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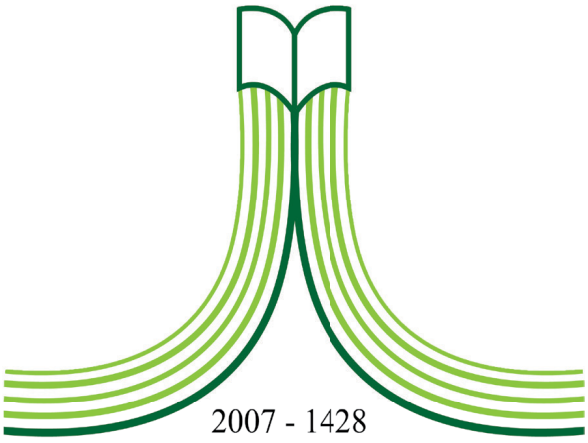
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THE MOST GRACIOUS, THE MOST MERCIFUL



جامعة الحدود الشمالية

NORTHERN BORDER UNIVERSITY

Kingdom of Saudi Arabia

Journal of the North for Basic and Applied Sciences

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Nonlinear Wave solutions of the β-Fractional Burgers–Huxley Equation via Modified Extended Direct Algebraic Method

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Abstract
In this paper, we study nonlinear wave solutions of the β-fractional Burgers-Huxley (FBH) equation in the sense of the Beta derivative. The modified extended direct algebraic method (MEDAM) is utilized to obtain the exact analytical traveling-wave solutions for the nonlinear fractional model. By adopting a suitable traveling-wave transformation, the fractional PDE is transformed into an ODE and explicit analytical solutions can be obtained. For different values of the parameters, a number of solution families, namely hyperbolic, trigonometric and rational type solutions, are generated and plotted. It is found from the analysis that the changes of the fractional order have significant effect on the amplitude and the wave localization. The results demonstrate the effectiveness and generality of the MEDAM method to deal with nonlinear fractional PDEs and disclose more interesting wave phenomena in nonlinear systems.

Keywords: Keywords: Fractional Burgers-Huxley equation; traveling wave transformation; Beta fractional derivative; modified extended direct algebraic method.

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1. Introduction:

Nonlinear partial differential equations (NlPDEs) are the central instruments for the description of complicated nonlinear processes observed in science and technology. Nonlinear physical processes such as diffusion transport, reaction kinetics, solid-state reactions, plasma physics, fluid mechanics, waves, and capillary–gravity wave motion can be effectively modelled using NPDE equations. These formulas are commonly applied to fields like engineering, financial modeling, fluid dynamics and physical chemistry, where nonlinear relationships define the behavior of the system in question. These couplets sometimes result in a menagerie of time-dependent phenomena such as soliton propagation, wave modulation and stability, pattern formation and space–time structures in a number of physical contexts [1–9]. Hence, in order to describe and analyze the fundamental nonlinear dynamics, it is necessary for analytical solutions of partial differential equations to be obtained. Several scientists have been introduced different analytic and numerical methods for finding the exact solution of NLPDEs and nonlinear fractional partial differential equations (NLFPDEs).The Kudryashov method [10], Lie group method [11], generalized Riccati equation mapping [12], Riccati–Bernoulli sub-ode method [13], Improved modified extended tanh function method [14], Extended hyperbolic function method [15], Extended *(G'/G)*-expansion method [16], and He's homotopy perturbation method [17]. Recently, the study of solution for the fractional PDEs (FPDEs) has been developed rapidly by using different approached including Beta fractional derivative, conformable fractional derivatives, Truncated M-Fractional Derivative Caputo fractional derivatives, etc. ([18]-[25]).

The Burgers-Huxley (BH) equation is one of the key nonlinear reaction-convection–diffusion equation which is obtained by merging the classical Burgers convection-diffusion model that has been originally proposed by Bateman [26], later on studied by Burgers [27], with the nonlinear reaction described by the Hodgkin-Huxley model [28]. The BH expresses the balance between diffusion and convection mechanisms of fluid flow and the reaction–diffusion features of the Huxley equation which describes the dynamics of nerve impulse propagation in neurophysics and the flame front propagation in patterned liquids which thus ends up as a crucial equation in nonlinear wave propagation in biological, chemical, physical, financial, population dynamical systems [29]. The Generalized BH is defined by [29]:

$$p_t - \nu p_{xx} + \varrho p p_x = \kappa \mathrm{p}(\mu - \mathrm{p}^{\eta})(\mathrm{p}^{\eta} - 1), \quad (1)$$

where *p(x,t)* is a scalar field that is a function of the spatial variable *x* and the temporal variable *t*, and $\boldsymbol{\nu}$,ϱ,κ,μ and η are constants. The term $\varrho \mathrm{p}\mathrm{p}_x$ characterizes the nonlinear convection effect, $\boldsymbol{\nu}\mathrm{p}_{xx}$ represents the diffusion mechanism, and κp(μ-p$^{\eta}$)(p$^{\eta}$-1) relates to the reaction kinetics. For the parameter values $\eta = \kappa = \boldsymbol{\nu} = \boldsymbol{1}$, $\varrho = \boldsymbol{-1}$, Eq. (1) is reduced to the famous BH equation [31].

$$p_t - p_{xx} - pp_x - \mathrm{p}(\mu - \mathrm{p})(\mathrm{p} - 1) = 0. \quad (2)$$

The fractional Burgers–Huxley equation (FBH) equation, which is defined as:

$${}_0^A D_t^{\beta} p - {}_0^A D_{xx}^{\beta} \mathrm{p} - p\, {}_0^A D_x^{\beta} p - \mathrm{p}(\mu - \mathrm{p})(\mathrm{p} - 1) = 0, \quad (3)$$

where ${}_0^A D_t^{\beta}$ and ${}_0^A D_x^{\beta}$ represent the BFD of order $\beta \in (0, 1]$ with respect to time *t* and space *x* respectively, and ${}_0^A D_{xx}^{\beta}$ is second BFD with respect to space *x*.

In this work, we concentrate on two-dimensional line-shaped wave solutions of Eq. (3) using BFD. The BFD, pioneered by [18], are a path-breaking development in the realm of fractional calculus. These operators have very interesting properties and it turns out that they have far reaching consequences in many fields such as Economics, engineering, financial mathematics, physics. The usefulness of BFD in soliton theory is that it well describes the soliton waves and it leads to deep physical understanding. The modified extended direct algebraic method (MEDAM) is applied to obtain traveling wave solutions of Eq. (3).

The MEDAM approach is efficacious in constructing traveling wave solutions for NPDEs. This paper deals with application of the MEDAM for finding exact solutions of FBH equation and illustrating the role of the solutions in nonlinear system dynamics. The novelty of study is to investigates further development of the existing research into fractional dimensions which gained popularity particularly through the FBH equation supported by references [18-19]. The paper is organized as follows: In Section 2, we briefly discuss BFD and their properties. Section 3 gives a detailed description of the MEDAM. Section 4 discusses the implementation of the technique. In Section 5, we provide plots which illustrate some physical features of the obtained solutions. Finally, Section 6 concludes the paper.

2. Definition of BFD and properties:

In this section, we present the definition of Beta Fractional Derivative (BFD) and its properties.

Definition. The BFD is defined as [18]

Let *p(x)* be a real-valued function defined on the interval $[\tau, \infty)$, the Beta fractional derivative of the function *p(x)* is defined as follows:

$$ {}_0^A D_x^\beta p(t) = \lim_{\varepsilon \to 0} \frac{p\left(x+\epsilon\left(x+\frac{1}{\Gamma(\beta)}\right)^{1-\beta}\right)-p(x)}{\epsilon}, \; x > \tau, \beta \in (0,1]. $$

Theorem 3. If $0<\beta\leq 1, a, b \in \mathbb{R}$, p and q are functions β-differentiable and $\beta \in (0,1]$, the BFD satisfies the follows properties:

- $ {}_0^A D_x^\beta (a\, p + bq) = a\, {}_0^A D_x^\beta (p) + \mathrm{b}\ {}_0^A D_x^\beta (q).$
- $ {}_0^A D_x^\beta (a) = 0.$
- $ {}_0^A D_x^\beta (p\, q) = q\, {}_0^A D_x^\beta (p) + p\, {}_0^A D_x^\beta (q).$
- $ {}_0^A D_x^\beta \left(\frac{p}{q}\right) = \frac{q\, {}_0^A D_x^\beta (p) - p\, {}_0^A D_x^\beta (q)}{q^2}.$
- $ {}_0^A D_x^\beta (p\,(q(x)) = \left(x+\frac{1}{\Gamma(\beta)}\right)^{1-\beta} q'(x) p'(q(x)).$

The proofs of these properties are given in [18]. The BFD is a novel fractional operator that preserves some properties of classical calculus while simultaneously incorporating memory and nonlocal effects typical of fractional calculus. Owing to these properties, it is widely applied in the nonlinear modeling of physical and engineering systems. Compared with other fractional derivatives, the BFD preserves many properties of classical calculus while providing greater flexibility and accuracy in modeling memory and nonlocal behaviors in complex physical systems [18–21, 25].

3. Description of the MEDAM:

In this section, we propose the MEDAM [32-34]. This method provides a neat and elegant procedure for exact traveling-wave solutions of FBH equation. The basic concept of the method is to transform the governing nonlinear fractional partial differential equation (NFPDEs) into an ordinary differential equation (ODE) by using a suitable wave transform. Next, an algebraic ansatz is used to find explicit closed-form solutions. The main stages of the MEDAM method are briefly summarized below.

Step 1: Suppose that the FBH equation in the spatial variable and the temporal variable t is given by:

$$ Q\left(\mathrm{p}, {}_0^A D_t^\beta \mathrm{p}, {}_0^A D_x^\beta \mathrm{p}, {}_0^A D_{tx}^{2\beta} \mathrm{p}, {}_0^A D_{xx}^\beta \mathrm{p}, {}_0^A D_{xxx}^\beta \mathrm{p}, \ldots\right) = 0, \tag{4} $$

where $p(x,t)$ is the unknown function, and Q is a polynomial differential operator in terms of $p(x,t)$ and its corresponding fractional derivatives.

Step 2: To convert Eq. (4) into an ordinary differential equation, a suitable traveling-wave transformation is employed.

$$ p(x,t) = P(\Omega), \; \Omega = \frac{1}{\beta}\left(x+\frac{1}{\Gamma(\beta)}\right)^\beta \pm \frac{\sigma}{\beta}\left(t+\frac{1}{\Gamma(\beta)}\right)^\beta, \tag{5} $$

where σ a positive parameter to be determined. This transformation transforms the FBH equation into an ordinary differential equation (ODE):

$$ M(\mathrm{P}, \mathrm{P}', \mathrm{P}'', \mathrm{P}''', \cdots) = 0, \tag{6} $$

where M is a polynomial in P(Ω), and prime (') denotes derivative with respect to Ω.

Step 3: Let us assume that Eq. (6) has a solution in the form of

$$ P(\Omega) = a_0 + \sum_{i=1}^N a_i \Psi^i(\Omega) + \sum_{i=1}^N b_i \Psi^{-i}(\Omega), \tag{7} $$

where N is a positive integer that obtained by balancing the term involving the highest-order derivative with the nonlinear term of highest power in the reduced equation (6), the coefficients a_i ($i=0,1,2, \ldots, N$) and b_i ($i=1,2, \ldots, N$) are constants, and Ψ(Ω) is solution of the equation

$$ \Psi'(\Omega) = \Upsilon + \Psi^2. \tag{8} $$

with Υ is constant.

Step 4: Eqs. (7) and (8) are inserted into Eq. (6) after the N is determined. Then the coefficients of the same powers of Ψ(Ω) are collected and set equal to zero. This process leads to an algebraic system of equations for the unknown coefficients a_0, a_i, b_i and σ that can be solved by means of symbolic computation software such as Maple. The solution sets of Eq. (8) can be divided into three cases according to the sign of Υ .

Family 1: Hyperbolic-type Solutions (Υ<0),

$$ \Psi(\Omega) = -\sqrt{-\Upsilon}\, tanh\left(\sqrt{-\Upsilon}\Omega\right) \text{ or } \Psi(\Omega) = -\sqrt{-\Upsilon}\, coth\left(\sqrt{-\Upsilon}\,\Omega\right). \tag{9} $$

Family 2: Trigonometric-type Solutions (Υ>0),

$$ \Psi(\Omega) = \sqrt{\Upsilon}\, tan\left(\sqrt{\Upsilon}\Omega\right) \text{ or } \Psi(\Omega) = -\sqrt{\Upsilon}\, cot\left(\sqrt{\Upsilon}\,\Omega\right). \tag{10} $$

Family 3: Rational-type Solutions (Υ=0),

$$ \Psi(\Omega) = -\frac{1}{\Omega}. \tag{11} $$

4. Application of the method:

In this part, the MEDAM is applied to acquire the traveling wave solutions for Eq. (3)

$$ {}_0^A D_t^\beta p - {}_0^A D_x^{2\beta} \mathrm{p} - p\, {}_0^A D_x^\beta p - \mathrm{p}(\mu - \mathrm{p})(\mathrm{p} - 1) = 0. $$

Apply the following traveling wave transformation

$$ p(x,t) = P(\Omega),\ \Omega = \frac{1}{\beta}\left(x + \frac{1}{\Gamma(\beta)}\right)^\beta - \frac{\sigma}{\beta}\left(t + \frac{1}{\Gamma(\beta)}\right)^\beta. $$

. (12)

By applying the BFD and the traveling wave transformation, we get the following equations: ${}_0^A D_t^\beta p = -\sigma P'$, ${}_0^A D_x^\beta p = P'$, ${}_0^A D_x^{2\beta} p = P''$. By inserting Eq. (12) into Eq. (3), then Eq. (3) convert to the following ODE.

$$ \sigma P' + P'' + PP' + P(\mu - P)(P - 1) = 0. \quad (13) $$

By balancing the nonlinear power term P^3 with the highest order derivative P'', we get N=1. Thus, Eq. (7) is simplified as follows:

$$ P(\Omega) = a_0 + a_1 \Psi(\Omega) + \frac{b_1}{\Psi(\Omega)}. \quad (14) $$

By plugging in Equation (14) into Equation (13) and grouping terms by powers of Ψ, a system of algebraic equations is found by setting the coefficient of each power of Ψ to zero. The resulting algebraic equations are solved by using the computer algebra system Maple, and the following sets of solutions are obtained.

set 1:

$$ a_0 = \frac{1}{2},\ a_1 = -1, b_1 = 0,\ \sigma = \mu - 1, \Upsilon = -\frac{1}{4}. $$

(15)

set 2:

$$ a_0 = \frac{\mu}{2} + \frac{1}{2},\ a_1 = 2, b_1 = 0,\ \sigma = \frac{\mu}{2} + \frac{1}{2} $$
$$ \Upsilon = -\frac{\mu^2}{16} + \frac{1}{8}\mu - \frac{1}{16} = -\frac{(\mu-1)^2}{16}, (\mu - 1 \neq 0). $$

(16)

set 3:

$$ a_0 = \frac{\mu}{2} + \frac{1}{2},\ a_1 = -1, b_1 = 0,\ \sigma = -\mu - 1, $$
$$ \Upsilon = -\frac{\mu^2}{4} + \frac{1}{2}\mu - \frac{1}{4} = -\frac{(\mu-1)^2}{4}, (\mu - 1 \neq 0). $$

(17)

set 4:

$$ a_0 = \frac{\mu}{2},\ a_1 = 2, b_1 = 0,\ \sigma = \frac{\mu}{2} - 2, \Upsilon = -\frac{\mu^2}{16}. $$

(18)

set 5:

$$ a_0 = \frac{1}{2},\ a_1 = 2, b_1 = 0,\ \sigma = \frac{1}{2} - 2\mu, \Upsilon = -\frac{1}{16}. $$

(19)

set 6:

$$ a_0 = \frac{\mu}{2},\ a_1 = -1, b_1 = 0,\ \sigma = -\mu + 1, \Upsilon = -\frac{\mu^2}{4}. $$

(20)

The wave Solutions expressions for *P(x,t)* are given below set by set

Set 1: For the solution families presented below, the variable Ω is defined as

$$ \Omega = \frac{1}{\beta}\left(x + \frac{1}{\Gamma(\beta)}\right)^\beta + \frac{\mu-1}{\beta}\left(t + \frac{1}{\Gamma(\beta)}\right)^\beta, \text{ and } \Upsilon = -\frac{1}{4} $$

Family 1: Hyperbolic-type Solutions Υ<0,

$$ P_1(\Omega) = \frac{1}{2} + \sqrt{-\Upsilon}\, tanh\left(\sqrt{-\Upsilon}\Omega\right) \text{ or } P_2(\Omega) = \frac{1}{2} + \sqrt{-\Upsilon}\, coth\left(\sqrt{-\Upsilon}\Omega\right). $$

Family 2: Trigonometric-type Solutions Υ >0,

$$ P_3(\Omega) = \frac{1}{2} + \sqrt{-\Upsilon}\, tan\left(\sqrt{-\Upsilon}\Omega\right) \text{ or } P_4(\Omega) = \frac{1}{2} + \sqrt{-\Upsilon}\, cot\left(\sqrt{-\Upsilon}\Omega\right). $$

Family 3: Rational-type Solutions Υ = 0,

$$ P_5(\Omega) = \frac{1}{2} - \frac{1}{\Omega}. $$

Set 2: The solution families presented below are expressed in terms of the traveling-wave variable Ω defined by

$$ \Omega = \frac{1}{\beta}\left(x + \frac{1}{\Gamma(\beta)}\right)^\beta - \frac{\left(\frac{\mu}{2}+\frac{1}{2}\right)}{\beta}\left(t + \frac{1}{\Gamma(\beta)}\right)^\beta \text{ with } \Upsilon = -\frac{(\mu-1)^2}{16} $$

Family 1: Hyperbolic-type Solutions Υ<0

$$ P_6(\Omega) = \frac{\mu}{2} + \frac{1}{2} - 2\sqrt{-\Upsilon}\, tanh\left(\sqrt{-\Upsilon}\Omega\right) \text{ or } P_7(\Omega) = \frac{\mu}{2} + \frac{1}{2} - 2\sqrt{-\Upsilon}\, coth\left(\sqrt{-\Upsilon}\,\Omega\right). $$

Family 2: Trigonometric-type Solutions Υ >0,

$$ P_8(\Omega) = \frac{\mu}{2} + \frac{1}{2} + 2\sqrt{\Upsilon}\, tan\left(\sqrt{\Upsilon}\Omega\right) \text{ or } P_9(\Omega) = \frac{\mu}{2} + \frac{1}{2} - 2\sqrt{\Upsilon}\, coth\left(\sqrt{\Upsilon}\,\Omega\right). $$

Family 3: Rational-type Solutions ϒ=0,

$$P_{10}(\Omega) = \frac{\mu}{2} + \frac{1}{2} + \frac{2}{\Omega}.$$

Set 3: For all solution families listed below

$$\Omega = \frac{1}{\beta}\left(x + \frac{1}{\Gamma(\beta)}\right)^{\beta} + \frac{(\mu+1)}{\beta}\left(t + \frac{1}{\Gamma(\beta)}\right)^{\beta}$$

and $\Upsilon = -\frac{(\mu-1)^2}{4}$. The obtained solutions are written in terms of the variable Ω and the parameter ϒ.

Family 1: Hyperbolic-type Solutions ϒ<0,

$$P_{11}(\Omega) = \frac{\mu}{2} + \frac{1}{2} + \sqrt{-\Upsilon}\, tanh\left(\sqrt{-\Upsilon}\Omega\right).$$

$$\text{Or } P_{12} = \frac{\mu}{2} + \frac{1}{2} + \sqrt{-\Upsilon}\, coth\left(\sqrt{-\Upsilon}\,\Omega\right).$$

Family 2: Trigonometric-type Solutions ϒ>0,

$$P_{13}(\Omega) = \frac{\mu}{2} + \frac{1}{2} - \sqrt{\Upsilon}\, tan\left(\sqrt{\Upsilon}\Omega\right).$$

$$\text{Or } P_{14}(\Omega) = \frac{\mu}{2} + \frac{1}{2} + \sqrt{\Upsilon}\, cot\left(\sqrt{\Upsilon}\,\Omega\right).$$

$$P_{15}(\Omega) = \frac{\mu}{2} + \frac{1}{2} - \frac{1}{\Omega}.$$

Utilizing the approach used for the preceding sets, we can similarly find wave solutions for sets (4-6). The computational details are omitted for brevity and to avoid repetition.

5. Graphical representations of the solutions:

Graphical visualizations of the obtained wave solutions are generated for solutions $P_1(x,t), P_8(x,t)$ and $P_{15}(x,t)$ using Maple software to demonstrate their dynamic behaviors and structural characteristics. The profiles of the waves show that the propagation mode and the amplitude can be modulated by the free parameters of the solutions, and thus the corresponding surfaces in the graphical spaces are significantly changed. To study the effect of the fractional order, we set

$$\mu = 2, \text{ with } x \in [0,10] \text{ and } t \in [0,10].$$

Figure 1: Panels (a)-(c) depict 3D surface plots and panel (d) shows the corresponding 2D profile of the wave solution for , and , respectively. The 3D plots reveal that when the fractional order β decays from 1 to 0.90, the amplitude of traveling wave 3D diminishes, the profile becomes more unlocalized, and the effective wave speed becomes slower. The 2D graph also demonstrates that smaller values of β lead to the close spacing among the curves indicates that the influence of β is moderate. The smooth and bounded nature of the curves confirms the stability of the solution over the considered time interval.

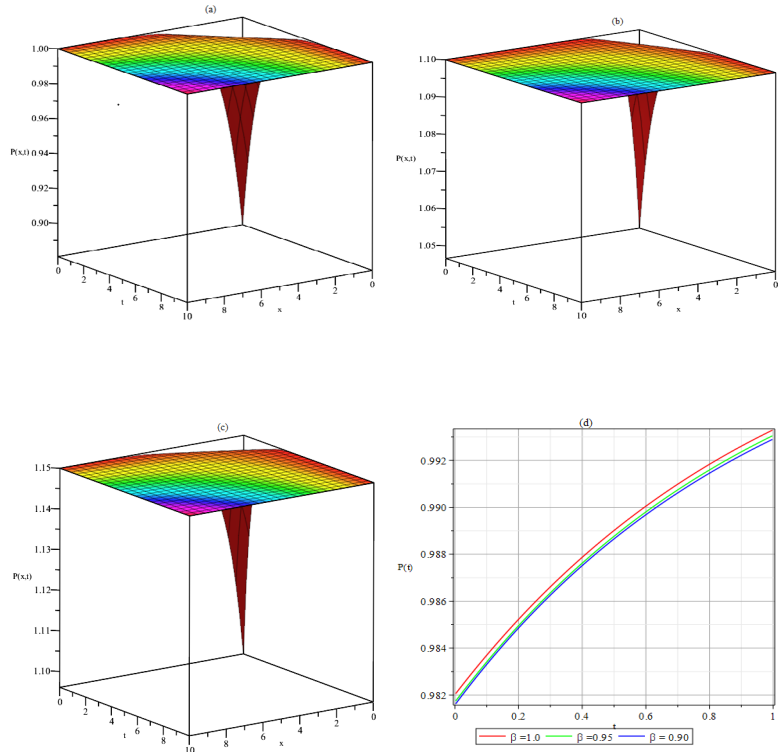


Figure 1: ***3D plots (a)–(c) of the solution*** P1 (x,t) ***for μ=2, and β=1,0.95,0.90, respectively, followed by the corresponding 2D plot at x=2.***

Figure 2: panels (a)–(c) depict 3D surface plots and panel (d) shows the corresponding 2D profile of the wave solution $P_8\ (x,t)$ for β =1,0.95, and 0.90 respectively. In the 3D plots, the solution exhibits an increase in the peak amplitude and the formation of steep fronts as the fractional order decreases from β =1 to β =0.90 and ϒ=1, the wave velocity is observed to vary with β\betaβ, consistent with the β -dependent traveling-wave coordinate. In panel (d), the amplitude decays with time. Moreover, as β decreases from 1 to 0.90, the 2D waveform becomes more localized and steeper.

