specific complementary and alternative medicine (CAM) modalities individually, using larger sample sizes and more rigorous designs to more clearly determine their effectiveness in reducing cardiovascular risk.

5. Conclusions

Although CAM approaches were associated with higher HDL levels, their overall relationship with cardiovascular risk management appears limited. The observed association between CAM use and elevated blood pressure and stress levels underscore the importance of considering how CAM interacts with conventional practices to support both physical and psychosocial well-being. These results also suggest that adherence to conventional medications should be carefully monitored when CAM modalities are used. Overall, the findings highlight that exploring integrative approaches may help healthcare practitioners better understand patterns of CAM use alongside conventional medicine in middle-aged women. Public health efforts could focus on improving awareness and accessibility of underutilized CAM modalities, such as yoga and acupuncture, to support informed use. Further research using longitudinal designs is needed to better assess the relationships between CAM use and cardiovascular risk factors. Additionally, randomized controlled trials comparing integrative approaches with conventional care may help clarify the potential role of CAM modalities in cardiovascular risk management.

5.1 List of abbreviations

BMI, body mass index; CAM, complementary and alternative medicine; CVD, cardiovascular disease; DBP, diastolic blood pressure; HDL, high-density lipoprotein; LDL, low-density lipoprotein; PSS, Perceived Stress Scale; SBP, systolic blood pressure

5.2 Declarations

- **Ethics approval and consent to participate**: The study was approved by the Research Ethical Committee of Jazan Health Cluster Facilities (Approval number: No. 2486, dated November 24, 2024).
- **Consent for publication**: Not applicable
- **Availability of data and materials**: The data that support the findings of this study are available from the corresponding author upon reasonable request.
- **Competing interests**: The authors declare that they have no competing interests" in this section.

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- **Authors' contributions**: RA confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation and approval.

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3) تعبئة النماذج الآتية:

أ - نموذج طلب نشر بحث في المجلة.

ب - نموذج تعهد بأن البحث غير منشور أو مقدم للنشر في مكان آخر.

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2) الآراء الواردة في البحوث المنشورة تعبر عن وجهة نظر أصحابها.

شروط النشر

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1) ألا تزيد صفحاته عن (35) صفحة من القطع العادي (A4).
2) أن يحتوي على عنوان البحث وملخصه باللغتين العربية والإنجليزية في صفحةٍ واحدة، بحيث لا يزيد عن (250) كلمة للملخص، وأن يتضمن البحث كلمات مفتاحيةٍ دالةٍ على التخصص الدقيق للبحثً 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:

المقدمـــة: تكون دالة على موضوع البحث، والهدف منه، ومنسجمة مع ما يَردُ في البحث من معلومات وأفكار وحقائق علمية، كما تشير باختصار إلى مشكلة البحث، وأهمية الدراسات السابقة.

العـرض: 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 تلخيصًا موجزًا 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 متبوعا بفاصلة، فسنة النشر، مثلا: (مجاهد، 1988م). وفي حالة الاقتباس المباشر يضاف رقم الصفحة مباشرة بعد تاريخ النشر مثلا: (خيري، 1985م، ص:33). أما إذا كان للمصدر مؤلفان فيذكران مع اتباع الخطوات السابقة مثلا: (الفالح وعياش، 1424هـ). وفي حالة وجود أكثر من مؤلفين فتذكر أسماء عوائلهم أول مرة، مثلا: (مجاهد والعودات والشيخ، 1408هـ)، وإذا تكرر الاقتباس من المصدر نفسه فيشار إلى اسم عائلة المؤلف الأول فقط، ويكتب بعده وآخرون مثل: (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 البيليوغرافية 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 مرجعًا علميًا 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 بالمناهج 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 مستلٌ.

للمراسلة

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