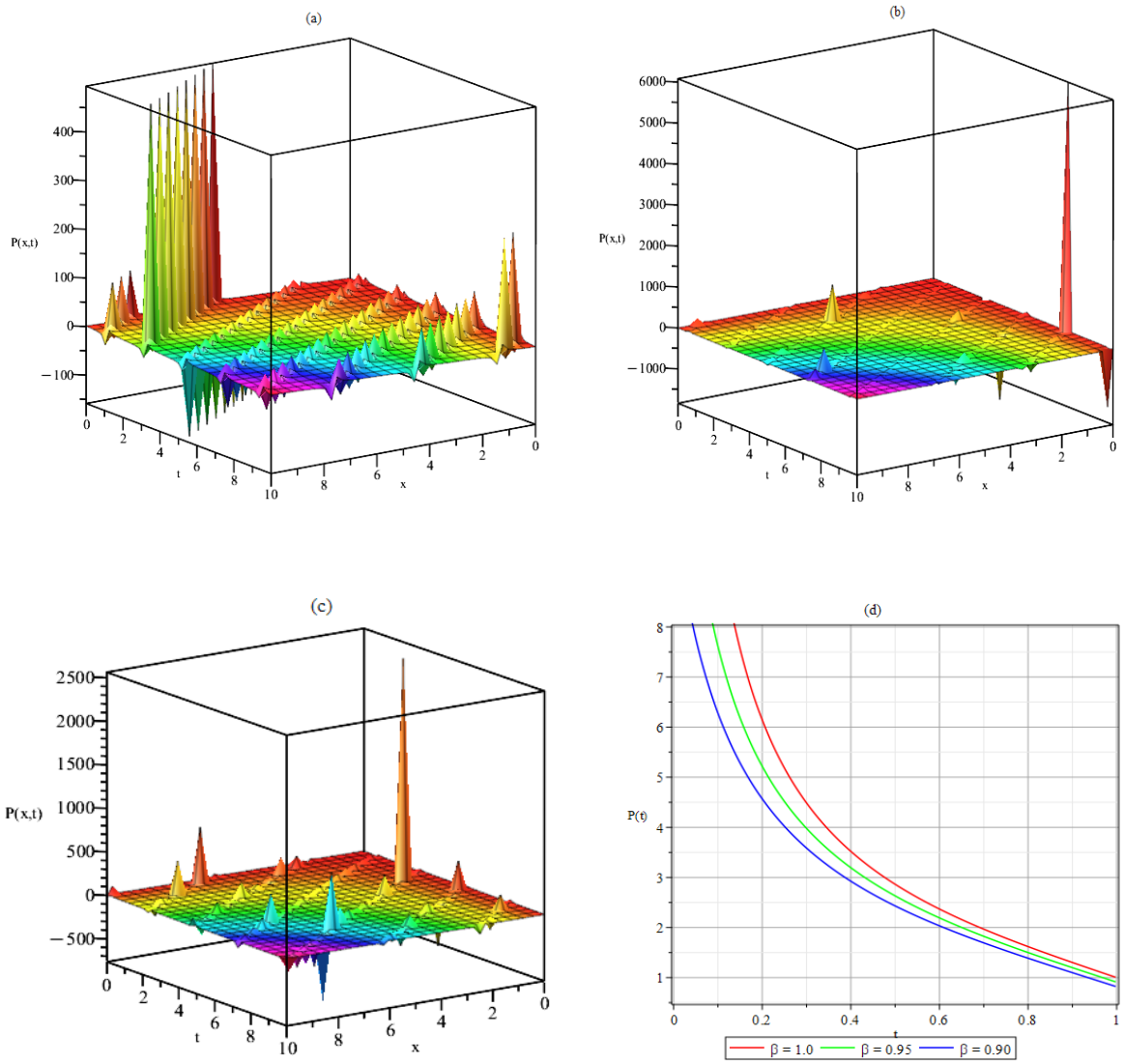


Figure 2: 3D plots (a)–(c) of the solution $P_8\ (x, t)$ for β =1,0.95,0.90, respectively, followed by the corresponding 2D plot at x=2.

Figure 3: Shows the solution $P_{15}\ (x,t)$. Panels (a)- (c) show 3D plots of the wave solution for fractional order β=1, 0.95 and 0.90, respectively, and the corresponding 2D profiles are displayed in (d). In panels (a)-(c), the amplitude is gradually decreased and the wave surface gets smoother with vanished spatial oscillations when the fractional order drops from β =1 to β=0.90. This demonstrates that the memory effect enhancement inhibits the wave propagation and the nonlinear fractional medium becomes more dissipative. The 2D profiles further verify that smaller fractional-order values result in a more rapid decline of the wave amplitude with time.

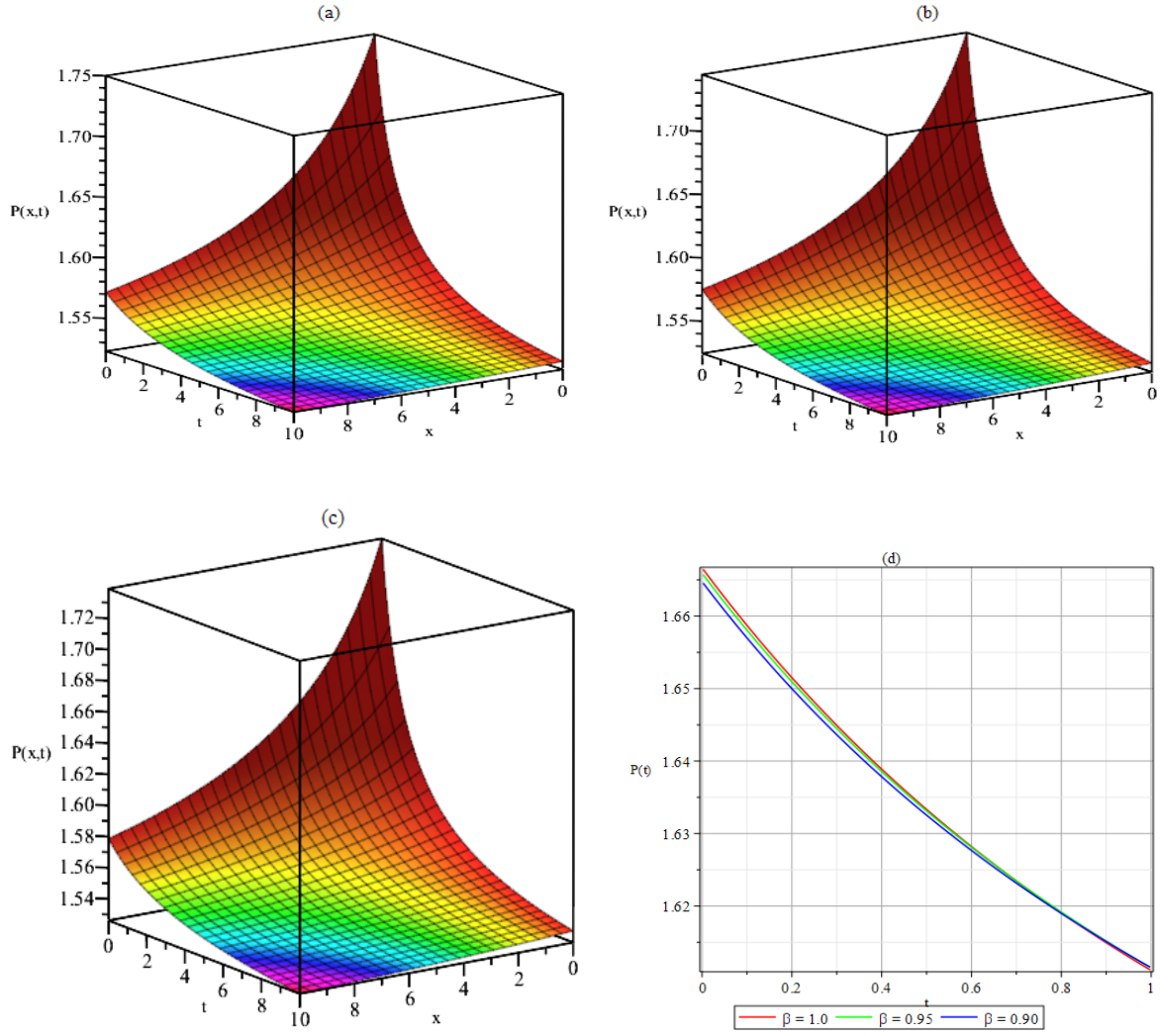


Figure 3: ***3D plots (a)–(c) of the solution P_{15} (x,t) for μ=2 and β=1,0.95,0.90, respectively, followed by the corresponding 2D plot at x=2.***

6. Discussion and conclusion

In this study, exact traveling-wave solutions of the FBH equation were derived using the MEDAM within the BFD framework. Hyperbolic, trigonometric, and rational solution families were obtained, revealing rich nonlinear wave dynamics. The graphical analysis demonstrated that the fractional-order parameter significantly affects the wave amplitude, localization, dissipation, and propagation behavior, where lower fractional-order values produce stronger memory effects and smoother localized wave profiles.

The obtained results are consistent with previous studies on nonlinear fractional differential equations and wave propagation models [10, 14, 15, 32–36]. Similar influences of the fractional-order parameter on wave attenuation and propagation behavior have been reported in earlier investigations of fractional Burgers-type and nonlinear evolution equations. In particular, Bilal et al. [32], Ghayad et al. [33], and Hubert et al. [34] confirmed the effectiveness of the MEDAM in constructing explicit analytical wave and soliton solutions without relying on perturbation or iterative procedures. Compared with other analytical approaches, such as the Kudryashov method, the Riccati–Bernoulli sub-ODE method, the modified extended tanh-function method, the extended expansion method, and the homotopy perturbation method [10, 13, 14, 16, 17], the MEDAM provides a more direct, systematic, and efficient framework for obtaining exact traveling-wave solutions. Furthermore, the incorporation of the BFD improves the modeling of memory and nonlocal effects in nonlinear media.

From a physical viewpoint, the obtained solutions provide valuable insight into nonlinear transport and reaction-diffusion phenomena governed by convection,

diffusion, and reaction mechanisms. Therefore, the FBH model may contribute to a better understanding of nonlinear processes arising in fluid dynamics, plasma physics, biological wave propagation, and chemical reaction systems. Moreover, the Beta fractional derivative offers greater flexibility in modeling memory and hereditary effects that are difficult to capture using classical integer-order differential models.

One of the major strengths of the present work is the use of the BFD, which preserves important properties of classical calculus while simultaneously incorporating fractional memory and nonlocal behaviors. In addition, the MEDAM proved to be an efficient and reliable technique for deriving multiple exact traveling-wave solutions and for analyzing the influence of the fractional-order parameter on nonlinear wave dynamics. Moreover, the theoretical questions concerning the existence, uniqueness, stability, and well-posedness of the solutions of the FBH equation remain open and require further mathematical investigation. Although the present MEDAM results provide explicit closed-form wave structures that compare favorably with other analytical and numerical approaches available in the literature, a rigorous well-posedness and stability analysis would further strengthen the mathematical validity and physical reliability of the obtained solutions [18, 25, 35, 36].

Future research may extend the present analysis to higher-dimensional, variable-coefficient, and stochastic FBH models, together with numerical simulations and stability investigations of the derived solutions. Comparative studies involving other analytical and computational techniques may also provide additional insight into the applicability and robustness of the MEDAM. Overall, the present results confirm that the MEDAM is an effective and reliable method for constructing exact solutions of nonlinear fractional differential equations, while emphasizing the important role of fractional-order effects in modeling nonlinear systems with memory and nonlocal characteristics.

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Nurses' Knowledge, Practices, and Educational Roles in Pediatric Type 1 Diabetes Management: A Cross-Sectional Study in Atbara, Sudan

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Abstract
Background: Type 1 Diabetes Mellitus (T1DM) is a chronic endocrine disorder requiring continuous care, education, and psychosocial support, especially in children. Nurses play an essential role in pediatric diabetes management.

Objective: To assess nurses' knowledge, practices, and educational/supportive roles in managing children with T1DM at Atbara Teaching Hospital, Sudan.

Methods: A descriptive cross-sectional study was conducted among 92 pediatric nurses at Atbara Teaching Hospital between January and March 2025. Data were collected using a structured self-administered questionnaire and analyzed using SPSS version 20.

Results: Almost 54.3% of nurses demonstrated good knowledge regarding T1DM, while 63.0% showed adequate clinical practices. No statistically significant associations were found between knowledge and years of experience ($p = 0.068$) or between practice and educational qualification ($p = 0.057$). Gaps were identified in structured education, documentation, and psychosocial support.

Conclusion: Although most nurses demonstrated adequate knowledge and practice, important gaps remain in pediatric diabetes education and psychosocial support. Continuous training and standardized care protocols are recommended to improve pediatric T1DM care.

Keywords: Type 1 Diabetes Mellitus; Pediatric Nursing; Diabetes Care; Nursing Practice.

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1. Introduction

One of the prevalent chronic endocrine diseases among children in the world is Type 1 Diabetes Mellitus (T1DM) (Syed, 2022). It is defined as autoimmune pancreatic beta cells destruction that results in the total lack of insulin and the inability to survive without exogenous insulin (Libman et al., 2022). The disease tends to appear in those childhood or adolescence stage and requires life-long medical management, careful maintenance of glycemic level, and thorough education, so as to avoid acute and chronic complications (Phelan et al., 2022). T1DM in children is a growing health issue in the world, and it represents a major threat to health among children, especially in low- and middle-income nations, where the availability of healthcare services can be constrained (dos Santos, 2025).

Type 1 Diabetes Mellitus is a disease that predisposes children to acute complications, including diabetic ketoacidosis and hypoglycemia, and to chronic complications of the disease, including complications involving the eyes, kidneys, nerves, and the cardiovascular system(Foti Randazzese et al., 2025; Rivetti et al., 2023). The management of T1DM in children requires not only the administration of insulin but also regular blood glucose levels, nutritional, physical exercise control, psychosocial, and lifelong education of the child and their guardians (Małachowska et al., 2023).

In the case of Atbara Teaching Hospital, nurses lead the frontline when attending to children with T1DM, especially in hospitals. They will be involved in clinical management, educating patients and families, emotional support, coordination of care and complications monitoring(Khatri et al., 2023). Children and their families can also face pediatric nurses as the first point of contact, which is why they can play a crucial role in encouraging compliance with treatment plans and developing self-management skills in accordance with the developmental stage of a child (Sińska et al., 2023). Nurses continue to interact with children and their caregivers to educate them about the disease process, insulin therapy, methods of blood glucose monitoring and how hypo- and hyperglycemia can be recognized and managed(McCall et al., 2023).

In resource-constrained environments, including most areas in Sudan, the role of nurses is even more important because of the problem of unspecialized medical professionals and the lack of access to modern technologies in diabetes care (Clapin et al., 2022). Nurses play a key role in filling care gaps at Atbara Teaching Hospital through constant monitoring, individualized education, and culturally relevant counseling. They are also very instrumental in avoiding hospital readmissions as they make sure that the caregivers are well equipped to deal with the conditions of the child at home.

Diabetes management is based on education(Davis et al., 2022). They educate the insulin administration methods, such as dosage calculation, injection site, and insulin storage(Ibrahim Eldesouky Mohamed et al., 2024). Besides, nurses educate the families about meal planning, counting carbohydrates, and the role of physical activity(Abdelrahman et al., 2025). In the case of school-aged children and adolescents, nurses assist in the progressive development of self-care skills that will enable them to volunteer in the management of the condition, keeping them safe and under supervision (Sińska et al., 2023).

Another critical component of nursing interventions with children with T1DM is the psychosocial support(Małachowska et al., 2023). Children and their families may also be scared, anxious, and emotionally distressed when they are diagnosed with a chronic illness(Hilliard et al., 2016). Nurses offer reassurance, counseling, and emotional support and assist families to manage the disease that is lifelong(Afenigus & Sinshaw, 2025). They also determine psychosocial factors, which could influence treatment adherence, including family dynamics, socioeconomic status, and access to healthcare resources.

Despite the increasing burden of Type 1 Diabetes Mellitus (T1DM) among pediatric populations, there is limited evidence in Sudan assessing nurses' knowledge, clinical practices, and educational and supportive roles in the management of children with T1DM (Bhagat et al., 2020). In particular, few studies have explored nurses' levels of knowledge and practice in this context, as well as their associations with socio-demographic characteristics such as years of experience and educational qualification. This gap is more pronounced in sub-Saharan Africa, where nurses' knowledge of diabetes care has been reported to be suboptimal (Beran et al., 2005; Lumu et al., 2024). This gap hinders the development of evidence-based strategies to strengthen pediatric diabetes nursing care in resource-limited settings.

Therefore, this study aims to assess nurses' knowledge, practices, and educational and supportive roles in the management of children with Type 1 Diabetes Mellitus at Atbara Teaching Hospital, Sudan, and to examine their association with socio-demographic characteristics.

2. Methodology

2.1 Study Design and Setting

A descriptive cross-sectional study design was conducted to assess nurses' knowledge, practices, and educational/supportive roles in the management of children with Type 1 Diabetes Mellitus (T1DM) at Atbara Teaching Hospital, River Nile State, Sudan. The study was carried out between January and March 2025. The

hospital is a major referral center providing inpatient and outpatient pediatric services, including care for children with T1DM.

2.2 Study Population

The study population included all nurses working in pediatric wards and pediatric outpatient clinics at Atbara Teaching Hospital who were involved in the care of children with T1DM.

2.3 Sample Size and Sampling technique

A census (total population sampling) approach was adopted to include all eligible pediatric nurses working at Atbara Teaching Hospital (N = 120). Therefore, no sample size calculation formula was required. All eligible nurses were invited to participate during the data collection period.

Out of the total eligible nurses, 92 completed the questionnaire, resulting in a response rate of 76.7%. Non-participation (n = 28) was due to absence during the data collection period (leave or shift unavailability) and voluntary refusal.

1. Inclusion Criteria

- Nurses working in pediatric wards or outpatient pediatric clinics
- Nurses involved in the care of children with T1DM
- Nurses who agreed to participate in the study

2. Exclusion Criteria

- Nurses not working in pediatric units
- Nurses on leave during the data collection period

2.4 Data Collection Tool

The questionnaire was developed based on an extensive review of literature and internationally recognized guidelines, including the American Diabetes Association (Committee, 2025) and the International Society for Pediatric and Adolescent Diabetes standards (Libman et al., 2022).

The tool consisted of 43 items distributed across four domains:

1. Knowledge domain (15 items): included questions on insulin administration, recognition of hypoglycemia and diabetic ketoacidosis, and long-term complications of Type 1 Diabetes Mellitus (e.g., "signs of hypoglycemia" and "principles of insulin dose adjustment").

2. Practice domain (18 items): assessed routine nursing care such as blood glucose monitoring, insulin administration techniques, documentation practices, and patient education at discharge.

3. Education and psychosocial support domain (10 items): included items on family counseling, dietary education (carbohydrate counting), emotional support, and diabetes self-management education for caregivers.

The scoring system was based on predefined cut-off points adopted from previously published studies using similar instruments, where knowledge and practice scores were categorized into standard levels for analysis.

All items were adapted and aligned with evidence-based recommendations from ADA 2025 and ISPAD 2022, ensuring content validity and clinical relevance(Committee, 2025; Libman et al., 2022). These scoring approaches are consistent with methods commonly used in validated nursing assessment studies.

The scoring system was adapted from previously published studies using similar instruments in nursing research. Knowledge and practice levels were categorized based on Bloom's taxonomy cut-off points, where a score ≥75% was considered good, 50–74% fair, and <50% poor (Emire et al., 2022). This classification is widely used in health sciences research to ensure standardized interpretation of competency levels.

2.5 Data Collection Procedure

After obtaining official approval from the hospital administration, eligible nurses were approached and informed about the purpose and objectives of the study. Written informed consent was obtained from all participants prior to data collection.

The questionnaire was distributed in paper format during working hours and completed during designated break periods to minimize disruption of clinical duties. Data collection was conducted in a quiet and separate area within pediatric wards and outpatient clinics to ensure privacy and reduce discussion among participants.

To minimize response bias and ensure independence of responses, participants were instructed not to share or discuss questionnaire items during completion. The researcher was present throughout the data collection process to provide clarification when needed and ensure adherence to study procedures.

2.6 Validity and Reliability of the Instrument

Content validity was ensured through expert evaluation. Reliability was assessed using Cronbach's alpha coefficient, which indicated acceptable internal consistency ($\alpha = 0.88$).

2.7 Data Analysis

Data were analyzed using SPSS version 20. Descriptive statistics (frequencies, percentages, and standard deviations) were used to summarize the data. Inferential analysis was performed using the Chi-square test to examine associations between categorical variables such as knowledge level, practice level, years

of experience, and educational qualification. Statistical significance was set at $p < 0.05$.

Missing data were minimal and handled through listwise deletion. Assumptions for Chi-square test were checked to ensure validity of analysis.

2.8 Ethical Considerations

Ethical approval was obtained from the Institutional Review Board (IRB) of Atbara Teaching Hospital, River Nile State, Sudan (IRBATH-5-109-2024, dated 22 December 2024). The committee operates under the administration of the Ministry of Health, River Nile State, Sudan. Administrative permission was also obtained prior to data collection.

3. Results

3.1 Study Participants Flow

Figure 1 illustrates the flow of study participants. A total of 120 eligible pediatric nurses were approached for participation. Of these, 28 nurses did not participate due to absence during data collection (shift unavailability or leave) or voluntary refusal.

Consequently, 92 nurses completed the questionnaire and were included in the final analysis, yielding a response rate of 76.7%, as shown in figure 1.

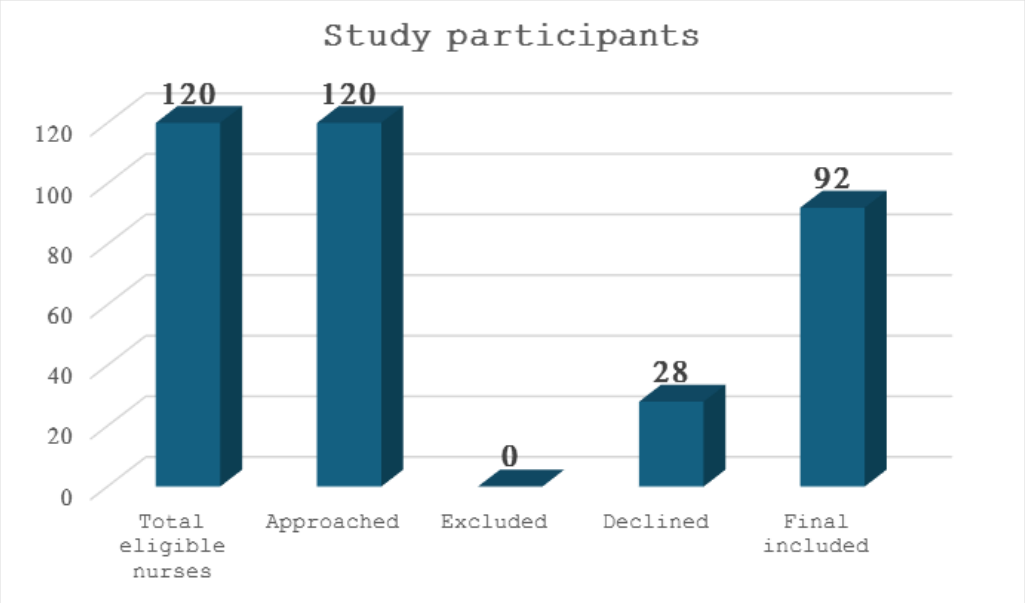


Figure 1. Flow diagram of study participants

3.2 Reliability of the Study Instrument

The internal consistency of the questionnaire was high, with an overall Cronbach's alpha coefficient of 0.88. All domains demonstrated acceptable reliability levels above 0.70, indicating that the instrument was consistent and suitable for assessing nurses' knowledge, practices, and educational/supportive roles in the management of children with Type 1 Diabetes Mellitus (T1DM), as shown in table 1.

Table 1. Reliability Analysis of the Questionnaire

Domain	Number of Items	Cronbach's Alpha
Knowledge items	15	0.82
Practice items	18	0.86
Education & support items	10	0.79
Overall reliability	**43**	**0.88**

3.3 Socio-Demographic Characteristics of Nurses

A total of 92 nurses participated in the study. The majority were female (69.6%). Nearly half of the participants held a bachelor's degree (48.9%), while 7.6% had postgraduate qualifications. Regarding clinical experience, 41.3% had five years or less of experience, indicating a relatively young nursing workforce in pediatric services. This reflects a moderately experienced pediatric nursing workforce, as shown in table 2.

Table 2. Distribution of Nurses According to Socio-Demographic Characteristics (n = 92)

Variable	Frequency	Percentage (%)
Gender		
Male	28	30.4
Female	64	69.6
Educational Level		
Diploma	40	43.5

Variable	Frequency	Percentage (%)
Educational Level		
Bachelor	45	48.9
Postgraduate	7	7.6
Years of Experience		
≤ 5 years	38	41.3
6–10 years	34	37.0
> 10 years	20	21.7

3.4 Nurses' Knowledge Regarding Type 1 Diabetes Mellitus

More than half of the nurses demonstrated good knowledge (54.3%), while 30.4% had fair knowledge and 15.3% had poor knowledge.

Despite this overall moderate level of knowledge, item-level analysis indicated deficiencies in key clinical areas, particularly insulin dose adjustment, recognition of acute complications such as hypoglycemia and diabetic ketoacidosis, and prevention of long-term complications, according to the study cut-off classification.

As shown in figure 2.

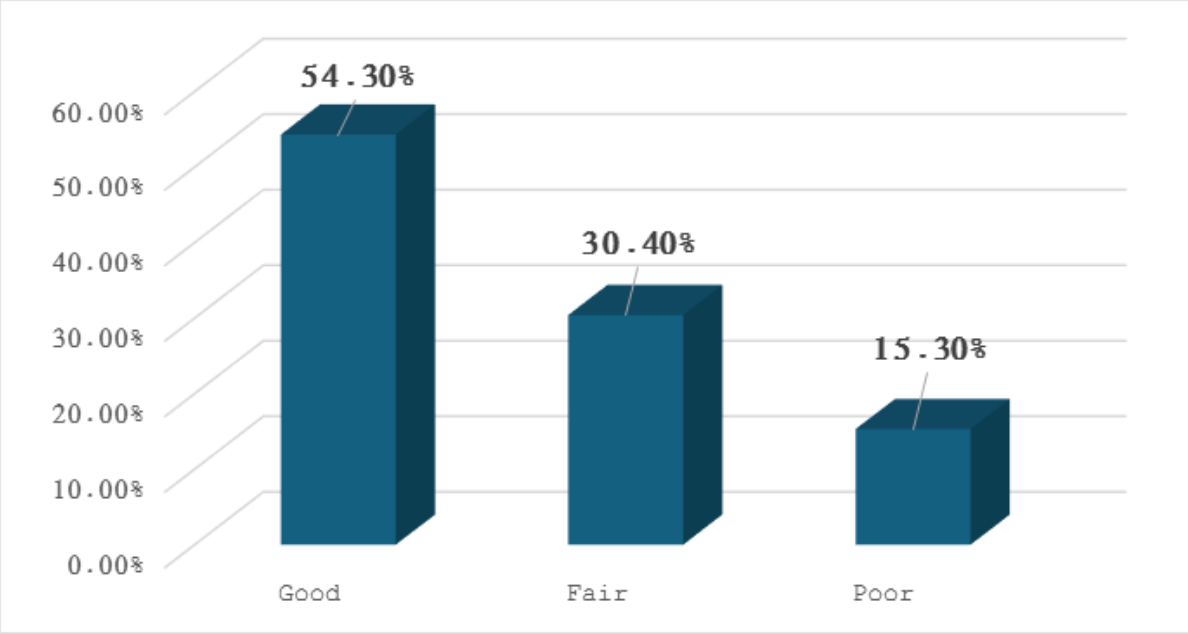


Figure 2. Distribution of nurses according to knowledge level

3.5 Association Between Knowledge Level and Years of Experience

No significant relationship was observed between nurses' knowledge level and years of clinical experience ($\chi^2 = 8.72$, $p = 0.068$, Cramer's $V = 0.22$). However, nurses with more than 10 years of experience demonstrated relatively higher proportions of good knowledge compared to less experienced nurses, indicating a small-to-moderate effect size. although the association was not statistically significant, the effect size suggests a potential practical trend, as shown in table 3.

Table 3. Relationship Between Nurses' Knowledge Level and Years of Experience

Years of Experience	Good	Fair	Poor	Total
≤ 5 years	15	16	7	38
6–10 years	21	10	3	34
> 10 years	14	2	4	20
Total	50	28	14	92

3.6 Nurses' Practice in Managing Children with Type 1 Diabetes Mellitus

Overall, 63.0% of nurses demonstrated adequate practice, while 37.0% had inadequate practice levels.

A domain-based analysis of practice items indicated strengths in routine clinical care, particularly in basic insulin administration and blood glucose monitoring. However, deficiencies were identified in patient education consistency, documentation practices, and psychosocial support, especially among newly diagnosed children and their families, as shown in figure 3.

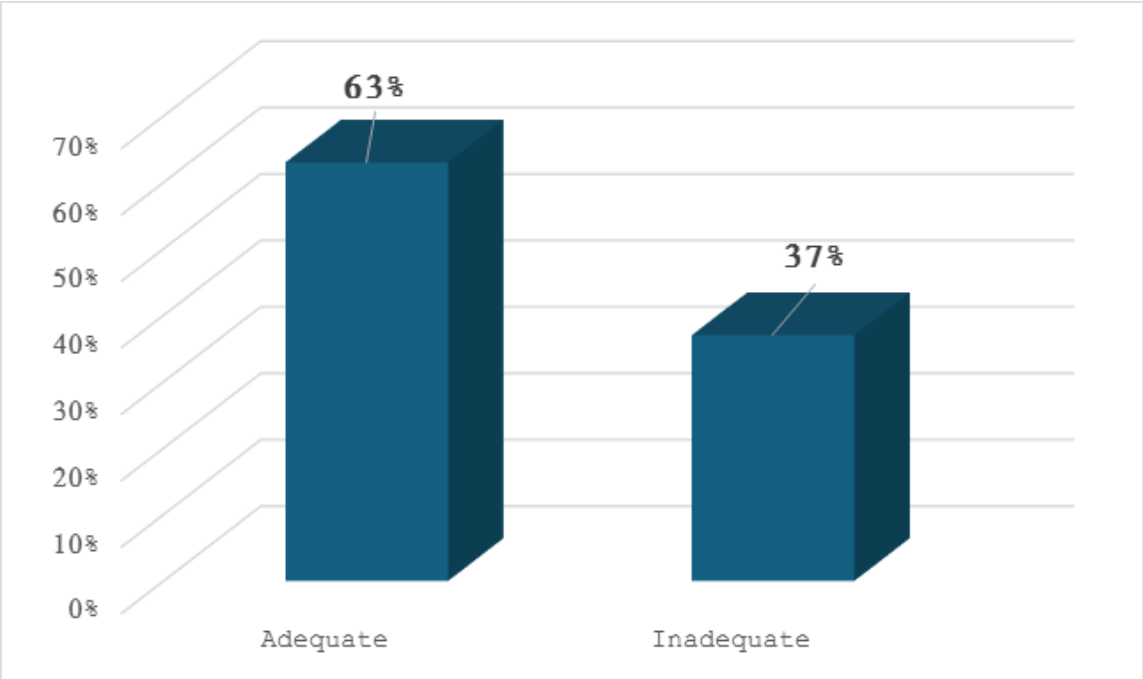


Figure 3. Distribution of nurses according to practice level

3.7 Association Between Practice Level and Educational Qualification

No significant relationship was observed between educational qualification and practice level ($\chi^2 = 5.72$, $p = 0.057$, Cramer's $V = 0.25$). Nevertheless, nurses with higher educational attainment (Bachelor's and postgraduate degrees) showed comparatively better practice scores, suggesting that higher education level may contribute to improved clinical performance despite the lack of statistical significance. Fisher's Exact Test was also applied due to small expected cell counts to confirm the robustness of the findings. The results are presented in Table 4.

Table 4. Relationship Between Practice Level and Educational Qualification

Educational Level	Adequate	Inadequate	Total
Diploma	20	20	40
Bachelor	32	13	45
Postgraduate	6	1	7
Total	58	34	92

4. Discussion

The present study assessed nurses' knowledge, clinical practices, and educational and supportive roles in the management of children with Type 1 Diabetes Mellitus (T1DM) at Atbara Teaching Hospital, Sudan.

The socio-demographic characteristics of the participants revealed a predominantly female nursing workforce, with many nurses holding bachelor's degrees and a considerable proportion having relatively limited clinical experience. This pattern is consistent with international trends in pediatric nursing, where female nurses constitute the majority of the workforce and early-career practitioners are commonly represented (Albagawi et al., 2023; Organization, 2025). While this workforce composition may facilitate family-centered care and communication with children and their caregivers, limited clinical experience may influence confidence and competency in managing complex chronic conditions such as T1DM, which require advanced clinical judgment and specialized patient education skills.

The findings demonstrated that nurses possessed a moderate level of knowledge regarding the management of children with T1DM. Nevertheless, important gaps were identified in critical areas, including insulin dose adjustment, recognition and management of acute diabetic complications, and prevention of long-term complications. These findings are consistent with previous studies conducted in low- and middle-income countries, where insufficient continuing education and limited access to specialized diabetes training programs have been identified as barriers to optimal nursing knowledge and competency (Albagawi et al., 2023; Lumu et al., 2024).

Although no statistically significant association was observed between knowledge level and years of experience, nurses with longer clinical experience tended to demonstrate better knowledge. This finding suggests that clinical exposure may contribute to professional growth and knowledge acquisition over time. However, experience alone may not be sufficient to ensure comprehensive competency in pediatric diabetes care. This observation supports Benner's theory of skill acquisition, which emphasizes that expertise develops through the integration of practical experience and formal learning opportunities(Gregory et al., 2022).

With regard to clinical practice, nurses generally demonstrated satisfactory performance in routine aspects of diabetes management, including insulin administration and blood glucose monitoring. However, weaknesses were identified in documentation practices, patient education, and psychosocial support. These findings suggest variability in the implementation of evidence-based nursing care and may reflect challenges related to workload pressures, limited training opportunities, and the absence of standardized protocols for pediatric diabetes management (Hayek et al., 2025; Sińska et al., 2023).

Similarly, although educational qualification was not significantly associated with practice performance, nurses with higher academic preparation appeared to demonstrate better clinical practice. This finding indicates that academic education may contribute to enhanced clinical reasoning and evidence-based decision-making. Nevertheless, educational attainment alone does not guarantee competency across all domains of diabetes care, highlighting the importance of continuous professional development and structured in-service training programs (Albagawi et al., 2023).

A particularly important finding of this study was the limited provision of psychosocial support and structured diabetes education for children and their families, especially among newly diagnosed cases. This issue is clinically significant because psychosocial support and diabetes self-management education are fundamental components of comprehensive pediatric diabetes care. International guidelines emphasize the integration of medical treatment with structured educational and psychological support interventions to improve treatment adherence and glycemic outcomes (Libman et al., 2022). However, these components remain insufficiently developed in many resource-limited settings due to staffing shortages, heavy workloads, and inadequate educational resources.

4.1 Study Limitations

This study has several limitations that should be considered when interpreting the findings. The use of a self-administered questionnaire may have introduced self-reporting and social desirability biases, potentially leading participants to overestimate their knowledge and practices. In addition, the study was conducted in a single healthcare institution, which limits the generalizability of the findings to other healthcare settings. Non-response bias may also have occurred because some eligible nurses were unavailable or declined participation. Furthermore, the cross-sectional design does not permit causal inferences regarding the relationships between nurses' characteristics and their knowledge or practice levels.

5. Conclusion

This study demonstrated that nurses possessed moderate knowledge and generally adequate clinical practice regarding the management of children with Type 1 Diabetes Mellitus. Despite these encouraging findings, deficiencies remained in several important areas, particularly diabetes-specific knowledge, documentation practices, patient education, and psychosocial support. The findings further suggest that competency in pediatric diabetes care is influenced by multiple factors beyond educational attainment and years of clinical experience alone. Strengthening continuous professional development initiatives, promoting evidence-based practice, and implementing standardized diabetes care protocols may contribute to improving the quality of nursing care and enhancing health outcomes among children with T1DM.

5.1 Implications for Nursing Practice, Education, and Research

The findings highlight the importance of strengthening nurses' competencies in pediatric diabetes management through continuous professional development and the implementation of standardized clinical protocols. Nursing education programs should incorporate comprehensive content related to pediatric diabetes care, with particular emphasis on insulin management, patient education, psychosocial support, and accurate clinical documentation. Healthcare institutions should support ongoing competency development through structured training initiatives and evidence-

based practice updates. Future research should employ longitudinal and interventional designs to evaluate the effectiveness of educational programs and their impact on patient outcomes, including glycemic control, treatment adherence, and diabetes-related complications.

6. Recommendations

Based on the findings of this study, healthcare institutions should prioritize the implementation of continuous and targeted educational programs to strengthen nurses' knowledge and competencies in pediatric diabetes management, particularly in areas related to insulin therapy, hypoglycemia, and diabetic ketoacidosis. Efforts should also focus on enhancing nurses' abilities to provide effective patient education and psychosocial support for children with Type 1 Diabetes Mellitus and their families. The development and consistent implementation of standardized nursing protocols for diabetes management, including monitoring, insulin administration, discharge planning, and follow-up care, are recommended to improve the consistency and quality of care. In addition, healthcare facilities should promote accurate documentation practices through the use of standardized documentation tools and regular clinical audits. Nursing education programs may further benefit from integrating simulation-based and competency-based learning approaches to strengthen practical skills and clinical decision-making abilities. Adequate staffing levels should also be ensured to facilitate comprehensive patient education and psychosocial care. Furthermore, future multicenter and interventional studies are recommended to evaluate the effectiveness of training interventions and their impact on clinical outcomes, including glycemic control and diabetes-related complications among children with T1DM.

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Operational Security Exposure and Attack Surface Analysis of Password Manager Browser Extensions

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Abstract
Password manager browser extensions have become widely used authentication tools for improving password security and reducing credential reuse across digital platforms. Despite the deployment of client-side encryption mechanisms, browser-integrated password managers may still introduce security exposure because of elevated browser permissions, runtime credential handling, synchronization behavior, and direct interaction with webpages and browser APIs.
This study analyzes the attack surface characteristics of password manager browser extensions operating in Chromium-based browser environments. The evaluation examines browser permissions, runtime interaction behavior, storage mechanisms, and synchronization-related communication patterns associated with browser-integrated password managers. To support structured analysis, the study adopts a multidimensional security evaluation framework integrating permission exposure analysis, runtime injection assessment, browser-side storage interaction analysis, and exploratory correlation analysis.
Experimental results obtained from seven widely used password manager browser extensions show measurable differences in exposure characteristics across the evaluated platforms. The findings suggest that password manager browser extensions rely on different integration strategies involving privileged browser permissions, runtime webpage interaction, browser-side persistence mechanisms, and synchronization-related communication behavior. The analysis additionally shows that encryption deployment alone does not fully eliminate runtime exposure within browsercentric authentication environments.

Keywords: Credential Protection; Autofill Exposure; Synchronization Complexity; Runtime Interaction; Browser APIs.

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1. Introduction

Password managers have become a widely adopted mechanism for improving authentication security and reducing password reuse across online services. In modern computing environments, these systems are commonly deployed as browser extensions that generate, store, synchronize, and automatically fill user credentials across multiple platforms. Their widespread adoption is largely driven by their ability to improve both security and usability while reducing the burden of managing large numbers of credentials (Wiefling, Jørgensen, Thunem, & Iacono, 2022; Alodhyani, Theodorakopoulos, & Reinecke, 2020; Jubur, Shrestha, & Saxena, 2025).

Although encryption remains a fundamental component of password-manager security, the protection of credentials increasingly depends on a broader set of operational safeguards. Modern authentication environments rely on secure interaction workflows, browser-side isolation mechanisms, credential-handling protections, and exposure-reduction strategies throughout the authentication lifecycle (P. Wang, Boodraj, & Baskerville, 2025; Saadi, Sadiq, Akif, & Farhan, 2024). Consequently, understanding the security posture of password managers requires evaluating not only how credentials are encrypted, but also how they are processed, accessed, and exposed during browser operation.

However, browser-integrated password managers also introduce new cybersecurity issues since they operate within highly dynamic environments of browsers and require high permissions to interact with webpages, browser APIs, autofill mechanisms, and browser sessions. Browser extensions often request additional permissions, which can increase exposure and security risk to the browser. Picazo et al. (Picazo-Sanchez, Ortiz-Martin, Schneider, & Sabelfeld, 2022) showed that many extensions do not follow the least privilege principle and Wang et al. (K. Wang et al., 2022) showed that malicious extensions can target sensitive data and user credentials in the browser.

Browser security and the risks associated with extensions have become an important cybersecurity concern as a result. Chalyi et al. (Chalyi, Driaunys, & Rudˇzionis, 2025) investigated the vulnerabilities of browsers with evaluation metrics based on CVE and highlighted the persistence of browser security weaknesses in modern environments. Jin et al. (Jin, Li, & Zou, 2024) investigated the operational impact of extensions on Chromium-based browser environments and demonstrated that browser extensions could have a significant impact on the browser's behaviour during runtime. Other studies concentrated on browserside protection mechanisms to defend against extension-based threats. Wang et al. (X. Wang, Du, Wang, Wang, & Fang, 2021) proposed WebEnclave, which leverages the software enclave concepts to safeguard sensitive web secrets from malicious browser extensions. Further studies also investigated browser extension abuse, privilege abuse and browser API exposure in modern browser ecosystems.

Recent studies have increasingly examined cybersecurity risk assessment, security exposure and structured security evaluation in modern digital systems (Ganin et al., 2020; Amro, Gkioulos, & Katsikas, 2023; Atlam, Azad, Alassafi, Alshdadi, & Alenezi, 2020; Cornwell, Bilson, Gepp, Stern, & Vanstone, 2022; Uddin, Mollah, Islam, & Ali, 2023). The significance of risk management, attack modelling and runtime exposure analysis, and dynamic cybersecurity evaluation across cyber-physical and digitally transformed environments was highlighted in existing studies (Amro et al., 2023; Uddin et al., 2023). Other work pointed to the importance of structured risk-oriented evaluation to understand the cybersecurity exposure in complex operational systems (Atlam et al., 2020; Cornwell et al., 2022).

Encryption alone, however, does not remove the security exposure; clientside encryption is widely deployed in password managers, but active browser sessions can leak sensitive information through runtime credential handling, memory exposure, autofill abuse, session persistence, and excessive browser permissions. Prior work indicated that, even with encryption mechanisms in place, processing on the browser side and interaction at runtime can provide other potential pathways for exposure (X. Wang et al., 2021). Previous work studied the attack surface of password managers, browser extensions or browser vulnerabilities separately, but not their combined attack surface in browser-based authentication environments.

In this study, attack surface is defined as the set of browser-accessible interaction pathways that may increase exposure during active extension operation. These pathways include privileged browser permissions, interaction with webpages at runtime, browser-session access, browser-side persistence mechanisms, synchronization-related communication behaviour, and extension interaction with browser APIs and webpages. Most of the current research focuses on individual topics like encryption design, malware detection, permission analysis, browser vulnerabilities, or authentication usability, but does not systematically evaluate the operational cryptographic exposure during runtime browser operation.

This study makes three contributions. First, it provides a multidimensional security analysis of password manager browser extensions. Second, it evaluates seven widely used extensions with respect to permissions, runtime interaction, storage behavior, and synchronization-

related communication. Third, it introduces a structured perspective for assessing browser-centric attack-surface exposure during password-manager operation.

Therefore, in this study we provide an attack surface and operational cryptographic risk analysis of password manager browser extensions. The work focuses on assessing operational exposure associated with browser permissions, runtime credential management, autofill activity, synchronisation processes, session persistence, and browser-extension interaction. The study also provides a structured view to assess the cryptographic exposure of browser-based password management systems.

2. Related Work

2.1 Password Manager Security

Password managers have been broadly studied as mechanisms to enhance password security, decrease password reuse, and encourage secure authentication practices on digital platforms. Existing studies have shown that password managers improve password management behaviour, improve credential organization, and simplify authentication workflows while reducing unsafe password practices (Wiefling et al., 2022; Alodhyani et al., 2020; Jubur et al., 2025). Other studies highlighted the importance of usability, transparency, operational trust, and user-centred protection in password manager adoption and authentication effectiveness (Alodhyani et al., 2020; P. Wang et al., 2025).

Several studies also investigated vulnerabilities associated with authentication systems, password storage, and browser-integrated authentication environments. Saadi et al. (Saadi et al., 2024) discussed vulnerabilities in graphical password systems and different protection approaches for authentication security. Previous studies additionally examined browser-integrated password managers, credential accessibility, runtime interaction, and browser-related dependencies (Jubur et al., 2025; Wiefling et al., 2022; P. Wang et al., 2025). Other works explored cybersecurity awareness, user perception, and behavioural security practices associated with authentication systems and operational digital environments (Kennison & Chan-Tin, 2020; Moustafa, Bello, & Maurushat, 2021).

Recent research also examined security implications associated with authentication technologies and machine-learning-driven security systems (Bitton et al., 2021). Existing studies further indicated that complexity, privacy concerns, and runtime exposure remain important considerations in modern authentication infrastructures (Petronio & Child, 2020; Senna, Reis, Castro, & Dias, 2020).

Most previous studies focused on usability, trust, and credential protection. Less attention has been given to the combined impact of permissions, runtime interaction, storage behavior, and synchronization mechanisms on operational security exposure.

2.2 Browser Extension Security

Browser extensions have become an important cybersecurity research area because of their elevated privileges and direct interaction with browser APIs, webpages, browser sessions, and sensitive user information. Picazo et al. (PicazoSanchez et al., 2022) investigated whether Chrome extensions comply with the principle of least privilege and reported that many extensions request excessive permissions beyond operational requirements. Existing studies also examined browser extension abuse, browser API exposure, runtime interaction risks, and extension-related threats within browser ecosystems (Zahid, Inayat, Daneva, & Mehmood, 2021).

Malicious browser extensions have attracted increasing research attention in recent years. Wang et al. (K. Wang et al., 2022) analyzed cryptocurrencythemed malicious browser extensions and showed that browser extensions can be used to steal credentials and sensitive browser information through deceptive behaviours. Other studies discussed browser-related exposure, manipulation techniques, runtime browser interaction risks, and extension abuse concerns associated with browser-integrated environments (Petronio & Child, 2020; Smart, Sood, & Vaccaro, 2022).

Several studies explored browser security from broader operational and defensive perspectives. Chalyi et al. (Chalyi et al., 2025) analyzed browser vulnerabilities using CVE-based security metrics and highlighted the persistence of browser-side vulnerabilities in modern browser environments. Jin et al. (Jin et al., 2024) examined the operational impact of browser extensions on Chromiumbased browser environments and showed that browser extensions may significantly influence runtime browser behaviour and browser performance. Wang et al. (X. Wang et al., 2021) proposed WebEnclave to protect browser-side secrets from malicious browser extensions using software enclave concepts. Additional studies discussed browser privacy exposure, browser-side uncertainty, interaction risks, and runtime browser manipulation associated with modern browser-centric platforms (Smart et al., 2022; Petronio & Child, 2020).

Existing studies additionally emphasized that browser extensions significantly contribute to attack surface expansion because of privileged interaction with webpages, browser APIs, synchronization mechanisms, and browser-session operations (Picazo-Sanchez et al., 2022; K. Wang et al., 2022).

Existing research has mainly examined permissions, malicious extensions, or browser vulnerabilities separately. A broader evaluation that combines these dimensions remains relatively limited.

2.3 Operational and Cybersecurity Risk Analysis

Cybersecurity evaluation has become increasingly important in modern digital and cyber-physical environments. Ganin et al. (Ganin et al., 2020) proposed a multicriteria framework for cybersecurity risk assessment and operational security management, while Atlam et al. (Atlam et al., 2020) reviewed adaptive risk-based access control approaches for dynamic security evaluation in modern computing systems. Additional studies emphasized the importance of structured operational cybersecurity assessment, uncertainty evaluation, and management, and automated cybersecurity analysis mechanisms in modern digital infrastructures (Eckhart et al., 2022). Additional studies investigated cybersecurity exposure associated with machine learning systems and operational decision-making mechanisms (Bitton et al., 2021).

Recent works further highlighted the importance of runtime exposure evaluation, operational attack modeling, and structured cybersecurity assessment across browser-centric and distributed operational systems (Cheng, Cai, Wang, Dong, & Li, 2026). While these studies provide valuable cybersecurity-evaluation methodologies, they are generally designed for broader operational environments rather than browser-integrated authentication ecosystems. As a result, their direct applicability to password-manager browser extensions remains limited.

2.4 Research Gap

The existing literature confirms that password managers, browser extensions, browser vulnerabilities, and cybersecurity mechanisms introduce multiple security and operational challenges. However, most prior studies analyze these components separately. Existing works mainly focus on password usability, authentication trust, browser extension permissions, malware detection, browser vulnerabilities, or general cybersecurity risk assessment.

Current literature provides limited analysis of the combined security exposure associated with browser-integrated password manager extensions, particularly in relation to runtime credential handling, browser-session interaction, autofill behaviour, synchronization mechanisms, and attack surface expansion. Existing studies also lack structured evaluation frameworks that integrate browser permissions, extension behaviour, browser interaction, runtime exposure, and cryptographic deployment within unified browser security analysis environments.

This study addresses this gap by presenting an attack surface and security risk analysis framework for password manager browser extensions based on runtime exposure assessment and structured cybersecurity evaluation.

runtime exposure analysis in digital infrastructures (Chandna & Tiwari, 2021; Eckhart, Ekelhart, & Weippl, 2022).

Other studies investigated security exposure and cyber risk assessment in digitally transformed infrastructures and cyber-physical systems. Amro et al. (Amro et al., 2023) applied ATT&CK-based methodologies for cyber risk assessment and operational security analysis in cyber-physical environments. Amro et al. (Amro & Gkioulos, 2022) additionally explored threat-informed cyber risk management strategies in autonomous systems.

Existing literature also discussed operational exposure, adaptive security

Table 1: Comparison Between Prior Studies and the Proposed Framework

Study	Permission Analysis	Runtime Interaction Analysis	Communication Exposure Evaluation	Storage Unified
Picazo et al. (Picazo-Sanchez et al., 2022)	✓	–	–	–
Wang et al. (K. Wang et al., 2022)	✓	✓	–	–
Jin et al. (Jin et al., 2024)	–	✓	–	–
Wang et al. (X. Wang et al., 2021)	–	✓	–	–
Proposed Study	✓	✓	✓	✓

Table 1 highlights that most previous studies focused on isolated aspects of browser extension security such as permission analysis, runtime interaction, or browser-side protection mechanisms. Unlike these studies, the proposed framework evaluates permission exposure, runtime interaction behavior, storage interaction mechanisms, and synchronization-related communication characteristics within a unified operational exposure perspective. This integrated view enables a broader assessment of browser-centric attack-surface expansion in passwordmanager environments.

3. Methodology

This study adopts a cybersecurity evaluation methodology to analyze password manager browser extensions from an attack surface and security exposure perspective. The methodology focuses on how browser permissions, runtime credential handling, browser-extension interaction, synchronization behavior, and browser-session operations contribute to security exposure during active browser sessions. Existing studies showed that browser extensions operate with elevated browser privileges and may significantly influence browser behavior, runtime interaction, and browser-related exposure (Picazo-Sanchez et al., 2022; K. Wang et al., 2022; Jin et al., 2024).

The study evaluates seven browser-integrated password manager extensions deployed within Chromium-based browser environments. The evaluated extensions include Bitwarden, LastPass, Dashlane, NordPass, Proton Pass, Keeper, and RoboForm. These extensions were selected because of their widespread adoption, browser integration capabilities, synchronization functionality, and active interaction with authentication-related browser operations. Existing literature demonstrated that password managers improve authentication usability and credential management while also introducing browser-related dependencies and runtime interaction risks (Wiefling et al., 2022; Alodhyani et al., 2020; Jubur et al., 2025; P. Wang et al., 2025).

The security analysis pipeline consisted of several sequential stages. First, the evaluated password manager extensions were collected from the Chrome Web Store as Chromium extension packages (CRX format). Second, the CRX packages were extracted and analyzed to identify manifest permissions, optional permissions, host permissions, content scripts, browser-side storage interaction, and synchronization-related communication references. Third, runtime characteristics including injected JavaScript behavior, browser-session interaction patterns, browser-side persistence mechanisms, and external communication exposure were evaluated. Finally, exploratory correlation analysis was conducted to investigate relationships between permission exposure, runtime interaction behavior, browser-side storage mechanisms, and synchronization-related communication behavior across the evaluated extensions.

The methodology combines concepts from browser security analysis, operational cybersecurity risk evaluation, and runtime exposure assessment (Ganin et al., 2020; Atlam et al., 2020; Cornwell et al., 2022). Additional studies also emphasized the importance of adaptive cybersecurity evaluation, uncertaintyaware security analysis, and operational risk-oriented assessment within digitally transformed infrastructures and distributed operational systems (Gupta, Shankar, Lai, & Kumar, 2023; Eckhart et al., 2022; Uddin et al., 2023). These perspectives support the use of exposure analysis for evaluating browser-integrated authentication systems and runtime security behavior.

The security analysis pipeline was implemented using automated Pythonbased analysis scripts for CRX extraction, manifest parsing, browser permission identification, content-script inspection, storage-reference extraction, and synchronization-related URL analysis. The automated analysis process was designed to improve consistency, reproducibility, and structured operational comparison across the evaluated browser extensions. To improve reproducibility, all extension packages were extracted and analyzed using identical Chromiumbased environments and standardized parsing procedures. The automated analysis workflow applied consistent manifest extraction, permission identification, storage-reference analysis, and runtime interaction inspection across all evaluated extensions.

Table 2: Extracted Operational Features Used in the Security Analysis

Feature Category	Extracted Features
Permission Exposure	Manifest permissions, optional permissions, host permissions
Runtime Interaction	Content scripts, injected JavaScript files, webpage match patterns
Sensitive Browser Access	Clipboard access, scripting permissions, tab interaction permissions
Storage Interaction	localStorage references, sessionStorage references, IndexedDB interaction, chrome.storage usage
Communication Exposure	External URL references, synchronization-related communication indicators
Operational Indicators	Runtime interaction scope, browser-session interaction behavior

The analysis focuses on browser permissions, runtime credential handling, autofill operations, browser-session persistence, extension-browser interaction, synchronization mechanisms, and communication

behavior associated with password manager browser extensions.

Unlike prior studies that focused on isolated aspects of password-manager security, the proposed framework evaluates permission exposure, runtime interaction behavior, storage interaction mechanisms, and synchronization-related communication characteristics within a unified operational exposure perspective.

Table 2 summarizes the primary operational browser-security features extracted during the experimental evaluation. The selected features support structured comparative analysis across browser permissions, runtime interaction behavior, browser-side persistence mechanisms, and synchronization-related communication exposure.

Browser permissions were evaluated because previous studies demonstrated that excessive browser permissions may violate least privilege principles and significantly expand browser attack surfaces (Picazo-Sanchez et al., 2022). Additional works discussed browser interaction risks, malicious extension behavior, and runtime exposure pathways associated with browser ecosystems (K. Wang et al., 2022; Asif, Lodhi, Sarwar, & Ashfaq, 2023; Zahid et al., 2021).

The study also investigates security exposure associated with client-side encryption deployment in browser-integrated password managers. Although encryption mechanisms protect stored credentials, previous studies indicated that runtime interaction and browser-side processing may still expose sensitive information during active browser sessions (X. Wang et al., 2021; Jubur et al., 2025). Existing literature additionally emphasized that runtime exposure, synchronization complexity, and browser-side interaction remain important cybersecurity concerns in modern authentication environments (Petronio & Child, 2020; Senna et al., 2020).

To support structured evaluation, this study adopts a structured security perspective for analyzing browser extension exposure. Prior studies highlighted the importance of structured cybersecurity assessment, operational resilience evaluation, and runtime exposure analysis in modern digital systems (Amro et al., 2023; Amro & Gkioulos, 2022; Chandna & Tiwari, 2021). Other works discussed adaptive cybersecurity management, AI-driven operational evaluation, and uncertainty-aware cybersecurity analysis in operational infrastructures (Butnaru, Mylonas, & Pitropakis, 2021; Eckhart et al., 2022). Based on these perspectives, the proposed methodology evaluates how browser permissions, extension behavior, runtime credential processing, synchronization mechanisms, and browser interaction collectively contribute to operational attack surface expansion in password manager browser extensions.

4. Threat Model

This study considers a browser-centric threat environment in which password manager browser extensions operate inside modern web browsers while interacting with webpages, browser APIs, browser sessions, synchronization services, and external communication channels. Browser-integrated password managers operate with elevated privileges and direct access to sensitive authenticationrelated information, making them important targets within browser ecosystems (Picazo-Sanchez et al., 2022; K. Wang et al., 2022).

The threat model assumes that attackers may exploit operational exposure associated with browser-extension interaction, excessive permissions, malicious webpages, runtime credential handling, synchronization mechanisms, or browser-side operational weaknesses. Existing studies demonstrated that malicious browser extensions and browser-side manipulation techniques may expose sensitive credentials and browser-related information through deceptive behaviors and runtime interaction mechanisms (K. Wang et al., 2022; Asif et al., 2023; Smart et al., 2022).

The model focuses primarily on security threats rather than direct cryptographic algorithm compromise. The analysis therefore emphasizes runtime exposure pathways associated with browser-session interaction, autofill operations, synchronization behavior, extension communication mechanisms, and browser API interaction. Previous research highlighted that runtime browser interaction and browser-side processing may introduce operational exposure even when strong encryption mechanisms are deployed (X. Wang et al., 2021; Jubur et al., 2025).

The study does not attempt to identify or exploit zero-day vulnerabilities, compromise commercial password manager infrastructures, bypass deployed cryptographic protections, or perform offensive penetration testing against evaluated products. Instead, the analysis focuses on exposure characteristics associated with browser permissions, runtime interaction behavior, browser-session processing, synchronization mechanisms, and browser-integrated attack surface expansion. All experimental evaluations were conducted within controlled local environments without interacting with real user credentials, compromising external infrastructures, or performing unauthorized offensive activities against commercial password management services.

The considered threat environment includes malicious webpages, browserside script injection, unauthorized browser-session access, extension compromise, clipboard

monitoring, synchronization abuse, runtime credential interception, and application-level exposure arising from browser-integrated authentication workflows. Existing studies additionally discussed operational uncertainty, browser-side manipulation risks, and adaptive runtime exposure associated with modern browser ecosystems and digital interaction environments (Petronio & Child, 2020).

The targeted assets include stored credentials, runtime decrypted credentials, browser-session information, autofill-related data, synchronization tokens, and authentication-related browser interaction data. These assets are considered highly sensitive because they directly influence authentication security, credential confidentiality, and browser security exposure. Previous studies emphasized that browser-integrated systems and browser extensions may significantly contribute to attack surface expansion because of privileged interaction with browser APIs, webpages, synchronization services, and operational browser mechanisms (Picazo-Sanchez et al., 2022; K. Wang et al., 2022; Jin et al., 2024). The experimental analysis did not involve human participants, real credential collection, unauthorized access attempts, or interaction with private user authentication data. All evaluations were conducted within controlled local environments using publicly available browser extension packages.

5. Experimental Design

The experimental design of this study focuses on evaluating password manager browser extensions from an operational cryptographic security perspective. The evaluation investigates how browser permissions, runtime credential handling, synchronization behavior, browser-session persistence, and extension-browser interaction contribute to security exposure during active browser operation.

The study evaluates widely used browser-integrated password manager extensions operating within Chromium-based browser environments. Browserbased password managers were selected because they directly interact with webpages, browser APIs, browser sessions, synchronization services, and autofill mechanisms while simultaneously handling highly sensitive authenticationrelated information. Existing literature confirmed that browser extensions may significantly influence browser operational behavior and runtime exposure because of elevated browser privileges and direct interaction with browser components (Jin et al., 2024; Picazo-Sanchez et al., 2022; K. Wang et al., 2022).

5.1 Dataset and Evaluated Extensions

The selected extensions were chosen according to their popularity, availability within the Chrome Web Store ecosystem, active maintenance status, and support for browser-based credential synchronization. The final dataset included seven password manager extensions spanning different vendors, synchronization architectures, permission configurations, and browser-integration approaches. The analysis focuses on seven widely used password manager browser extensions: Bitwarden, LastPass, Dashlane, NordPass, Proton Pass, Keeper, and RoboForm. These extensions were selected because of their widespread adoption, browser integration capabilities, synchronization functionality, and active interaction with authentication-related browser operations. In addition, they represent some of the most widely deployed password-manager browser extensions discussed in recent password-manager surveys and authentication studies (Jubur et al., 2025). This selection was intended to provide a representative cross-section of commonly used browser-based password-management solutions rather than focusing on a single vendor or architectural design.

The evaluated extensions were downloaded as Chromium extension packages (CRX format) and extracted within controlled experimental environments for security analysis. The experimental pipeline included manifest extraction, browser permission analysis, runtime interaction assessment, content-script evaluation, browser-side storage analysis, synchronization-related communication analysis, and exploratory correlation analysis. To improve experimental consistency, the operational extraction and browser-extension analysis procedures were repeated across controlled execution environments using identical Chromiumbased configurations and standardized extension analysis workflows.

The analysis specifically focused on extension operational behavior associated with browser permissions, injected scripts, browser-session interaction, browser-side persistence mechanisms, synchronization complexity, and runtime exposure. Existing literature emphasized that browser extensions may significantly contribute to browser attack surface expansion because of privileged interaction with webpages, browser APIs, browser sessions, and browser-side operational mechanisms (Picazo-Sanchez et al., 2022; K. Wang et al., 2022; Jin et al., 2024).

The experimental analysis focuses on evaluating browser permissions, operational browser interaction, runtime credential processing, browser-session behavior, synchronization mechanisms, and extension communication behavior associated with password manager browser extensions. Existing studies highlighted that excessive browser permissions and privileged browser interaction may significantly increase browser attack surface exposure and operational cybersecurity risks (Picazo-Sanchez et al., 2022; K. Wang et al., 2022). Additional works also emphasized runtime browser exposure, browser-side uncertainty, and interaction risks

associated with browser-centric digital environments (Petronio & Child, 2020).

The evaluation additionally investigates security exposure associated with client-side encryption deployment within password manager browser extensions.

Although encryption protects stored credentials, previous research demonstrated that runtime interaction and browser-side processing may still expose sensitive information during active browser sessions (X. Wang et al., 2021; Jubur et al., 2025). Existing literature further highlighted that synchronization complexity, browser-session persistence, and runtime credential handling remain important operational cybersecurity concerns in modern authentication systems (Senna et al., 2020; Gupta et al., 2023).

To support comparative analysis, the study evaluates operational exposure across seven password manager browser extensions using a structured operational cybersecurity perspective. The evaluation investigates how differences in browser permissions, synchronization architecture, runtime interaction mechanisms, and extension operational behavior influence operational attack surface expansion and runtime exposure characteristics. Previous studies emphasized the importance of structured operational cybersecurity assessment, adaptive security evaluation, and runtime exposure analysis within digitally transformed operational systems (Ganin et al., 2020; Atlam et al., 2020; Cornwell et al., 2022; Uddin et al., 2023).

6. Results and Security Analysis

This section presents the experimental findings obtained from the security analysis of password manager browser extensions. The evaluation was conducted within controlled Chromium-based browser environments using extracted CRX extension packages and browser-extension security analysis procedures. The experimental pipeline included manifest extraction, permission analysis, contentscript evaluation, browser-side storage assessment, synchronization-related communication analysis, and exploratory correlation analysis.

The evaluation focuses on browser permission exposure, runtime interaction behavior, browser-side storage interaction, synchronization-related communication behavior, and operational attack surface characteristics associated with browser-integrated password manager extensions.

6.1 Permission Exposure Analysis

The first stage of the analysis evaluated the browser permissions requested by each password manager extension after extracting and analyzing the corresponding CRX extension packages. The analysis focused on manifest permissions, optional permissions, and host permissions associated with runtime browser interaction and operational browser exposure.

The results indicate noticeable differences in permission exposure across the evaluated extensions. Table 3 summarizes the comparative operational exposure indices.

To support structured comparative evaluation, an operational exposure index was calculated using a weighted heuristic model integrating manifest permissions, optional permissions, and host permissions:

Table 3: Operational Exposure Index Across Password Manager Browser Ex-tensions

Extension	Permission	Optional	Host	Exposure Index
Bitwarden	16	2	2	20.0
Keeper	14	0	3	17.6
RoboForm	13	3	1	16.6
LastPass	12	2	2	16.0
Dashlane	12	1	2	15.2
Proton Pass	8	5	2	14.4
NordPass	10	2	2	14.0

$$\text{ExposureIndex} = (1.0 \times \text{Permission}) + (0.8 \times \text{Optional}) + (1.2 \times \text{Host})$$

To evaluate the robustness of the weighting strategy, a sensitivity analysis was additionally performed using alternative weighting configurations. The analysis was designed to determine whether the relative ranking of extensions remained stable under different reasonable weighting assumptions.

Host permissions were assigned slightly higher weights because they directly influence webpage interaction scope and external browser exposure surfaces, while optional permissions were weighted lower because they may not always be activated during routine browser operation. The exploratory sensitivity analysis indicated

that the overall ordering of extensions remained broadly consistent across alternative weighting configurations. Minor variations were observed only among extensions with similar exposure scores, while the highest- and lowestranked extensions remained unchanged. These observations provide additional confidence that the reported exposure trends are not solely dependent on a single weighting configuration.

Table 3 shows that Bitwarden demonstrated the highest operational exposure index among the evaluated extensions, followed by Keeper and RoboForm. NordPass exhibited the lowest overall exposure index, while LastPass, Dashlane, and Proton Pass occupied intermediate positions. The results indicate measurable variation in permission-related exposure across the seven evaluated password-manager extensions.

The findings indicate that password manager extensions frequently require elevated browser privileges to support synchronization, autofill functionality, runtime credential handling, and browser integration operations.

The results are consistent with previous studies highlighting that browser extensions may request excessive permissions beyond minimal operational requirements (Picazo-Sanchez et al., 2022). The analysis additionally confirms that browser exposure cannot be evaluated solely based on encryption deployment because browser permissions significantly influence attack surface characteristics during runtime browser operation.

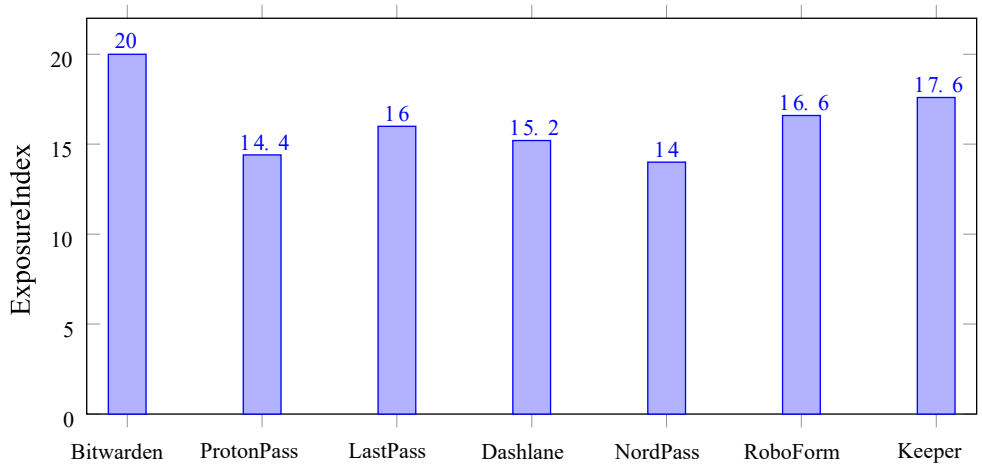


Figure 1: Comparative Operational Exposure Index Across Seven Password Manager Extensions

Figure 1 illustrates the comparative operational exposure distribution across the evaluated extensions immediately following the permission analysis results.

The expanded evaluation demonstrates that exposure characteristics vary considerably across commercially deployed password-manager extensions. Although Bitwarden exhibited the highest overall permission-related exposure score, Keeper and RoboForm also demonstrated relatively elevated exposure levels, suggesting that browser-integration strategies differ substantially across vendors.

6.2 Runtime Injection and Browser Interaction Exposure

The second stage of the analysis evaluated runtime webpage interaction exposure through content-script deployment and injected JavaScript behavior extracted from the evaluated CRX extension packages. Browser content scripts directly interact with webpages and therefore contribute to runtime exposure and browser attack surface expansion. Injected JavaScript activity refers to extension-associated runtime scripts deployed into webpages during browser interaction. Match patterns represent webpage scope definitions extracted from extension manifests and used to determine operational webpage interaction coverage. Table 4 presents the runtime interaction characteristics observed across the evaluated password manager browser extensions.

Table 4 demonstrates substantial variation in runtime interaction behavior across the evaluated extensions. NordPass exhibited the broadest webpage matching scope with 13 match patterns, while Dashlane demonstrated the highest content-script deployment and injected JavaScript activity. In contrast, Bitwarden, Proton Pass, and RoboForm relied on comparatively smaller runtime interaction footprints.

These findings indicate that exposure is multidimensional and cannot be measured exclusively through permission counts. Although Bitwarden demonstrated

Table 4: Runtime Injection and Browser Interaction Exposure

Extension	Content Scripts	Injected JS	Match Patterns
Dashlane	6	8	9
NordPass	5	6	13
LastPass	4	4	7
Keeper	2	3	7
Bitwarden	2	2	4
Proton Pass	2	2	4
RoboForm	2	2	2

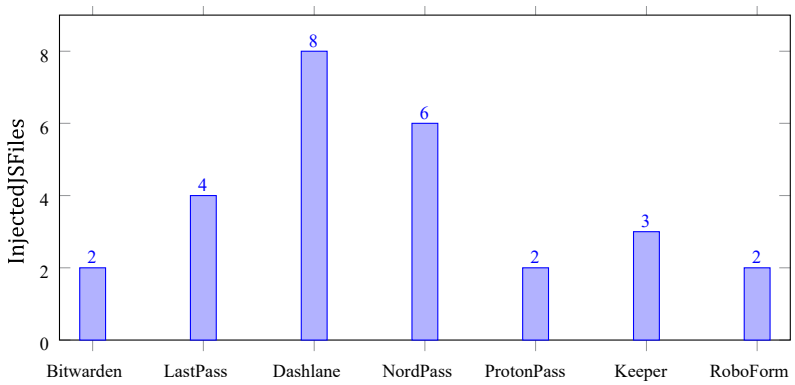


Figure 2: Injected JavaScript Exposure Across Seven Password Manager Extensions

The highest permission-related exposure index, Dashlane and NordPass exhibited considerably broader runtime interaction characteristics. Proton Pass showed relatively high permission exposure while maintaining a comparatively limited runtime interaction footprint. This observation suggests that different extensions rely on distinct architectural and browser-integration strategies within Chromium-based environments.

The results further support previous discussions regarding runtime browser interaction exposure and operational browser-side risks associated with browser extensions (Jin et al., 2024; K. Wang et al., 2022). Figure 2 visualizes the distribution of injected JavaScript activity across the evaluated extensions.

The expanded evaluation confirms that runtime exposure characteristics do not necessarily correlate with permission exposure levels. Extensions with moderate permission scores may still exhibit extensive runtime webpage interaction through content-script deployment and injected browser-side functionality.

Table 5: Sensitive Permission Exposure

Extension	Sensitive Permission Count
Bitwarden	11
Dashlane	9
LastPass	9
NordPass	8
Proton Pass	8
RoboForm	7
Keeper	7

6.3 Sensitive Permission Analysis

The analysis additionally evaluated the presence of sensitive browser permissions associated with browser monitoring, runtime interaction, scripting, clipboard access, and browser-session exposure. The evaluated permissions were identified through manifest analysis of the extracted browser-extension packages.

Table 5 summarizes the sensitive permission distribution across the evaluated extensions.

As shown in Table 5, Bitwarden demonstrated the highest number of sensitive permissions among the evaluated extensions. Dashlane and LastPass followed with nine sensitive permissions each, while NordPass and Proton Pass exposed eight sensitive permissions. RoboForm and Keeper exhibited the lowest counts among the evaluated extensions. The evaluated sensitive permissions included clipboard access, scripting capabilities, tab interaction, browser monitoring permissions, and runtime communication permissions.

The findings indicate that password manager extensions consistently rely on privileged browser interaction to support autofill operations, credential synchronization, runtime webpage integration, and browser-session management. However, elevated permission sensitivity may simultaneously increase operational attack-surface exposure and browser dependency during active execution.

Figure 3 illustrates the comparative distribution of sensitive browser permissions observed during the Chromium-based security analysis.

The expanded evaluation demonstrates that sensitive browser permissions are common across modern password-manager extensions. Although the absolute counts vary, all evaluated extensions required multiple permissions associated with browser interaction, scripting, or credential-related functionality, indicating that privileged browser access remains an inherent characteristic of browser-integrated password-management systems.

6.4 Browser-Side Storage Interaction Analysis

The experimental analysis further evaluated browser-side storage interaction behavior associated with password manager browser extensions extracted from Chromium-compatible CRX packages. The analysis focused on storage references, local storage interaction, IndexedDB usage, and browser-side persistence

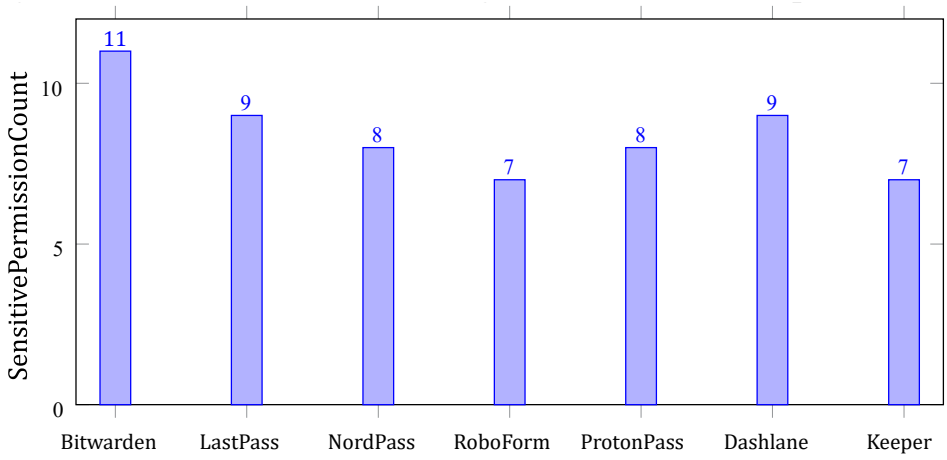


Figure 3: Sensitive Browser Permission Distribution Across Seven Password Manager Extensions

Table 6: Browser-Side Storage Interaction Analysis mechanisms identified within browser-extension operational components.

Extension	Storage	localStorage	sessionStorage	indexedDB	chrome.storage
Bitwarden	368	37	0	1	45
LastPass	207	175	16	16	10
Dashlane	565	60	39	36	41
NordPass	294	10	18	61	0
Proton Pass	260	36	0	12	0
Keeper	621	2	46	60	66
RoboForm	269	6	8	2	0

Table 6 summarizes the browser-side storage interaction characteristics observed during the experimental analysis.

Table 6 demonstrates substantial variation in browser-side storage interaction across the evaluated extensions. Keeper exhibited the highest overall storage-reference activity, while LastPass demonstrated the highest localStorage interaction frequency. NordPass showed the highest IndexedDB interaction activity, closely followed by Keeper. The results indicate that browser-integrated password managers employ substantially different persistence and browser-side storage architectures.

These observations indicate that password manager extensions rely on different browser-side persistence and storage strategies. Some extensions appear to emphasize browser-managed storage mechanisms, whereas others exhibit heavier reliance on local persistence references or IndexedDB-based interaction. The findings additionally suggest that browser interaction complexity differs substantially across browser-integrated password-manager architectures.

The results further support previous discussions regarding runtime exposure, browser-side operational interaction, and synchronization complexity in

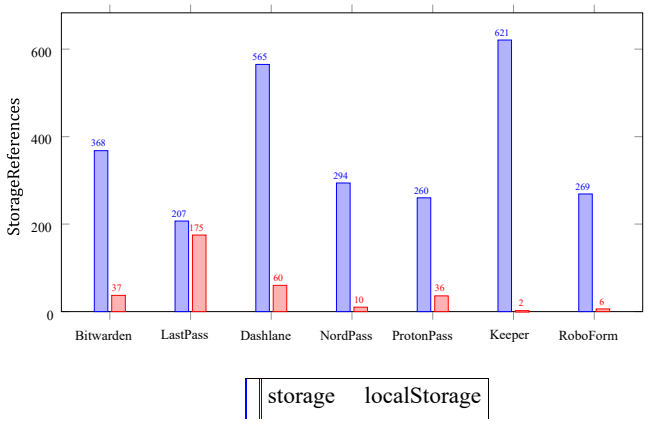


Figure 4: Browser-Side Storage Interaction Behavior Across Seven Password Manager Extensions

browser-centric authentication systems (Petronio & Child, 2020; Senna et al., 2020). Figure 4 presents the comparative browser-side storage interaction behavior across the evaluated extensions.

The expanded seven-extension evaluation reinforces the observation that browser-side storage behavior varies considerably across password-manager implementations. While some extensions demonstrate extensive storage interaction activity, others rely on more limited browser-side persistence footprints, highlighting architectural diversity in credential-management and synchronization strategies.

6.5 External Communication Exposure

The analysis additionally evaluated external communication complexity by identifying unique URL references associated with browser-extension operational interaction and synchronization behavior extracted from Chromium-based extension environments.

The results presented in Table 7 indicate substantial variation in external communication complexity across the evaluated extensions. RoboForm demonstrated the largest number of unique URL references, followed by Keeper, NordPass, and Dashlane. In contrast, Proton Pass exhibited the smallest number of external communication references. These findings suggest notable differences in synchronization architecture, external service integration, and operational.

Table 7 summarizes the external communication exposure characteristics identified during the security analysis.

Extension	Unique URLs Found
RoboForm	1065
Keeper	570
NordPass	507
Dashlane	445
Bitwarden	241
LastPass	235
Proton Pass	102

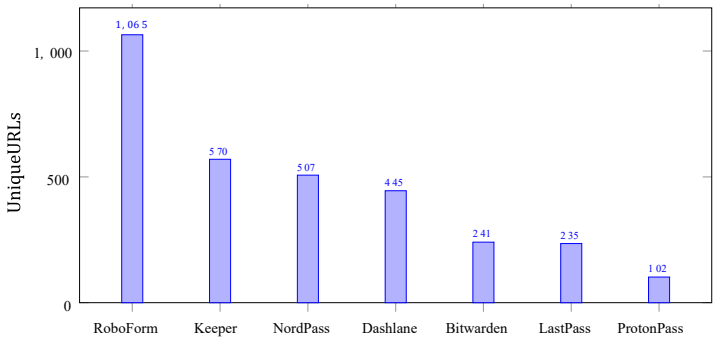


Figure 5: External Communication Exposure Across Seven Password Manager Extensions
interaction surfaces within browser-integrated environments.

The findings do not necessarily indicate insecure communication behavior. However, broader external interaction references may increase operational communication complexity and expand synchronization-related exposure pathways within browser ecosystems.

Figure 5 illustrates the comparative external communication exposure observed across the seven evaluated password manager browser extensions.

The expanded evaluation reveals that communication exposure varies considerably among password-manager implementations. Extensions with larger numbers of external communication references may rely on broader synchronization infrastructures, telemetry services, cloud integration components, or external authentication mechanisms. These observations further highlight the diversity of browser-extension operational architectures across modern passwordmanagement ecosystems.

6.6 Exploratory Correlation Analysis

The final stage of the experimental evaluation investigated exploratory operational relationships between permission exposure, runtime interaction behavior, browser-side storage interaction, and synchronization-related communication behavior within Chromium-based browser environments.

The exploratory correlation analysis was conducted using the operational metrics extracted from the evaluated browser extensions after CRX extraction and runtime security analysis procedures.

The exploratory analysis revealed a strong positive relationship between injected JavaScript activity and webpage interaction scope as measured through match patterns ($r = 0.802$). In addition, match-pattern coverage exhibited a strong positive relationship with IndexedDB interaction activity ($r = 0.824$). These observations suggest that extensions with broader runtime interaction behavior may also rely on more extensive browser-side storage mechanisms.

The analysis further identified a moderate positive relationship between the overall permission-risk score and the number of sensitive permissions ($r = 0.475$), indicating that extensions requesting broader permission sets tend to include larger numbers of security-sensitive browser capabilities. In contrast, only a very weak relationship was observed between the overall permission-risk score and external communication exposure ($r = 0.043$). This finding suggests that permission-related exposure and communication complexity represent distinct dimensions of operational security exposure and do not necessarily increase together.

The expanded seven-extension evaluation produced more stable exploratory observations than the initial smaller sample. Although the results remain exploratory, the larger extension set improves comparative coverage and reduces the influence of individual extension-specific behaviors on the reported trends.

Because the analysis was conducted on a limited number of evaluated extensions, the reported correlations should be interpreted as exploratory observations rather than statistically generalizable conclusions. Nevertheless, the findings provide useful insights regarding operational interaction trends and browser-centric exposure characteristics within password manager browser extensions.

7. Discussion

The findings of this study demonstrate that security exposure remains an important concern in browser-integrated password management systems despite the use of client-side encryption mechanisms. The experimental analysis revealed substantial differences in permission exposure, runtime interaction behavior, browser-side storage interaction, and external communication complexity across the evaluated password manager browser extensions. The findings additionally support the importance of evaluating password managers through multiple security dimensions rather than relying exclusively on cryptographic protection mechanisms. While encryption remains essential for protecting stored credentials, operational exposure can also emerge through browser permissions, runtime interaction behaviour, browser-side persistence mechanisms, and synchronizationrelated communication pathways.

The permission analysis demonstrated that several extensions require elevated browser privileges to support synchronization, autofill functionality, runtime credential handling, and browser integration operations. Bitwarden demonstrated the highest overall operational exposure index, followed by Keeper and RoboForm. NordPass exhibited the lowest overall exposure score among the evaluated extensions. These findings indicate noticeable differences in permissionrelated exposure across password-manager architectures. These findings are consistent with previous studies indicating that browser extensions frequently request permissions exceeding minimal operational requirements (Picazo-Sanchez et al., 2022). The results additionally support prior discussions regarding browser exposure and browser interaction risks associated with privileged browser extensions (K. Wang et al., 2022; Zahid et al., 2021).

However, the findings indicate that browser security behavior cannot be evaluated solely through permission counts. Although Bitwarden demonstrated the highest operational exposure index, it simultaneously exhibited relatively limited runtime interaction activity compared with Dashlane and NordPass. Conversely,

NordPass demonstrated broader webpage interaction behavior, while RoboForm exhibited the largest external communication footprint. Proton Pass displayed comparatively lower communication exposure despite maintaining a relatively high permission-risk score. These observations suggest that password manager browser extensions rely on substantially different integration and synchronization strategies within browser ecosystems. These observations suggest that password manager browser extensions rely on different integration strategies within browser ecosystems. Unlike previous studies that primarily focused on isolated permission analysis, malicious extension behavior, or browser vulnerability assessment (Picazo-Sanchez et al., 2022; K. Wang et al., 2022), the current analysis combines permission exposure, runtime interaction, browser-side storage behavior, and synchronization-related communication behavior within a unified operational evaluation framework.

The runtime injection analysis demonstrated that Dashlane and NordPass exhibited broader runtime webpage interaction compared with Bitwarden and LastPass. Previous studies highlighted that browser extensions may significantly influence browser behavior because of direct interaction with webpages, browser APIs, and runtime browser components (Jin et al., 2024; K. Wang et al., 2022). The current findings extend these observations by showing that interaction complexity differs substantially across password manager browser extensions.

The browser-side storage analysis additionally revealed substantial variation in persistence behavior and browser-side interaction mechanisms. The findings also highlight broader application-level security exposure considerations. Similar to other application ecosystems, browser-integrated password managers operate within complex software environments that involve persistent storage.

Table 8: Operational Exposure Observations and Security Implications

Observation	Potential Security Implication
High injected JavaScript activity	Increased runtime webpage interaction exposure and expanded DOM interaction surface
Large external URL references	Broader synchronization-related communication behavior and increased external interaction pathways
Elevated sensitive permissions	Increased privileged browser access and operational attack surface expansion
Extensive browser-side storage interaction	Increased persistence-related exposure and local operational dependency

external communication channels, user-interaction mechanisms, and privileged access to sensitive information. These operational characteristics may increase exposure pathways even when strong credential-protection mechanisms are deployed. Consequently, evaluating password-manager security requires consideration of both credential protection and application-level exposure behavior. Keeper demonstrated the highest overall storage interaction activity, while LastPass exhibited the highest localStorage interaction frequency among the evaluated extensions. NordPass demonstrated the highest IndexedDB interaction frequency, closely followed by Keeper. These observations suggest substantial architectural diversity in browser-side persistence and credential-management strategies. These observations suggest that password manager browser extensions rely on different browser-side persistence architectures and storage strategies.

The findings suggest that password manager extensions exhibit several interacting exposure characteristics rather than a single isolated behavior. To further support operational interpretation of the experimental findings, Table 8 summarizes several observed browser-extension behaviors together with their potential cybersecurity implications within browser-based authentication environments. Some extensions demonstrated higher permission sensitivity, while others demonstrated broader runtime interaction or synchronization-related communication behavior. This observation is important because many previous studies focused primarily on permission analysis, browser vulnerabilities, malware detection, or isolated browser-extension risks without integrating multiple runtime interaction dimensions within unified browser-centric evaluation environments (Picazo-Sanchez et al., 2022; Chalyi et al., 2025; K. Wang et al., 2022). The current study extends prior work by experimentally combining permission analysis, runtime interaction assessment, browser-side storage evaluation, and communication exposure analysis within a single operational cybersecurity framework.

The external communication analysis further demonstrated substantial differences in synchronization-related interaction complexity across the evaluated extensions. RoboForm demonstrated the largest number of external URL references, followed by Keeper, NordPass, and Dashlane. In contrast, Proton Pass exhibited the smallest external communication footprint among the evaluated extensions. Although these findings do not necessarily indicate insecure communication behavior, they suggest broader communication surfaces and increased synchronization-related interaction complexity within browser-integrated authentication environments. These differences may reflect architectural design variations involving cloud synchronization intensity, distributed credential management strategies,

telemetry integration mechanisms, and browser-session persistence behavior adopted by different password manager ecosystems.

The exploratory correlation analysis additionally revealed several important operational interaction trends. Injected JavaScript activity demonstrated a strong positive relationship with webpage interaction scope as measured through match patterns, while match-pattern coverage also exhibited a strong positive relationship with IndexedDB interaction activity. These observations suggest that extensions with broader runtime interaction behavior may simultaneously rely on more extensive browser-side persistence mechanisms.

The analysis further identified a moderate positive relationship between overall permission-risk scores and sensitive-permission counts, suggesting that extensions requesting broader permission sets often incorporate larger numbers of security-sensitive browser capabilities. However, only a very weak relationship was observed between permission-risk scores and external communication exposure. This observation indicates that permission-related exposure and communication complexity represent different operational characteristics and should be evaluated independently.

The expanded seven-extension evaluation strengthens the robustness of the comparative analysis by reducing the influence of individual extension-specific characteristics. The broader sample provides improved visibility into architectural differences among contemporary password-manager ecosystems and offers a more representative view of browser-centric exposure behavior.

The results additionally support previous studies emphasizing that browserside processing and runtime interaction may still introduce operational exposure despite the deployment of encryption mechanisms (X. Wang et al., 2021; Jubur et al., 2025). Although client-side encryption protects stored credentials, runtime credential handling, synchronization behavior, browser-session persistence, and privileged browser interaction remain important operational security considerations in browser-integrated authentication systems.

The findings suggest that encryption alone may not fully address exposure concerns within browser-integrated password management environments. Browser attack surface characteristics are additionally influenced by permission sensitivity, runtime interaction behavior, synchronization architecture, browserside persistence mechanisms, and communication complexity. This observation aligns with previous research discussing browser-side interaction risks and runtime browser exposure despite the presence of encryption mechanisms (X. Wang et al., 2021; Jubur et al., 2025), while the current work expands the analysis through a broader multidimensional operational evaluation perspective.

Overall, the study emphasizes the importance of structured cybersecurity evaluation for browser-based password manager extensions. The proposed multidimensional analysis framework supports comparative evaluation across browserintegrated authentication systems by combining permission exposure analysis, runtime interaction assessment, browser-side storage evaluation, synchronization exposure analysis, and exploratory correlation analysis within unified browser-centric security evaluation environments.

8. Limitations

This study has several limitations that should be considered when interpreting the findings and observations presented in the experimental analysis.

First, the evaluation focuses on seven widely used password manager browser extensions operating primarily within Chromium-based browser environments. Although the selected extensions represent a broader cross-section of widely used browser-integrated password managers, the analyzed sample size remains limited and therefore does not necessarily represent the entire browser extension ecosystem. Consequently, the reported operational relationships and exploratory interaction trends should not be interpreted as universally generalizable conclusions across all password manager architectures or browser platforms.

Second, the study emphasizes security exposure, browser interaction behavior, runtime credential handling, and attack surface analysis rather than formal cryptographic verification or cryptographic algorithm evaluation. The analysis therefore focuses on browser-centric exposure characteristics associated with browser permissions, synchronization behavior, runtime interaction, browserside persistence, and extension communication mechanisms. Existing literature similarly highlighted the importance of cybersecurity evaluation and runtime exposure analysis in modern browser-integrated environments (Picazo-Sanchez et al., 2022; X. Wang et al., 2021).

Third, the experimental evaluation primarily relies on static extension analysis and operational browser interaction assessment. The study does not attempt to exploit real-world zero-day vulnerabilities, compromise commercial password manager infrastructures, or perform offensive penetration testing against evaluated products. Consequently, dynamically triggered behaviors, environmentspecific runtime conditions, obfuscated execution paths, or browser interactions activated only

during real-world user activity may not be fully captured within the current experimental analysis. Similarly, the analysis does not directly intercept real user credentials or conduct malicious browser-session exploitation experiments. The goal of the study is therefore to evaluate exposure characteristics rather than demonstrate practical credential compromise scenarios.

Fourth, the runtime exposure analysis was conducted within controlled experimental environments and may not fully represent all real-world deployment conditions, enterprise authentication infrastructures, or organization-specific browser security policies. Browser permission models, synchronization architectures, browser APIs, and extension ecosystems continuously evolve over time, which may influence operational exposure behavior in future browser versions and extension releases.

Fifth, the exploratory correlation analysis was conducted using a limited number of evaluated extensions. Although the observed operational relationships provide useful insights regarding browser interaction complexity, synchronization behavior, and runtime exposure characteristics, the reported correlations should be interpreted as exploratory observations intended to highlight operational interaction tendencies rather than statistically generalizable causal relationships.

Finally, the study focuses specifically on browser-integrated password manager extensions and does not evaluate standalone desktop password managers, enterprise password governance systems, mobile password management environments, or cloud-native authentication infrastructures. Future work may therefore extend the proposed cybersecurity evaluation framework to broader authentication ecosystems and cross-platform password management environments.

9. Conclusion

This study presented a security and attack-surface analysis of password manager browser extensions operating within modern browser environments. The analysis focused on browser permissions, runtime credential handling, browser-session interaction, synchronization behavior, browser-side storage interaction, and external communication exposure associated with browser-integrated password management systems.

The experimental evaluation of seven widely used password manager browser extensions showed substantial differences across browser-related security characteristics. The findings showed that some extensions relied more heavily on privileged browser permissions, while others demonstrated broader runtime webpage interaction, synchronization-related communication behavior, operational browser attack surface expansion, or browser-side storage interaction behavior. The expanded evaluation additionally demonstrated that extensions exhibiting lower permission exposure may still present broader runtime interaction, storage interaction, or communication complexity, reinforcing the need for multidimensional security assessment.

The results additionally demonstrated that client-side encryption alone does not fully eliminate runtime security risks during active browser operation. Runtime credential processing, browser-session persistence, extension interaction, synchronization mechanisms, and browser integration remain important security considerations even when strong encryption mechanisms are deployed.

To support structured browser-centric evaluation, this study proposed a multidimensional security analysis framework integrating permission exposure analysis, runtime interaction evaluation, browser-side storage analysis, synchronization exposure assessment, and exploratory correlation analysis. The proposed framework supports comparative operational evaluation across multiple password manager browser extensions while emphasizing runtime exposure and attack surface expansion within browser-integrated authentication environments.

The expanded seven-extension evaluation improves the representativeness of the analysis and provides broader visibility into architectural differences among contemporary browser-based password-management ecosystems.

Overall, the study highlights the importance of evaluating password manager browser extensions from both cryptographic and browser-interaction perspectives. The findings further demonstrate the importance of multidimensional browser-security evaluation for understanding operational exposure characteristics in modern authentication environments.

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Awareness and behavior of Vitamin D among Students at Jazan University: Health Belief Model

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Abstract: Vitamin D deficiency remains a significant health issue, even in sunny regions such as Saudi Arabia, where sociocultural practices often limit adequate sun exposure. The study assessed awareness and behaviors related to vitamin D using the Health Belief Model (HBM). A cross-sectional descriptive study was conducted from October to December 2025 among 480 students selected using a stratified convenience sampling approach based on college type. Data were collected using an online self-administered questionnaire and analyzed using SPSS. The study revealed significant associations between several HBM constructs and socio-demographic variables. Perceived susceptibility was significantly associated with sex, whereas perceived severity was associated only with age. Perceived benefits were significantly associated with sex, age, and college type. Perceived barriers were significantly associated with age and college type, whereas cues to action were associated with sex, age, and college type. Multivariable logistic regression analysis showed that perceived benefits and perceived barriers were significant predictors of daily sun exposure, whereas perceived susceptibility, perceived severity, and cues to action were not. The findings highlight critical gaps in vitamin D-related awareness and practices among university students and emphasize the importance of theory-based health education interventions to promote healthy vitamin D-related behaviors. However, the use of a stratified convenience sampling approach and the cross-sectional design may have introduced selection bias and limited the generalizability of the findings to all university students.

Keywords: Vitamin D deficiency, Health Belief Model, Awareness and practices, Sun exposure, Saudi Arabia.

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1. Introduction

Vitamin D, a vital fat-soluble vitamin, is crucial for calcium and phosphorus balance, bone mineralization, and musculoskeletal health. Recent studies also suggest links between vitamin D levels and immune function and overall metabolic health. Despite abundant sunlight in many regions, vitamin D deficiency has become a widespread public health issue worldwide, affecting both developed and developing nations [1,2].

Paradoxically, vitamin D deficiency is highly prevalent in sunny countries, including the Kingdom of Saudi Arabia (KSA), where cultural practices, clothing norms, limited sun exposure, and lifestyle factors contribute to this pattern. Several studies have documented widespread vitamin D deficiency across age groups and demographic categories in Saudi Arabia, underscoring that living in a sunny climate does not guarantee adequate vitamin D status. Specifically, a recent retrospective analysis of more than 22,000 Saudi individuals found a high prevalence (67.3%) of vitamin D deficiency (<30 ng/mL), particularly among females and adolescents [3].

University students are particularly vulnerable to vitamin D deficiency due to lifestyle transitions, academic demands, reduced outdoor activities, and inconsistent health behaviors. A recent KAP study conducted in Qassim, Saudi Arabia, identified significant gaps in knowledge, attitudes, and practices related to vitamin D deficiency, highlighting persistent challenges in awareness and preventive behaviors among adults [1,4].

The Health Belief Model (HBM) is one of the most widely used theoretical frameworks for understanding and predicting health-related behaviors. It holds that individuals' engagement in preventive health behaviors is influenced by perceived susceptibility to a condition, perceived severity of its consequences, perceived benefits of action, perceived barriers to action, cues to action, and self-efficacy. Evidence from global nutrition behavior research suggests that HBM-based approaches can improve dietary knowledge and practices, including micronutrient intake and preventive nutritional behaviors [5].

Additionally, recent studies have shown that the HBM is useful for predicting nutrition-related behaviors, including the consumption of nutrient - rich foods, supporting its role in dietary and micronutrient research [6].

In Saudi Arabia, the Health Belief Model has rarely been used to assess awareness and behaviors related to vitamin D, particularly among university students. In the Jazan region, where sociocultural and lifestyle factors may further influence sun exposure and dietary habits, there is a significant lack of research on vitamin D awareness and practices, particularly within a theoretical framework. Therefore, the present study adopted a conceptual framework based on the Health Belief Model to illustrate the relationship between sociodemographic characteristics, HBM constructs, vitamin D–related knowledge, and preventive behaviors, including sun exposure, dietary intake, and vitamin D supplement use, among students at Jazan University (Figure 1).

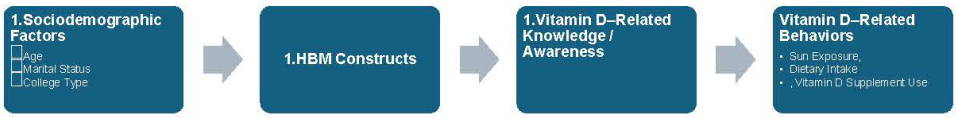


Figure 1: Conceptual framework illustrating the relationship between Health Belief Model construction and Vitamin D–Related Knowledge and Behaviors

Despite the growing importance of vitamin D–related health issues, there is still limited evidence from Saudi Arabia on studies that have applied the Health Belief Model (HBM) specifically to university students, indicating a gap in the current literature. Consequently, this study aims to apply the HBM to evaluate students' awareness and behaviors regarding vitamin D at Jazan University. Understanding these factors is crucial for designing effective, evidence-based health education programs that promote healthy vitamin D–related behaviors and improve long-term health outcomes among university students.

1.1 Research Questions

1. What is the level of awareness of vitamin D among students at Jazan University?
2. What are students' behaviors related to vitamin D (sun exposure, diet, and supplements)?
3. How do Health Belief Model factors influence students' vitamin D behaviors?
4. Is there a relationship between Health Belief Model factors and vitamin D awareness and practices?
5. Do vitamin D awareness and behaviors differ according to students' demographic characteristics

1.2 Research Hypotheses

- Health Belief Model (HBM) constructs, including perceived susceptibility, perceived severity, perceived benefits, perceived barriers, self-efficacy, and cues to action, are significantly associated with students' socio-demographic characteristics (sex, age, and college type).
- Health Belief Model (HBM) constructs are significantly associated with vitamin D-related preventive behaviors among Jazan University students.
- Health Belief Model (HBM) constructs significantly predict daily sun exposure behavior among university students.
- Students' awareness and vitamin D-related behaviors differ according to socio-demographic characteristics, including sex, age, and college type.
- Perceived benefits, perceived barriers, self-efficacy, and cues to action are associated with engagement in vitamin D-related health behaviors.

2. Materials and methods

2.1 Study Design

A cross-sectional, community-based descriptive study was conducted at Jazan University from October to December 2025 to assess awareness and behavior of Vitamin D using the HBM framework.

2.2 Sample Size

The sample size was calculated using Cochran's formula:

$$n0 = (Z^2 \times p \times (1-p)) / e^2$$

Where Z = 1.96 corresponds to a 95% confidence level, p = 0.5 represents the estimated population proportion, and e = 0.05 the margin of error. The minimum required sample size was calculated to be 384 participants. To enhance representativeness and compensate for potential non-response, 600 students were invited to participate. Of these, 480 students completed the questionnaire and were included in the final analysis, yielding a response rate of 80%.

The study population was divided into two strata: health-related colleges and non-health-related colleges. To ensure adequate representation of both groups, two university complexes were selected from the four main complexes at Jazan University: the Health Colleges Complex, representing health-related colleges, and the Academic Complex, representing non-health-related colleges. The total number of students in the selected strata was 9,528, including 5,266 students from health-related colleges and 4,262 students from non-health-related colleges. Proportional allocation was used to determine the sample size for each stratum. Accordingly, of the total sample size of 480 students, 265 were selected from health-related colleges and 215 from non-health-related colleges.

Participants were recruited using a convenience sampling technique within each group. With the assistance of student leaders, the electronic questionnaire was distributed online to students through various platforms. Participation was voluntary, and only students who completed the questionnaire were included in the final analysis.

3. Method of data collection

A self-administered standardized questionnaire was built based on relevant literature, including previous studies on vitamin D among Saudi university [1,4,7]. The questionnaire was initially designed in English, then translated into Arabic, and back-translated into English by independent specialists to ensure the reliability of the language and concepts. Content validity was assessed by three academic experts in public health, who reviewed the questionnaire for relevance, clarity, and comprehensiveness.

A pilot study was conducted among 48 participants to evaluate the clarity, accuracy and reliability of the questionnaire. Minor modifications included rephrasing unclear questions and improving the sequence of items for better comprehension. Internal consistency was assessed using Cronbach's alpha, which demonstrated acceptable reliability, with a value of 0.70.

3.1 The questionnaire consisted of four sections:

The first section provided information about the study's objectives, data confidentiality, and voluntary participation with electronic consent obtained by selecting "Agree" to continue. The second section gathered sociodemographic data, such as sex, age, and college type. The third section assessed participants' knowledge of vitamin D, including deficiency symptoms, health effects, dietary sources, and sunlight exposure. The fourth section assessed health beliefs about vitamin D deficiency using the constructs of the Health Belief Model. It included six domains measured on a 5-point Likert scale. Perceived susceptibility assessed risk perception (e.g., "I am at risk of vitamin D deficiency"). Perceived severity evaluated awareness of health consequences (e.g., "Vitamin D deficiency can cause serious health problems"). Perceived benefits measured beliefs about the advantages of preventive actions (e.g., "Sun exposure helps prevent vitamin D deficiency"). Perceived barriers identified obstacles to healthy behaviors (e.g., "Lack of time limits my sun exposure"). Cues to action assessed motivating factors (e.g., "Doctors' advice encourages me to take vitamin D"). Self-efficacy measured confidence in performing preventive behaviors (e.g., "I can maintain adequate sun exposure or take supplements").

4. Method of data analysis

Data were entered into Microsoft Excel and then analyzed using IBM SPSS version 29. Descriptive statistics, including frequencies and percentages, were computed and reported. A chi-square test examined associations between students' sociodemographic characteristics and HBM constraints related to vitamin D. In contrast, logistic regression was used to analyze HBM factors associated with daily sun exposure. A p-value < 0.05 was considered statistically significant.

5. Results

5.1 Socio-demographic characteristics of the participants

Out of the 600 individuals in the targeted sample, 480 responded to the survey, resulting in a response rate of 80%. The study presents the socio-demographic characteristics of the participants. The sample had a slightly higher proportion of females (57%) compared to males (43%). The age distribution was mainly between 18 and 20 years (40%), followed by 20–22 years (31%), 22–24 years (20%), and 24 years or older (9%). Regarding college type, (54%) were enrolled in health colleges, while the remaining (46%)belonged to non-health colleges (Table 1).

Table 1. Socio-demographic characteristics of the participants (n = 480)

Variable	Frequency (n)	Percentage (%)
Sex		
Female	274	57
Male	206	43
Age (years)		
18–20	192	40
20–22	149	31
22–24	96	20
≥24	43	9
College type		
Health college	265	55
Non-health college	215	45

5.2 Association between socio-demographic variables and Health Belief Model (HBM) constructs related to vitamin D deficiency.

This study summarizes associations between socio-demographic variables and Health Belief Model (HBM) constructs related to vitamin D deficiency. Perceived susceptibility was significantly associated only with sex (χ^2 = 17.738, p=0.001) and age (χ^2 = 11.660, p=0.02), but not with college type. Perceived severity was significantly associated with age (χ^2 = 9.480,p=0.049) but not with sex or college type. Perceived benefits were significantly associated with sex (χ^2 = 15.507,p=0.004), age (χ^2 = 11.134,p=0.025), and college type

(χ^2 = 14.796,p=0.005). Perceived barriers were significantly associated with age (χ^2 = 13.266,p=0.01) and college type (χ^2 = 9.481,p=0.05)but not with sex. Self-efficacy were significantly associated with sex(χ^2 = 5.992,p=0.023), age (χ^2 = 9.480,p=0.049)and college type (χ^2 = 12.210,p=0.014) Lastly, cues to action were associated with all three sociodemographic variables: sex (χ^2 = 18.358,p=0.001), age (χ^2 = 14.860,p=0.005), and college type (χ^2 = 24.837,p= 0.001) (Table 2).

Table 2. Association between socio-demographic variables and Health Belief Model (HBM) constructs related to vitamin D deficiency

HBM construct	Sex χ^2 (p-value)	Age χ^2 (p-value)	College type χ^2 (p-value)
Perceived susceptibility	17.738 (p=0.001)	11.660 (p=0.021)	0.307 (p=0.984)
Perceived severity	3.757 (p=0.153)	9.480(p=0.049)	6.851(p=0.121)
Perceived benefits	15.507 (p=0.004)	11.134 (p=0.025)	14.796 (p=0.005)
Perceived barriers	0.207 (p=0.995)	13.266 (p=0.011)	9.481 (p=0.05)
Self-efficacy	5.992 (p=0.023)	9.480 (p=0.049)	12.210 (p=0.014)
Cue to action	18.358 (p=0.001)	14.860(p=0.005)	24.837 (p= 0.001)

5.3 Multivariable logistic regression analysis of HBM factors associated with daily sun exposure (10–15 minutes)

Multivariable logistic regression analysis was used to examine associations between Health Belief Model (HBM) constructs and daily sun exposure. The logistic regression model showed a good fit according to the Hosmer–Lemeshow test (p = 0.2454). Results indicated that Perceived Benefit was a significant associated with odds of daily sun exposure (AOR = 0.28, 95% CI: 0.08–0.92, p = 0.036). Similarly, Perceived Barriers were significantly associated with low odds of sun exposure (AOR = 0.12, 95% CI: 0.02–0.64, p = 0.014) and self-efficacy was significantly associated with daily sun exposure (AOR = 0.25, 95% CI: 0.04–0.51, p = 0.024). In contrast, Perceived Susceptibility was not significantly associated (AOR = 0.60, 95% CI: 0.16–2.31, p = 0.461). Similarly, Perceived Severity did not show statistically significant (AOR = 0.66, 95% CI: 0.17–2.45, p = 0.415). Finally, Cue to Action was also not significantly associated with daily sun exposure (AOR = 0.30, 95% CI: 0.04–2.48, p = 0.262) (Table 3).

Table 3 Multivariable logistic regression analysis of HBM factors associated with daily sun exposure (10–15 minutes)

HBM Construct	Adjusted OR (AOR)	95% CI	p-value
Perceived Susceptibility	0.60	0.16–2.31	0.461
Perceived Severity	0.66	0.17–2.45	0.415
Perceived Benefit	0.28	0.08–0.92	0.036
Perceived Barriers	0.12	0.02–0.64	0.014
Self-efficacy	0.25	0.04-0.51	0.024
Cue to Action	0.30	0.04 -2.48	0.262

6. Discussion

This investigation used the Health Belief Model (HBM) to assess awareness and practices related to vitamin D among students at Jazan University. The socio-demographic profile indicated a relatively balanced distribution by sex(53% females,47% males)and college type(51% from health colleges, 49% from non- health colleges), with the majority of participants aged 18–22 years. This age group is a critical period for preventive health behaviors because of lifestyle transitions and increasing independence in health decision-making [7,8].

The results showed significant associations between socio-demographic factors and HBM constructs. Perceived susceptibility was significantly associated only with sex and age, but not with college type. These results indicated that age and gender play a greater role than academic discipline in awareness of vitamin D deficiency risks. For instance, younger or female students may feel more susceptible, possibly due to differences in lifestyle, health awareness, or sociocultural factors, whereas academic discipline alone does not. These findings align with previous studies that reported higher perceived susceptibility among females and younger participants [7,8,9,10,11]. The study found that perceived severity was associated with age but not with sex or college type. Older students perceived vitamin D deficiency as a more serious health issue, which may reflect accumulated health knowledge or awareness of long-term consequences such as musculoskeletal disorders and osteoporosis. These findings are consistent with [7,8], who reported that older individuals tend to recognize the potential seriousness of vitamin D deficiency more than younger individuals [12].

These perceptions may be attributed to greater exposure to health education, increased personal experience with health-related information, and a better understanding of the long-term risks associated with vitamin D deficiency [13].

Perceived benefits were significantly associated with sex, age, and college type. Females, older students, and participants enrolled in health colleges were more likely to recognize the benefits of sun exposure and vitamin D supplementation. This pattern may be explained by differences in health education and the perceived value of health-related information, as individuals with greater formal training in health-related topics are more likely to understand the preventive role of vitamin D supplementation and adequate sun exposure. These results are consistent with previous studies, which reported that individuals with higher health literacy are more likely to adopt preventive behaviors [14,15,16,17].

Perceived barriers showed significant associations with age and college type. These barriers were more prevalent among older students and those in non-health colleges. In this study, the most frequently reported barriers were cultural clothing practices, hot climate, academic workload, and concerns about skin damage from sun exposure. These barriers have also been reported in previous studies [9], and have been consistently documented in Saudi and regional studies, indicating that awareness alone does not guarantee behavioral change [7]. Elamin et al. (2025) reported that health college students showed greater knowledge and awareness than their non-health peers ($p < 0.05$)[18].

In the present study, self-efficacy was significantly associated with all socio-demographic variables (sex, age, and college type), indicating that students' confidence in performing sun-exposure behaviors varies across demographic groups. This suggests that self-efficacy is influenced by personal and contextual factors such as educational background and exposure to health-related information. Similar findings have been reported in previous studies, highlighting the role of health education and awareness in shaping self-efficacy and preventive health behaviors [13,15].

Cues to action were significantly associated with all sociodemographic variables, such as sex, age, and college type. Female students, older students, and those enrolled in health colleges were more likely to receive vitamin D prompts from healthcare providers, peers, or the media. However, consistent with findings from [16,19], the impact of these external cues may be limited if the perceived barriers identified earlier are not addressed. This emphasizes the importance of combining cues to action with strategies that reduce barriers to ensure effective behavioral change [13,20].

Multivariable logistic regression was used to examine associations between Health Belief Model (HBM) constructs and daily sun exposure. Results showed that perceived benefits and perceived barriers were predictors of daily sun exposure, whereas perceived susceptibility, severity, and cues to action were not. These findings underscore the importance of emphasizing the tangible benefits of sun exposure and supplementation while addressing barriers to behavior change, consistent with prior research in Saudi Arabia and other regions [14,15,16,18].

The present study has several limitations that should be considered when interpreting the findings. The use of convenience sampling and online data collection may have introduced selection bias, as participation was limited to students who were accessible and willing to complete the electronic questionnaire. In addition, volunteer bias may have occurred, as students with greater interest or awareness of vitamin D may have been more likely to participate. The use of a self-administered questionnaire may also introduce self-report bias, including recall and social desirability bias, which could affect the accuracy of responses. Finally, the absence of important confounding variables such as marital status, parity, and thyroid disorders may have limited the ability to fully control for factors influencing vitamin D-related behaviors.

7. Recommendation

The study recommends strengthening targeted health education programs on vitamin D, with special focus on non-health colleges, males, and younger students. Interventions should emphasize the benefits of sun exposure while addressing key barriers such as academic workload and fear of sun exposure.

Programs should also aim to enhance self-efficacy and reduce perceived barriers through practical, behavior-focused strategies. In addition, universities should increase cues to action using digital media and campus-based awareness campaigns.

Future research should include additional factors such as marital status, parity, and thyroid disorders to understand determinants of vitamin D status.

8. Conclusion

This study confirmed that the Health Belief Model effectively explains students' awareness and behaviors concerning vitamin D at Jazan University. While many students recognized vitamin D deficiency and its health consequences, this awareness did not always lead to appropriate preventive measures, particularly regular sun exposure. Perceived benefits and perceived barriers were the strongest predictors of behavior, whereas perceived susceptibility, perceived severity, and cues to action alone were insufficient to motivate behavioral change.

These findings highlight the need for theory-based health education programs that strengthen perceived benefits and reduce practical and psychological barriers to healthy behaviors. Interventions should particularly target younger students and those in non-health colleges, and provide clear, practical guidance on safe sun exposure and vitamin D supplementation. Integrating vitamin D education into university health programs may help bridge the knowledge- practice gap.

8.1 Ethical approval

The local Research Ethics Committee at Jazan University approved this study (Reference No: REC-47/06/1669). In accordance with the Helsinki Declaration, informed consent was obtained electronically before participation. Data were collected anonymously without personal identifiers, stored securely, and used only for research purposes. All data will be retained for five years, and then permanently deleted.

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Weighted Composition Operators on Bloch-Type Spaces in Infinite-Dimensional Hilbert Spaces: Norms and Dynamics

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Abstract
We study weighted composition operators (WCO) on Bloch-type spaces (BTS) defined over bounded domains in infinite-dimensional complex Hilbert spaces, extending classical results from the unit disk and finite-dimensional unit ball. Necessary and sufficient conditions are obtained for their boundedness and compactness in terms of the inducing map and the weight function. Explicit estimates for the operator norm and asymptotic formulas for the essential norm are derived via boundary limsup expressions. Finally, we analyze the dynamical behavior of iterations and establish conditions ensuring convergence to zero in the operator norm. These results unify and generalize known theorems in both finite- and infinite-dimensional settings and provide a framework for further investigations.

Keywords: Bloch-type spaces; weighted composition operators; Hilbert spaces; essential norm; compact operators; operator dynamics

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1. Introduction

Composition operators and (WCO) have been extensively studied on classical spaces of analytic functions such as Hardy (see [1-3]), Bergman (see [4-5]), and Bloch spaces (see [6-9]). Bloch spaces have attracted considerable attention due to their close connection with hyperbolic geometry and operator theory. In several complex variables, (BTS) have been investigated on domains such as the unit ball and the polydisk, where boundedness and compactness of (WCO)are typically characterized via boundary behavior and derivative growth conditions (see [10-14, 15-19]). In the infinite-dimensional setting, [20, 21] introduced BTS on the unit ball of a complex Hilbert space and established foundational results. Additional developments can be found in references [22-25]. Recently, there has been growing interest in (WCO)between BTS and other function spaces in Banach and Hilbert spaces (see [26-28, 16-18]). However, a unified treatment addressing boundedness, compactness, essential norm estimates, and dynamical behavior simultaneously in both finite- and infinite-dimensional settings is still lacking. The aim of this paper is to provide such a framework. The organization of this paper is as follows: Section 1 is the introduction to the investigation. Preliminaries are given in Section 2. The main results are described in Section 3. Finally, Section 4 is conclusion of the paper.

2. Preliminaries

- **Definition (2.1):**

Let H be a complex Hilbert space, and let D⊂H be a bounded domain. The main example to keep in mind is the open unit ball.

$$\boldsymbol{B_H} = \{\boldsymbol{z} \in \boldsymbol{H}: \| \boldsymbol{z} \| < 1\} \tag{2.1}$$

Denote by H(D) the space of all holomorphic (Fréchet-analytic) functions f:D→C. For f∈H(D)and z∈D, we write Df(z)for the Fréchet derivative of fat z, which is a bounded linear functional on H; its operator norm is denoted by ‖Df(z)‖.

- **Definition (2.2):**

The Bloch space B(D) consists of all holomorphic functions f∈H(D)such that

$$\boldsymbol{\beta(f)} = \sup_{\boldsymbol{z}\in\boldsymbol{D}} \boldsymbol{\delta(z)} \parallel \boldsymbol{Df(z)} \parallel < \infty \tag{2.2}$$

where δ(z) is a fixed boundary distance function on D(for instance, δ(z)=1-‖z‖ when D=B_H). The Bloch norm is defined by

$$\| \boldsymbol{f} \|_{\boldsymbol{\mathcal{B}(D)}} = | \boldsymbol{f(0)} | + \boldsymbol{\beta(f)} \tag{2.3}$$

Remark. The quantity β(f) is the Bloch seminorm and measures the growth of f near the boundary ∂D.

- **Definition (2.3):**

The little Bloch space B_0(D) is defined by

$$\boldsymbol{B_0(D)} = \{\boldsymbol{f} \in \boldsymbol{\mathcal{B}(D)}: \boldsymbol{\delta(z)} \parallel \boldsymbol{Df(z)} \parallel \to \boldsymbol{0} \text{ as } \boldsymbol{z} \to \boldsymbol{\partial D}\} \tag{2.4}$$

- **Definition (2.4):**

To work in a more general setting, we introduce BTS defined via a continuous weight function.

Let μ:D→(0,∞)be a continuous weight. We define the Bloch-type space $B_μ$(D)be a continuous weight. We define the Bloch-type space by

$$\mathbf{B}_{\boldsymbol{\mu}}(\boldsymbol{D}) = \left\{\boldsymbol{f} \in \boldsymbol{H(D)}: \| \boldsymbol{f} \|_{\boldsymbol{\mathcal{B}_\mu(D)}} := | \boldsymbol{f(0)} | + \sup_{\boldsymbol{z}\in\boldsymbol{D}} \boldsymbol{\mu(z)} \parallel \boldsymbol{Df(z)} \parallel < \infty\right\} \tag{2.5}$$

We assume throughout that μ is a normal weight in the sense that:

$$\boldsymbol{\mu(z)} \to \boldsymbol{0} \text{as } \boldsymbol{z} \to \boldsymbol{\partial D} \tag{2.6}$$

μ(z) is comparable to a boundary distance function; for example, on the Hilbert ball B_H,

$$\boldsymbol{c_1}(\boldsymbol{1} - \| \boldsymbol{z} \|) \le \boldsymbol{\mu(z)} \le \boldsymbol{c_2}(\boldsymbol{1} - \| \boldsymbol{z} \|) \tag{2.7}$$

for some constants c_1,c_2>0.

The associated little Bloch-type space is

$$\boldsymbol{\mathcal{B}_{\mu,0}(D)} = \{\boldsymbol{f} \in \boldsymbol{\mathcal{B}_\mu(D)}: \boldsymbol{\mu(z)} \parallel \boldsymbol{Df(z)} \parallel \to \boldsymbol{0} \text{ as } \boldsymbol{z} \to \boldsymbol{\partial D}\}.$$

3. Main Results

In this section, we study WCO on BTS in a Hilbert space.

Let D⊂H be a bounded domain in a complex Hilbert space H. Let φ:D→D be an analytic self-map (the symbol of the composition operator) and let ψ∈H(D) be an analytic weight function. We define the weighted composition operator

$$W_{\psi,\varphi}: H(D) \to H(D), W_{\psi,\varphi} f = \psi \cdot (f \circ \varphi) \tag{3.1}$$

This boundedness criterion extends and unifies several known results on WCO between BTS in the disk, the unit ball, and more general Banach-space balls; see [10, 11, 13, 14, 16-19, 25-28].

3.1 Theorem (Boundedness)

Let D be a bounded domain in a complex Banach space (in particular, a complex Hilbert space), and let $B_μ$ (D)be the BTS associated to a normal weight μ. Let φ:D→D and ψ∈H(D) be analytic Assume that there exists a family of test functions $\{f_a\}_{a\in D}$⊂$B_μ$(D) satisfying.

$$\sup_{a\in D} \| f_a \|_{B_{\mu(D)}} < \infty, \tag{T1}$$

$$\mu(a) \| Df_a(a) \| \ge c_0 > 0, \tag{T2}$$

and

$f_a \to 0$ locally uniformly as $a \to \partial D$ (T3)

Then the WCO $W_{\psi,\varphi}: B_\mu(D) \to B_\mu(D)$ is bounded if and only if the following two conditions hold:

$$\sup_{z\in D} \mu(z) \, \| D\psi(z) \| < \infty \quad (C1) \tag{3.2}$$

$$\sup_{z\in D} \frac{\mu(z)}{\mu(\varphi(z))} \, |\psi(z)| \, \| D\varphi(z) \| < \infty \quad (C2) \tag{3.3}$$

Proof.

Assume first that conditions (C1) and (C2) hold. Let $f \in B_\mu(D)$. By the product rule and the chain rule for Fréchet derivatives,

$$D(W_{\psi,\varphi} f)(z) = D\psi(z)\, f(\varphi(z)) + \psi(z)\, (Df)(\varphi(z)) \circ D\varphi(z). \tag{3.4}$$

Taking norms and multiplying by $\mu(z)$, we get

$$\mu(z) \, \|D(W_{\psi,\varphi} f)(z)\| \le \mu(z) \, \|D\psi(z)\| \, |f(\varphi(z))| + \mu(z) \, |\psi(z)| \, \|D\varphi(z)\| \, \|Df(\varphi(z))\|. \tag{3.5}$$

We now estimate the first term.Since point evaluations are bounded on for each $w \in D$ the evaluation functional $\delta_w(f) = f(w)$ is bounded. Hence there exists a constant $C_1 > 0$, depending only on D and μ, such that

$$| f(\varphi(z)) | \le C_1 \, \| f \|_{B_\mu(D)}, z \in D. \tag{3,6}$$

Therefore,

$$\mu(z) \, \|D\psi(z)\| \, |f(\varphi(z))| \le C_1 \, \mu(z) \, \|D\psi(z)\| \, \|f\|_{B_\mu(D)}. \tag{3,7}$$

For the second term, the definition of the Bloch-type norm implies

$$\mu(\varphi(z)) \, \|Df(\varphi(z))\| \le \|f\|_{B_\mu(D)},$$

Thus,

$$\mu(z) \, |\psi(z)| \, \|D\varphi(z)\| \, \|Df(\varphi(z))\| \le \frac{\mu(z)}{\mu(\varphi(z))} \, |\psi(z)| \, \|D\varphi(z)\| \, \|f\|_{B_\mu(D)}.$$

Combining this with (3.5), we obtain

$$\mu(z) \, \|D(W_{\psi,\varphi} f)(z)\| \le \left(C_1 \, \mu(z) \, \|D\psi(z)\| + \frac{\mu(z)}{\mu(\varphi(z))} \, |\psi(z)| \, \|D\varphi(z)\| \right) \|f\|_{B_\mu(D)}.$$

Taking the supremum over $z \in D$ and using assumptions (C1) and (C2) yields

$$\sup_{z\in D} \mu(z) \, \|D(W_{\psi,\varphi} f)(z)\| \le C \, \|f\|_{B_\mu(D)} \tag{3,8}$$

for some constant $C > 0$. Moreover, The zeroth-order term satisfies

$$|W_{\psi,\varphi} f(0)| = |\psi(0)| \, |f(\varphi(0))| \le C' \|f\|_{B_\mu(D)}$$

Hence

$$\|W_{\psi,\varphi} f\|_{B_\mu(D)} \le C'' \|f\|_{B_\mu(D)}$$

so $W_{\psi,\varphi}$ is bounded.

Now assume that $W_{\psi,\varphi}$ is bounded on $B_\mu(D)$. We prove the necessity of (C1) and (C2).

First, taking $f \equiv 1$, we have

$$W_{\psi,\varphi}(1) = \psi.$$

Since $W_{\psi,\varphi}$ maps $B_\mu(D)$ into itself, it follows that $\psi \in B_\mu(D)$, and therefore

$$\sup_{z\in D} \mu(z) \, \|D\psi(z)\| < \infty.$$

This gives (C1).

To prove (C2), let $z \in D$ and set $a = \varphi(z)$. By the test-function hypothesis, choose $f_a \in B_\mu(D)$ satisfying (T1)-(T3). Since $W_{\psi,\varphi}$ is bounded,

$$\mu(z) \, \| D(W_{\psi,\varphi} f_a)(z) \| \le C.$$

Using

$$D(W_{\psi,\varphi} f_a)(z) = D\psi(z)\, f_a(\varphi(z)) + \psi(z)\, (Df_a)(\varphi(z)) \circ D\varphi(z),$$

we obtain

$$\mu(z) \, | \psi(z) | \, \| (Df_a)(\varphi(z)) \circ D\varphi(z) \| \le C + \mu(z) \, \| D\psi(z) \| \, | f_a(\varphi(z)) |.$$

By (C1) and boundedness of point evaluations, the right-hand side is uniformly bounded. Since $a = \varphi(z)$, condition (T2) gives

$$\mu(\varphi(z)) \, \| Df_{\varphi(z)}(\varphi(z)) \| \ge c_0.$$

Hence

$$\frac{\mu(z)}{\mu(\varphi(z))} \, | \psi(z) | \, \| D\varphi(z) \| \le C',$$

uniformly in $z \in D$. Thus (C2) holds.

Therefore, $W_{\psi,\varphi}$ is bounded on $B_\mu(D)$ if and only if (C1) and (C2) hold.

3.2 Theorem (Compactness)

With the same assumptions and notations as in Theorem 3.1, consider the little Bloch-type space $B_{\mu,0}(D)$. Then $W_{\psi,\varphi}: B_{\mu,0}(D) \to B_{\mu,0}(D)$ is compact if and only if

$$\lim_{z\to\partial D} \mu(z) \, \| D\psi(z) \| = 0 \tag{3.9}$$

$$\lim_{z\to\partial D} \frac{\mu(z)}{\mu(\varphi(z))} \, \| \psi(z) D\varphi(z) \| = 0 \tag{3.10}$$

Proof

Assume first that $W_{\psi,\varphi}$ is compact. Let $(z_n)\subset D$ be any sequence with $z_n\to\partial D$. Since μ is a normal weight, we can choose a bounded sequence $(f_n)\subset B_{\mu,0}(D)$ such that $f_n\to 0$ locally uniformly in D and

$$\|f_n\|_{B_\mu(D)} \le 1, \mu(z_n)\|Df_n(z_n)\| \ge c > 0$$

for some constant $c>0$. Compactness implies

$$\|W_{\psi,\varphi}f_n\|_{B_\mu(D)} \to 0.$$

Using

$$D(W\psi,\varphi fn)(z) = D\psi(z)fn(\varphi(z)) + \psi(z)(Dfn)(\varphi(z))\circ D\varphi(z)$$

and evaluating near the boundary, we obtain that both boundary quantities in (3.9) and (3.10) must vanish; otherwise the derivative norm of $W_{\psi,\varphi}$ f_n would not tend to zero.

Conversely, assume (3.9) and (3.10).

By the standard sequential characterization of compact operators on $B_{\mu,0}(D)$ it suffices to show that every bounded sequence in $B_{\mu,0}(D)$ converging to zero locally uniformly is mapped to a sequence converging to zero in norm.

Let (f) be a bounded sequence in $B_{\mu,0}(D)$ converging locally uniformly to 0

On the compact set D \ U local uniform convergence implies uniform convergence of f_n to zero. By Cauchy estimates for Fréchet-holomorphic functions, the derivatives Df_n also converge uniformly to zero on compact subsets of D

Let (f_n)be a bounded sequence in $B_{(\mu,0)}(D)$ converging locally uniformly to. Fix $\varepsilon>0$. Since (3.9) and (3.10) hold, there exists a neighborhood U of ∂D such that for all $z\in U$,

$$\mu(z)\|D\psi(z)\| < \varepsilon, \frac{\mu(z)}{\mu(\varphi(z))}|\psi(z)|\|D\varphi(z)\| < \varepsilon.$$

On the compact set , local uniform convergence implies that and uniformly. Hence the derivative formula yields

$$\|W_{\psi,\varphi}f_n\|_{B_\mu(D)} \to 0.$$

Therefore $W_{\psi,\varphi}$ is compact

3.3 Proposition (Operator norm estimate

Under the assumptions of Theorem 3.1, there exists a constant $C>0$, depending only on the geometry of D and the weight μ, such that

$$\| W_{\psi,\varphi} \| \le C(|\psi(0)| + \sup_{z\in D}\mu(z) \| D\psi(z) \| + \sup_{z\in D}\frac{\mu(z)}{\mu(\varphi(z))} \| \psi(z)\, D\varphi(z) \|) \tag{3.11}$$

Proof

Let $f\in B_\mu$ (D). From the proof of Theorem 3.1 we already have

$$|W_{\psi,\varphi}f(0)| \le C_0|\psi(0)|\|f\|_{B_\mu(D)}$$

and

$$\sup_{z\in D}\mu(z)\|D(W_{\psi,\varphi}f)(z)\| \le C_1\left(\sup_{z\in D}\mu(z)\|D\psi(z)\| + \sup_{z\in D}\frac{\mu(z)}{\mu(\varphi(z))}|\psi(z)|\|D\varphi(z)\|\right)\|f\|_{B_\mu(D)}$$

Combining these estimates gives

$$\|W_{\psi,\varphi}f\|_{B_\mu(D)} \le C\left(|\psi(0)| + \sup_{z\in D}\mu(z)\|D\psi(z)\| + \sup_{z\in D}\frac{\mu(z)}{\mu(\varphi(z))}|\psi(z)|\|D\varphi(z)\|\right)\|f\|_{B_\mu(D)}.$$

Taking the supremum over all $\|f\|_{B\mu(D)}\le 1$ yields (3.11).

The dependence of comes only from the boundedness of point evaluations on $B_\mu(D)$ and from the comparability constants in the normality of μ .

3.4 Proposition (Essential norm estimate)

Let D,μ,ψ,φ be as above and assume that $W_{\psi,\varphi}$ is bounded on $B_\mu(D)$. Then the essential norm of $W_{\psi,\varphi}$ satisfies

$$\| W_{\psi,\varphi} \|_e \asymp \limsup_{z\to\partial D}\mu(z) \| D\psi(z) \| + \limsup_{z\to\partial D}\frac{\mu(z)}{\mu(\varphi(z))} \| \psi(z)\, D\varphi(z) \| \tag{3.12}$$

In particular, for the unit ball of a Hilbert space equipped with the standard Bloch weight, the essential norm is governed entirely by the boundary behavior of ψ and φ.

Here, the notation $\asymp$ means that there exist positive constants c and C, depending only on the domain D and the normal weight μ, c $A\le\|W_{\psi,\varphi}\|_e\le C$ A,

Proof

For the lower bound, let K be any compact operator on $B_\mu(D)$. Choose a bounded sequence $(f_n)\subset B_{\mu,0}(D)$ converging locally uniformly to 0, with derivatives concentrating near boundary points $z_n\to\partial D$. Since $Kf_n\to 0$, we get

$$\| W_{\psi,\varphi} - K \| \ge \limsup_{n\to\infty} \| (W_{\psi,\varphi} - K)f_n \| = \limsup_{n\to\infty} \| W_{\psi,\varphi}f_n \|.$$

By the derivative formula, the right-hand side dominates the boundary limsup terms in (3.12). This yields the lower estimate.

For the upper bound, we construct compact approximants K_r by cutting off the operator

near the boundary. Let χ_r be a smooth radial cutoff satisfying $\chi_r(z)=1$ on a smaller subdomain and $\chi_r(z)=0$ near ∂D. Define

$$K_r f := \chi_r \cdot W_{\psi,\varphi} f.$$

Since the support of χ_r is contained in a compact subset of D, the operator K_r f depends only on the behavior of $W_{\psi,\varphi}$ faway from the boundary. Moreover, bounded subsets of $B_\mu(D)$ are relatively compact in the topology of local uniform convergence on compact subsets. Therefore, K_r maps bounded sets into relatively compact sets and is thus a compact operator on $B_\mu(D)$. Similar arguments can be found in Zhao [10] and Wulan, Zheng and Zhu [11] for Bloch-type spaces.

Hence,

$$\| W_{\psi,\varphi} \|_e \leq \| W_{\psi,\varphi} - K_r \|.$$

Using the derivative estimate from Theorem 3.1 on the boundary layer where $\chi_r \neq 1$, we obtain

$$\| W_{\psi,\varphi} - K_r \| \lesssim \sup_{z \text{ near } \partial D} \left(\mu(z) \| D\psi(z) \| + \frac{\mu(z)}{\mu(\varphi(z))} | \psi(z) | \ \| D\varphi(z) \| \right).$$

Letting $r \to 1$ yields the upper estimate in (3.12).

3.5 Theorem (Dynamical behavior of iterates)

Let D be a bounded domain in a complex Banach space, let μ be a normal weight on D, and let $W_{\psi,\varphi}$ be a bounded weighted composition operator on $B_\mu(D)$ For each $n \in N$, define

$$\varphi^{\circ n} = \varphi \circ \cdots \circ \varphi. \tag{3.13}$$

$$\psi_n(z) = \prod_{k=0}^{n-1} \psi(\varphi^{\circ k}(z)), n \geq 1. \tag{3.14}$$

$$W^n_{\psi,\varphi} f = \psi_n \cdot (f \circ \varphi^{\circ n}) \tag{3.15}$$

Assume that φ has a Denjoy-Wolff point $\tau \in D$ and that

$$\lim_{n\to\infty} \sup_{z\in D} \mu(z) \| D\psi_n(z) \| = 0,$$

and

$$\lim_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \ \| D\varphi^{\circ n}(z) \| = 0. \tag{3.16}$$

Then

$$\| W^n_{\psi,\varphi} \| \longrightarrow 0 \text{as } n \to \infty.$$

Conversely, if

$$\| W^n_{\psi,\varphi} \| \longrightarrow 0,$$

then

$$\lim_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \ \| D\varphi^{\circ n}(z) \| = 0.$$

Proof

For each $n \in N$ and $f \in B_\mu(D)$,

$$W^n_{\psi,\varphi} f = \psi_n (f \circ \varphi^{\circ n}).$$

Differentiating, we obtain

$$D(W^n_{\psi,\varphi} f)(z) = D\psi_n(z) f(\varphi^{\circ n}(z)) + \psi_n(z) (Df)(\varphi^{\circ n}(z)) \circ D\varphi^{\circ n}(z).$$

Multiplying by μ(z) and taking norms yields

$$\mu(z) \| D(W^n_{\psi,\varphi} f)(z) \| \leq \mu(z) \| D\psi_n(z) \| \ | f(\varphi^{\circ n}(z)) | + \mu(z) | \psi_n(z) | \ \| D\varphi^{\circ n}(z) \| \| Df(\varphi^{\circ n}(z)) \|.$$

Since point evaluations are bounded on $B_\mu(D)$, there exists a constant $C_{ev} > 0$ such that

$$| f(\varphi^{\circ n}(z)) | \leq C_{\text{ev}} \| f \|_{B_\mu(D)}, z \in D.$$

Also, by the definition of the Bloch-type norm,

$$\mu(\varphi^{\circ n}(z)) \| Df(\varphi^{\circ n}(z)) \| \leq \| f \|_{B_\mu(D)}.$$

Hence,

$$\mu(z) \| D(W^n_{\psi,\varphi} f)(z) \| \leq \left(C_{\text{ev}} \mu(z) \| D\psi_n(z) \| + \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \ \| D\varphi^{\circ n}(z) \| \right) \| f \|_{B_\mu(D)}.$$

Taking the supremum over $z \in D$, we get

$$\| W^n_{\psi,\varphi} f \|_{B_\mu(D)} \leq C \left(\sup_{z\in D} \mu(z) \| D\psi_n(z) \| + \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \ \| D\varphi^{\circ n}(z) \| \right) \| f \|_{B_\mu(D)}.$$

Under the assumptions

$$\lim_{n\to\infty} \sup_{z\in D} \mu(z) | D\psi_n(z) | = 0 \text{ and } \lim_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \ \| D\varphi^{\circ n}(z) \| = 0,$$

the right-hand side tends to 0 as $n \to \infty$. Consequently,

$$\| W^n_{\psi,\varphi} \| \to 0.$$

Conversely, assume that $\|W^n_{\psi,\varphi}\| \to 0$. To recover the iterated symbol estimate, apply $W^n_{\psi,\varphi}$ to a family of test functions $\{f_a\}_{a\in D} \subset B_\mu(D)$ satisfying the same type of normalization used in Theorem 3.1, namely

$$\sup_{a\in D} \| f_a \|_{B_\mu(D)} < \infty, \mu(a) \| Df_a(a) \| \geq c_0 > 0.$$

Fix z∈D and set a=$\varphi^{\circ n}$ (z). Differentiating $W^n_{\psi,\varphi} f_a$ at z gives

$$D(W^n_{\psi,\varphi} f_a)(z) = D\psi_n(z)\, f_a(\varphi^{\circ n}(z)) + \psi_n(z)\, (Df_a)(\varphi^{\circ n}(z)) \circ D\varphi^{\circ n}(z).$$

Since $\|W^n_{\psi,\varphi}\| \to 0$, the left-hand side tends to 0 uniformly on bounded sets of test functions. Using the boundedness of point evaluations and the normalization

$$\mu(\varphi^{\circ n}(z)) \| Df_{\varphi^{\circ n}(z)}(\varphi^{\circ n}(z)) \| \geq c_0,$$

We obtain

$$\lim_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} \, | \psi_n(z) | \, \| D\varphi^{\circ n}(z) \| \to 0.$$

uniformly in z∈D.

3.6 Corollary (Special cases and convergence)

In the setting of Theorem 3.5, suppose in addition that:

1. the Denjoy-Wolff point τ lies in the interior of D, and φ is a strict contraction in a suitable invariant metric near τ, so that $\|D\varphi^{\circ n}(z)\|$ decays at least geometrically along orbits
2. the weight ψ is continuous at τ and $|\psi(\tau)| < 1$, so that $|\psi_n(z)|$ decays at least geometrically as $n\to\infty$ for each z∈D.
3. the weight μ is normal, hence the ratio $\mu(z)/\mu(\varphi^{\circ n}(z))$ remains controlled along the orbits of φ.

Then

$$\limsup_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} |\psi_n(z)| \, \|D\varphi^{\circ n}(z)\| = 0,$$

and consequently

$$\|W^n_{\psi,\varphi}\| \to 0$$

Proof

since φ is a strict contraction near its Denjoy-Wolff point, the derivative

$$\| D\varphi^{\circ n}(z) \|$$

decays geometrically along each orbit. The continuity of ψ at τ and the assumption

$$| \psi(\tau) | < 1$$

imply that $|\psi_n(z)|$ also decays geometrically.

Since the ratio

$$\frac{\mu(z)}{\mu(\varphi^{\circ n}(z))}$$

remains uniformly bounded along the orbits of φ , while both

$$| \psi_n(z) |$$

And $\| D\varphi^{\circ n}(z) \|$

decay geometrically, it follows that

$$\lim_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \| D\varphi^{\circ n}(z) \| = 0.$$

Hence, by Theorem 3.5,

$$\| W^n_{\psi,\varphi} \| \to 0.$$

3.7 Corollary (Power-compactness)

Under the assumptions of Theorem 3.5, if

$$\lim_{n\to\infty} \sup_{z\in D} \mu(z) \| D\psi_n(z) \| = 0$$

And

$$\lim_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \| D\varphi^{\circ n}(z) \| = 0.$$

Then

$$\| W^n_{\psi,\varphi} \| \to 0.$$

Consequently,

$$r_e(W_{\psi,\varphi}) = \lim_{n\to\infty} \| W^n_{\psi,\varphi} \|^{1/n}_e = 0 < 1.$$

Hence $W_{(\psi,\varphi)}$ is power-compact on B_μ (D).

By the assumptions,

$$\lim_{n\to\infty} \sup_{z\in D} \mu(z) \, | D\psi_n(z) | = 0,$$

and

$$\lim_{n\to\infty} \sup_{z\in D} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} | \psi_n(z) | \, \| D\varphi^{\circ n}(z) \| = 0.$$

Therefore, all hypotheses of Theorem 3.5 are satisfied. It follows that

$$\| W^n_{\psi,\varphi} \| \longrightarrow 0 (n \to \infty).$$

Since the essential norm is dominated by the operator norm,

$$\| W^n_{\psi,\varphi} \|_e \leq \| W^n_{\psi,\varphi} \|,$$

we also obtain

$$\| W_{\psi,\varphi}^{n} \|_e \longrightarrow 0.$$

Hence,

$$r_e(W_{\psi,\varphi}) = \lim_{n\to\infty} \| W_{\psi,\varphi}^{n} \|_e^{1/n} = 0 < 1.$$

Since $r_e(W_{\psi,\varphi})<1$, it follows from the standard characterization of power-compact operators that $W_{\psi,\varphi}$ is power-compact on $B_\mu(D)$.

3.8 Example (A contractive diagonal map on the Hilbert ball)

Let H be a complex Hilbert space and let $B_H=\{z\in H:\|z\|<1\}$ be its open unit ball. Consider the standard Bloch-type space $B_\mu(B_H)$ associated with the normal weight

$$\mu(z) = 1 - \|z\|, z \in B_H.$$

Fix a constant λ with $0<|\lambda|<1$, and define the analytic self-map

$$\varphi(z) = \lambda z, z \in B_H. \qquad (3,17)$$

Let the weight be constant, $\psi(z)\equiv c\in C$. Then the weighted composition operator

$$W_{\psi,\varphi} f(z) = c\, f(\lambda z), f \in B_\mu(B_H)$$

is bounded on $B_\mu(B_H)$.

Indeed,

$$D\varphi(z) = \lambda I_H, D\psi(z) = 0. \qquad (3,18)$$

Hence condition (3.2) is immediate, and condition (3.3) becomes

$$\sup_{z\in B_H} \frac{1-\|z\|}{1-\|\lambda z\|} |c|\,|\lambda| < \infty,$$

which holds because

$$\frac{1-\|z\|}{1-\|\lambda z\|} = \frac{1-\|z\|}{1-|\lambda|\cdot\|z\|}$$

is bounded on B_H whenever $0<|\lambda|<1$.

For the iterates, we have

$$\varphi^{\circ n}(z) = \lambda^n z, \psi_n(z) = c^n, D\varphi^{\circ n}(z) = \lambda^n I_H.$$

Therefore,

$$\frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} |\,\psi_n(z)\,|\,\|\,D\varphi^{\circ n}(z)\,\| = \frac{1-\|\,z\,\|}{1-|\,\lambda\,|^n\|\,z\,\|} |\,c\,|^n |\,\lambda\,|^n.$$

Since

$$\frac{1-\|z\|}{1-|\lambda|^n\|z\|} \le 1 \quad \text{for all } z \in B_H,$$

we obtain

$$\sup_{z\in B_H} \frac{\mu(z)}{\mu(\varphi^{\circ n}(z))} |\psi_n(z)|\,\|D\varphi^{\circ n}(z)\| \le (|c|\,|\lambda|)^n.$$

Consequently, if $|c\lambda|<1$, then the right-hand side tends to 0 as $n\to\infty$. By Theorem 3.5, it follows that

$$\|W_{\psi,\varphi}^{n}\| \to 0.$$

Hence $W_{\psi,\varphi}$ is power-compact, in agreement with Corollary 3.7.General diagonal operators in infinite-dimensional Hilbert spaces.

a diagonal map of the form

$$\varphi(z) = \sum_{j=1}^{\infty} \lambda_j \langle z, e_j\rangle e_j, 0 < \sup_j |\lambda_j| < 1,$$

with respect to an orthonormal basis $\{e_j\}$, and a constant weight $\psi\equiv c$. Then the same argument works with

$$\|D\varphi^{\circ n}(z)\| \le (\sup_j |\lambda_j|)^n$$

4. Conclusion

In this paper, we studied weighted composition operators acting on Bloch-type spaces defined on bounded domains in complex Hilbert spaces, using the standard operator . We established necessary and sufficient conditions for the boundedness of this operator on the Bloch space in terms of the analytic weight and the derivative of the inducing map , as reflected in the corresponding norm estimates, thereby extending related results in the literature.

In addition, we derived estimates for the operator norm and obtained a characterization of the essential norm through a boundary condition, which yields a compactness criterion and improves previously known essential norm estimates. Finally, we investigated the dynamical behavior of the iterates and gave conditions ensuring their convergence to zero in operator norm, formulated in terms of the weighted derivative growth along the orbits of , in the spirit of Denjoy-Wolff type dynamics for weighted composition operators.

These results extend several known theorems on composition and weighted composition operators to Bloch-type spaces over infinite-dimensional Hilbert domains and provide a solid foundation for further research in this direction.

Conflicts of Interest: The author declares that there are no conflicts of interest regarding the publication of this paper.

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SARS-CoV-2 Variants in the Eastern Region of Saudi Arabia: How Far from the Origin?

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Abstract
Infectious viruses, including SARS-CoV-2, use different strategies, such as mutations, to alter their phenotype in ways that confer a fitness advantage. These mutations play a critical role in facilitating the virus's successful entry into host cells. In this study, we used 18 whole-genome sequences of SARS-CoV-2 variants circulating in the Eastern Region of Saudi Arabia and compared them to the Wuhan strain hCoV-19/Wuhan/WIV04/2019. The current study analyzed population expansion of SARS-CoV-2 transmission (Tajima's D = -1.061; P < 0.28 for the normal distribution, P < 0.311 for the beta distribution). In total, 18 haplotypes were detected, among which 17 were singletons. Changes in evolutionary relationships among the 18 Saudi SARS-CoV-2 variants indicate that the analyzed genotypes clustered into distinct groups relative to the hCoV-19/Wuhan/WIV04/2019 strain. Genomic variation may reflect the high rate of amino acid (aa) mutations, especially in the spike protein. Over 428 mutations were mainly localized in the spike, and 2 sequences (OV079467.1 and OV090001.1) showed the highest number of mutations (68 and 96, respectively). A total of 192 recorded mutations were unique to the studied genomes according to GISAID. The spike protein regulates SARS-CoV-2's ability to bind the human ACE2 receptor or to participate in other steps in the invasion of host cells. Thus, understanding the main drivers of the emergence, spread, and dominance of pathogens over human defenses is necessary, as these mutations may undermine all drug repurposing efforts.

Keywords: SARS-CoV-2, Eastern Region of Saudi Arabia, haplotype, amino acid (aa), mutations, spike protein

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1. Introduction

In March 2020, the World Health Organization (WHO) declared the COVID-19 pandemic. The outbreak that began in Wuhan, Hubei Province, China, was caused by the emergence of a beta-coronavirus, SARS-CoV-2 (Huang et al., 2020; Wang et al., 2020; Zhu et al., 2020). By February 12, 2023, the viral infection had spread worldwide for over 2 years, resulting in over 677 million confirmed cases and 6.78 million deaths (https://www.who.int/). The Saudi Arabian government reported the first case of positive SARS-CoV-2 on 2 March 2020, and the first death was officially registered on 24 March 2020. Three years later, approximately 828 thousand confirmed cases and 9575 deaths were reported, placing Saudi Arabia as one of the most severely affected countries in the Middle East (https://covid19.moh.gov.sa/; https://covid19.who.int/data). During this period (March 2020 to the end of 2022), the official cumulative incidence rate was 1646 cases/100,000 inhabitants, while the mortality rate was 146 deaths/100,000 inhabitants, with a lethality of 8.9% (https://covid19.moh.gov.sa).

The contagiosity and pathogenic features, as well as the evolutionary trajectory of SARS-CoV-2, have been extensively studied, resulting in over 14 million sequences worldwide (https://gisaid.org/). Since the publication of the first viral genome reference (NCBI accession number NC-045512.2), the number of genome sequence publications has steadily increased. More than 2,000 variants/lineages are currently available in the GISAID database (http://www.gisaid.org), including recent reports of more contagious variants from the UK, South Africa, and Brazil.

Indeed, Saudi Arabia had already experienced a similar severe beta-coronavirus outbreak in 2012, when a pair of Saudi nationals were diagnosed with the Middle East respiratory syndrome coronavirus (MERS-CoV). The outbreak was closely monitored and dealt with in a professional way, which reduced mortality to 838 deaths among the reported cases (Rahman & Sarkar, 2019). Similar to SARS, MERS-CoV infection begins with minor upper respiratory symptoms and progresses to serious respiratory illness (Memish et al., 2013). The Eastern Region of Saudi Arabia was reported to be the first region hit by the pandemic (moh.gov.sa). The geographical distribution of cumulative COVID-19 cases in the country showed that the Eastern Region is among the most affected regions (Figure 1). For approximately 3 years, the region registered approximately 161744 confirmed cases and 1470 deaths (https://covid19.moh.gov.sa/).

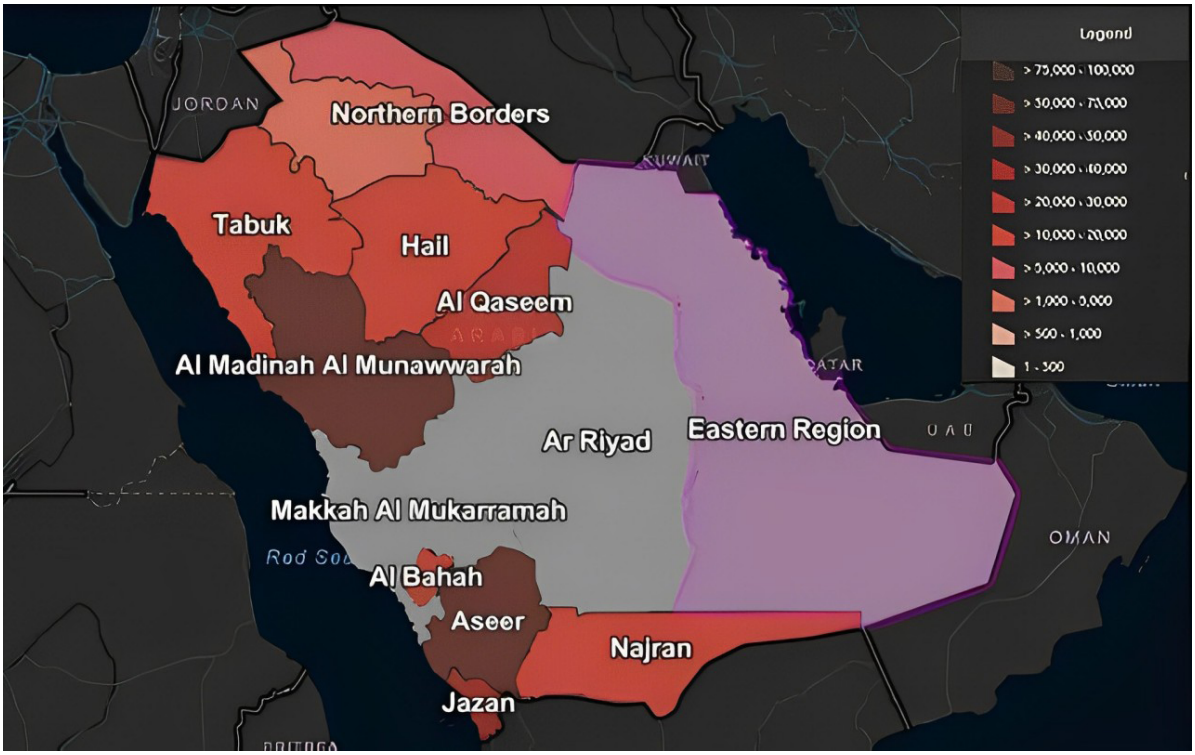


Figure 1. The thirteen regions of Saudi Arabia show the geographical distribution of cumulative COVID-19 cases. Riyadh region and Makkah Al Mukarramah region were the 2 regions with the highest cumulative confirmed cases. The eastern region, in pink, is the third region in the country with the highest cumulative number of affected cases in Saudi Arabia.

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), an RNA coronavirus, is responsible for the COVID-19 outbreak (a, b). The virus has been identified as the cause of the disease and belongs to the beta-CoV genus (8,c). SARS-CoV-2 has a linear, single-stranded RNA genome (~30 kilobases, kb) encoding approximately 29 proteins (1,3,5,6,7,8). Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) undergoes mutations as it replicates. These mutations have accumulated over time since the virus emerged, and new variants continue to appear as new mutations emerge.

In late 2020, after circulating for almost a year in the human population, severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) exhibited a major step change in its adaptation to humans (9). The pathogenic potential of SARS-CoV-2 can be influenced by adaptive mutations in its genome. Mutations that can lead to amino acid modifications could affect the virus's ability to evade the immune system and complicate the recently developed vaccines (12). Like other RNA viruses, SARS-CoV-2 adapts to its new human hosts and evolves over time, developing mutations (13).

SARS-CoV-2 consists of four main structural proteins: (i) nucleocapsid protein (N), (ii) spike protein (S), (iii) membrane protein (M), and (iv) envelope protein (E). The E protein is the smallest, ranging from 8 to 12 kDa, and is involved in a wide functional repertoire (Schoeman & Fielding, 2019). The E protein includes three domains: (i) a short hydrophilic N-terminus domain, consisting of 7-12 amino acids; (ii) a hydrophobic transmembrane domain, which is approximately 25 amino acids long; and (iii) a long hydrophilic C-terminal region (Corse & Machamer, 2000; Surya et al., 2018). The S protein has two major domains: S1, which facilitates attachment and binding to the host cell receptor, and S2, which mediates fusion to the host cell membrane (Chu et al., 2020). Both domains play a critical role in establishing the successful entry of the virion into its host cell. SARS-CoV-2 is known to mutate rapidly, especially the spike protein, to escape the host's immune system and adapt to its environment (Saha et al., 2020). Unlike the S protein, the N gene, with 90% amino acid homology and fewer mutations over time, is more conserved and stable (Grifoni et al., 2020; Holmes & Enjuanes, 2003; Marra et al., 2003; Pyrc et al., 2007; Zhu et al., 2005). In many SARS-CoV-2 cases, the M and N proteins were reported to be the most abundant viral proteins expressed during infection and key proteins in the assembly of both naked and enveloped virus particles (Kuo & Masters, 2002). The M protein plays a critical role in intracellular virus particle assembly, for which S is not required (He et al., 2004).

Given that adaptive mutations could be naturally selected in broader populations, studying SARS-CoV-2 genomic variants and tracking them over time might help us understand viral evolution, behavior, and development. The present study aims to (1) characterize the genomic variations of SARS-CoV-2, (2) infer the evolutionary relationships of the Saudi strains, and (3) deduce the transmission history of Saudi SARS-CoV-2 from the Wuhan strain using genomic data of SARS-CoV-2 from the eastern region as "a starting point of infection in the country".

2. Methods

2.1 Data collection

The genomic sequences of SARS-CoV-2 patients were retrieved from the NCBI database as of January 2023. Eighteen complete whole-genome sequences were reported from 18 patients in the eastern region of Saudi Arabia, covering the period from the onset of the pandemic in 2020 through December 2022. Sequence selection criteria were as follows: (i) sequences must originate from human hosts; (ii) sequences must be complete whole-genome sequences with coverage above 99% (≥29,903 bp); (iii) sequences must have been collected from patients in the Eastern Region of Saudi Arabia; and (iv) sequences must have been deposited in the NCBI SARS-CoV-2 data hub by January 2023. Sequences were excluded if they were incomplete, had low coverage (<99%), or lacked metadata confirming their collection from the Eastern Region. As this study is entirely based on publicly available sequences, individual patient clinical or demographic metadata were not available; this is acknowledged as a limitation (see Limitations subsection). The sequence of Wuhan strain hCoV-19/Wuhan/WIV04/2019 was included as the reference sequence.

2.2 Bioinformatics

All 19 sequences were aligned against the reference Wuhan strain hCoV19/Wuhan/WIV04/2019 using the MUSCLE algorithm (Edgar, 2004) as implemented in MEGA X (Kumar et al., 2018). Ambiguous positions in each sequence pair were excluded using the pairwise deletion option. The most appropriate nucleotide substitution model was determined based on the lowest Bayesian Information Criterion (BIC) score, and the Tamura-Nei (TN93) model was selected accordingly.

The evolutionary history was inferred using the Maximum Likelihood method in MEGA X (Kumar et al., 2018). The reliability of the resulting phylogenetic tree was assessed using a bootstrap test with 1,000 replicates (Felsenstein, 1985). The final alignment comprised a total of 29,903 nucleotide positions (~29.9 kb), consistent with the full-length SARS-CoV-2 genome.

2.3 Extraction and visualization of haplotypes

The haplotypes and sequence variations were extracted from the aligned sequences as a matrix using the R base package (28) to compare sequences and to

determine haplotype numbers and frequencies. Unique haplotype sequences were calculated by ignoring common nucleotides between haplotypes. The Hamming distance method is a calculation of the pairwise distance matrix for the corresponding symbols in two equal-length strings (Pinheiro et al., 2005). Our dataset consisted of haplotype sequences, 18,368 base pairs long, used to assess phylogenetic relationships using the analysis of phylogenetics and evolution (APE) package in R (Paradiset al., 2004). The estimated differences between the two sequences are classified as strong for 85% and above, moderate for 70-85%, weak for 50-70%, and poor for 50% and below. Indeed, the evolutionary analyses were conducted in MEGA X (Kumar et al., 2018) using the same aligned sequences used to estimate transition/ transversion rate ratios in the current population.

2.4 Statistical Analyses

Tajima's D (25), a neutral mutation hypothesis test, was calculated as described in the population and evolutionary genetics analysis system "Pegas" (Paradis, 2010). Both nucleotide substitution and maximum-likelihood estimation of the gamma parameter for site rates were performed. The transition/transversion ratio (R) represents the ratio of the number of transitions to the number of transversions for the included sequences. The R value indicates the bias toward either transitional or transversional substitution.

Amino acid (aa) mutation analysis was conducted using GISAID CoVsurver (http://gisaid.org/database-features/covsurver-mutations-app/), a tool developed to aid the research community in the identification and interpretation of aa changes in coronavirus genomes. For the 16 SARS-CoV-2 sequences from Saudi Arabia that were successfully processed by GISAID CoVsurver (two sequences, OV090001.1 and OV079467.1, were excluded due to truncation of the spike protein exceeding the threshold accepted by the tool), mutations and their positions on the viral genome were presented along with their frequency change(s) in each structural model, compared with the reference genome of the Wuhan strain hCoV-19/Wuhan/WIV04/2019 (30).

3. Results

3.1 Phylogenetic analyses

In total, 18 sequences with a coverage higher than 99% (29.903 Kb) of the SARS-CoV-2 genome were obtained in this study. This work is an in silico study aimed at evaluating genetic variations in SARS-CoV-2 in the eastern region of Saudi Arabia collected between 2020 and December 2022. SARS-CoV-2 sequences were obtained from the NCBI SARS-CoV-2 data hub (Jan/2023). The sequence of Wuhan strain hCoV-19/Wuhan/WIV04/2019 was included as outgroup. Phylogenetic trees were constructed based on the estimation of the neighbor-joining method supported by the APE package (Paradis et al., 2004). Phylogenetic analysis of the 18 Saudi SARS-CoV-2 sequences, with the Wuhan reference sequence (hCoV-19/Wuhan/WIV04/2019) included as an outgroup, inferred using the Maximum Likelihood method with 1,000 bootstrap replicates, revealed two major clusters within the ingroup, supported by strong bootstrap values, along with several divergent sequences that did not group within either cluster (Figure 2). The 15 sequences forming the main ingroup clade were separated from the more basal isolates (OV090001.1, OV090750.1, and OV079467.1) with maximal bootstrap support (100%), and this clade subsequently diverged into two well-supported clusters (100% bootstrap support at the node separating them). The first cluster comprised seven sequences (OV090846.1, OV090864.1, OU998690.1, OV005890.1, OU993040.1, OV091501.1, and OU993652.1). Within this cluster, OU998690.1 and OV005890.1 formed a closely related pair, supported by a moderate bootstrap value of 72%. The second cluster comprised eight sequences (OV091476.1, OV090004.1, OV091486.1, OV091533.1, OV091491.1, OV091561.1, OV009572.1, and OU992750.1). Within this cluster, OV091561.1 and OV009572.1 formed a distinct pair, although this grouping received only weak bootstrap support (58%), suggesting limited confidence in their close evolutionary relationship relative to the rest of the cluster.

Three sequences OV090001.1, OV090750.1, and OV079467.1 occupied more basal positions in the tree and did not cluster with either of the two main groups, indicating greater genetic divergence from the remaining Saudi isolates. OV079467.1 branched closest to the root among all ingroup sequences. The 18 Saudi sequences were phylogenetically compared with the Wuhan reference strain hCoV-19/Wuhan/WIV04/2019 (NC-045512.2), which formed a clearly distinct outgroup, confirming the expected evolutionary divergence of the analyzed Saudi isolates from the ancestral Wuhan lineage.

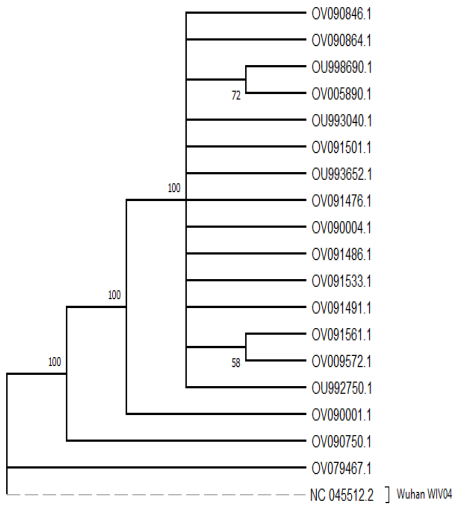


Figure 2. Plotting the multiple sequence alignments with a phylogenetic tree. The phylogenetic tree of the 18 SARS-CoV-2 genomes and nucleotide differences has been reconstructed relative to Wuhan (NC-045512.2). The evolutionary history was inferred using the Maximum Likelihood method with the Tamura-Nei (TN93) substitution model as implemented in MEGA X. Bootstrap consensus tree inferred from 1,000 replicates is taken to represent the evolutionary history of the taxa analyzed. Branches corresponding to partitions reproduced in less than 50% bootstrap replicates are collapsed. The percentage of replicate trees in which the associated taxa clustered together in the bootstrap test (1,000 replicates) are shown next to the branches. This analysis involved 18 Saudi SARS-CoV-2 sequences and one Wuhan reference sequence (NC-045512.2) as outgroup (19 nucleotide sequences in total). Codon positions included were 1st+2nd+3rd+Noncoding. All positions containing gaps and missing data were eliminated (complete deletion option). There was a total of 29,661 positions in the final dataset. Evolutionary analyses were conducted in MEGA X.

3.2 Haplotype analysis

Using the R base package and the 18 aligned sequences of SARS-CoV-2 in the Eastern Region of Saudi Arabia as a matrix, we revealed 18 different haplotypes. The total length of the sequence of the generated haplotypes was 18,368 bp (61.43% of the aligned sequence and 61.23% of the SARS-CoV-2 genome). Seventeen of eighteen identified haplotypes were singletons (5.26%). Additionally, H11 (10.53%) was found in two sequences (OU998690.1 and OV091533.1). The distance matrix allowed analysis of differences in the number of nucleotides between haplotypes, showing the smallest difference of 1 nucleotide between 4 combinations of described haplotypes: H9-H11, H10-H11, H12-H15, and H15-H16. However, the largest difference was 35 nucleotides between haplotypes H5 and H14.

To understand the dynamics of these mutations, we constructed a frequency heatmap of the number of nucleotide differences between the 18 haplotypes. Each branch of the phylogenetic tree corresponds to the haplotype in the matrix; thus, it is fully compatible with the haplotype distance matrix. The results indicate a high rate of nucleotide differences between haplotypes.

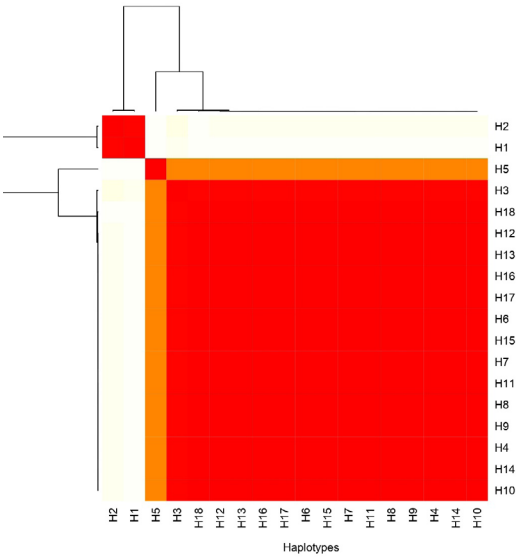


Figure 3. Heatmap of the number of nucleotide differences between haplotypes. Each branch of the phylogenetic tree corresponds to the haplotype in the matrix. Close relationships are defined by the "dark red" color, and distant relationships by the "light" color.

3.3 Maximum Likelihood Estimate of Transition/ Transversion Bias

The transition/transversion (Ti/Tv) ratio is a measure of the nucleotide mutation process and is a well-established aspect of substitution models (Kimura, 1980). The Ti/Tv ratio is calculated as the ratio of the transition of a single nucleotide polymorphism (changes from

one purine to another purine or from one pyrimidine to another pyrimidine) to the number of transversion SNPs (changes from a purine to a pyrimidine or vice versa).

The estimated transition/transversion bias parameter (R) in the Kimura 2-parameter model is 0.50, reflecting the ratio used in the substitution model parameterization. Note that the pairwise Ti/Tv values reported in Table 1 (ranging from 8.3285 to 8.3430) represent a separate maximum-likelihood estimation of nucleotide substitution rates between specific base pairs, and these two values are not directly comparable. Substitution patterns and rates were estimated under the Kimura (1980) 2-parameter model (+G). A discrete gamma distribution of SARS-CoV-2 genomes was used to model evolutionary rate differences among sites (5 categories, [+G], parameter = 5.2554). To estimate ML values, tree topology was automatically computed (Table 1). The maximum log-likelihood for this computation was -104971.438. This analysis involved 19 nucleotide sequences. The codon positions included were 1st+2nd+3rd+Noncoding. All positions with less than 95% site coverage were eliminated, i.e., fewer than 5% alignment gaps, missing data, and ambiguous bases were allowed at any position (partial deletion option). The current analysis included a total of 29677 positions in the final dataset. The estimated (Ti/Tv) bias analysis showed, relative to the reference genome, 51% as transition mutations and 49% as transversion mutations. As shown in Table 2, after examining all the variations, we noticed that the Ti/Tv ratio was high (the ratio varied between 8.3285 and 8.3430).

Table.1: The estimated Transition/Transversion bias.

From\To	A	T	C	G
A	-			
T	8.3285	-		
C	8.3285	8.3430	-	
G	8.3430	8.3285	8.3285	-

3.4 Genomic variation and population expansion

Phylogenetic analysis, haplotype networking, and genetic diversity analysis were performed on 18 genomic sequences from 18 patients confirmed to be SARS-CoV-2-positive in the eastern region of Saudi Arabia. These analyses revealed more than 428 mutations, mainly localized in the spike protein. Two sequences (OV079467.1 and OV090001.1) showed the highest number of mutations, with 68 and 96 modifications in the amino acid sequences, respectively. A total of 192 of the recorded 428 mutations were reported for the first time and have never been reported before. The phylogenetic analysis showed that 2 clusters can be recognized in Eastern Region Saudi Arabian SARS-CoV-2 genome sequences, with the first cluster (Cluster A) comprising the majority (84.21%) of the genotypes and represented by 16 of the 18 Saudi sequences included in the present study.

The second cluster included only 3 genotypes and was closely related to the Wuhan sequence (NC-045512.2). The 2 sequences (OV079467.1 and OV090001.1) appear closely related to the Wuhan sequence, NC-045512.2, with a high degree of genetic similarity. The study of these sequences can provide valuable insights into the virus's spread and evolution in the eastern region of Saudi Arabia and its potential impact on public health. Understanding the genetic differences between these sequences and the Wuhan sequence can also help inform the development of effective treatments and vaccines. Continuous surveillance and monitoring of these and other related SARS-CoV-2 sequences are crucial to our efforts to control the virus's spread and mitigate its impact on global health.

Similarly, the haplotype network analysis showed the same two clusters, comprising a total of 18 haplotypes. The mismatch distribution analysis of 18 SARS-CoV-2 genomes exhibited nonsignificant population expansion of SARS-CoV-2 transmission (Tajima's D= -1.061; P<0.28 for the normal distribution, P<0.311 beta distribution). Although no significant changes were observed, the nucleotide transition/transversion ratio was mostly observed in the viral spike protein, which accounts for less than 10% of the virus's total genome.

Indeed, amino acid (aa) mutations confirmed a significant effect on the viral spike protein. Both OV079467.1, with 68 mutations, of which 34% and 33 mutations are unique, and OV090001.1, with 96mutations, of which 62% and 33 mutations are unique, had their spike protein truncated by 64.5% of its original length (>10%). Mutations in the isolates ranged from 15 to 19, with >0.1% unique mutations; however, all were recorded at the spike protein except OV091533.1. All other included genomes had a Spike-D614G mutation recorded during this analysis, as well as Spike-L5F in OV090004.1. OV090004.1 had several other unique mutations that are mostly located on the spike protein. The aa mutation of OV091533.1 was recorded for the first time in Victoria, Australia, in March 2020, and in Trentino-Alto Adige, Italy, in March 2020 for mutations in OV090004.1. All other mutations in the remaining current genomes were recorded for the first time at Port of Spain, Trinidad and Tobago, in January 2020, GISAID.

4. Discussion

Mutations in RNA viruses, including SARS-CoV-2, are common, and they can alter several properties, such as the ability of the virus to cause disease, how easily it can infect its host, how strongly it binds to the host's receptors, and how it spreads (Harvey et al., 2021; J. Ou et al., 2021). Understanding these mutations in the

SARS-CoV-2 genome is important for understanding the nature of the infection and for documenting the virus's evolution and spread (Kim et al., 2020; Shen et al., 2020).

In the present study, SARS-CoV-2 strains in the eastern region of Saudi Arabia showed 100% bootstrap values separating the basal sequences from the two main clusters. Both clusters are close to Wuhan and showed nonsignificant population expansion or distribution, as indicated by Tajima's test. The phylogenetic topology obtained in this study clearly distinguished at the backbone level, with the separation of the three basal isolates (OV090001.1, OV090750.1, and OV079467.1) both main clusters, as well as the divergence between the two clusters themselves, both receiving maximal bootstrap support (100%). This indicates strong statistical confidence in the overall branching pattern and the major evolutionary relationships among the sampled Saudi isolates.

In contrast, two internal groupings within the clusters including OU998690.1/OV005890.1 (72%) and OV091561.1/OV009572.1 (58%) received comparatively lower bootstrap support. While a value of 72% falls within an acceptable range and lends moderate confidence to the close relationship between OU998690.1 and OV005890.1, the 58% support for the OV091561.1/OV009572.1 pairing falls below the conventional threshold of ≥70% typically used to designate a well-supported node (Hillis & Bull, 1993). This weaker support may reflect limited sequence divergence among isolates collected within a short sampling period, insufficient phylogenetic signal at the informative sites distinguishing these two sequences, or a degree of topological uncertainty inherent to closely related, recently diverged viral genomes. Consequently, while these two sequences cluster together in the inferred tree, their sister-taxon relationship should be interpreted with caution and would benefit from confirmation using additional data, such as whole-genome SNP analysis or a larger, more geographically or temporally diverse dataset.

Overall, the strong backbone support underscores the reliability of the major clustering pattern identified in this study, while the weaker internal node values highlight the limitations of resolving fine-scale relationships among highly similar SARS-CoV-2 isolates using a single alignment-based Maximum Likelihood approach. The differences in the recorded frequencies of certain haplotypes in our case may change rapidly due to founder effects caused by local outbreaks. Previous studies have shown that these changes rarely confer a selective advantage on SARS-CoV-2 strains (Hryhorowicz et al., 2021). Indeed, rapid changes in the frequency of certain haplotypes across populations may result from founder effects caused by local outbreaks, and this does not necessarily imply a selective advantage for these strains. Therefore, an unguided assumption about the prevalence of any given SARS-CoV-2 strain indicates that its advanced virulence should be avoided, and some coronavirus mutations require further investigation due to their global spread (Hryhorowicz et al., 2021). The SARS-CoV-2 genome evolves relatively slowly, thanks to the "proofreading" activity of the Nsp12 exonuclease; the SARS-CoV-2 mutation rate is slower than that of other RNA viruses (van Dorp et al., 2020). Previous results showed that the nucleotide mutation rate of the whole genome was 6.677×10^{-4} substitutions per site per year, and the nucleotide mutation rate of the S gene was 8.066×10^{-4} substitutions per site per year, which was at a medium level compared with other RNA viruses (Wang et al., 2022).

At 30 kb, coronaviruses possess the largest genome, which includes structural and accessory genes, ample replicases, and other nonstructural proteins (Nsps) (E et al., 2020). The majority of the SARS-CoV-2 genome contains the ORF1a/b region that is translated into 2 polyproteins, pp1a (Nsp1-Nsp11) and pp1ab (Nsp1-Nsp16) (Cui, Li, and Shi, 2019). The other 4 structural proteins, envelope (E), matrix (M), nucleocapsid (N) phosphoprotein, and spike (S), function together with viral RNA and Nsp1-16 to assist the replication of the virus within the host cell (Hakmaoui et al., 2021). Therefore, mutations in small proteins such as the spike may be unnoticed when analyzing the whole genome. Although the spike protein accounts for less than 10% of the SARS-CoV-2 genome, it plays a critical role in facilitating viral entry into the human body. Our results showed that the vast majority of mutations occurred in the gene encoding the spike protein, and 426 of 428 mutations (99.53%) were detected in this gene. This corroborates previous findings that the spike protein is one of the mutational hot spots (Kubik et al., 2021; Lee et al., 2021; Thakur et al., 2022).

A study of infectivity and reactivity to a panel of neutralizing antibodies and sera from convalescent patients confirmed several mutations and glycosylation site modifications in human SARS-CoV-2 spike proteins (Korber et al., 2020). The SARS-CoV-2 spike protein has an S1 domain at the N-terminus comprising a receptor-binding domain (RBD) and an S2 domain at the C-terminus containing fusion peptides. The spike RBD binds to the host cell's ACE2 receptor, triggering proteolytic cleavage of the S1 and S2 domains, exposing fusion peptides that then insert into the host plasma membrane, facilitating the virus's entry into the host cell (Huang et al., 2020). The D614G mutation is reported to be relatively common and known to increase infection rates (Singh et al., 2021). The p. D614G substitution in the spike protein-A23403G (Brufsky, 2020; Korber et al., 2020), is recorded in both genomes OV079467.1 with 68 mutations, of which 34% are unique, and OV090001.1 with 96 mutations, of which

62% are unique and have their spike protein truncated by 64.5% of its original length. This mutation is located between the receptor binding domain (amino acids 451-509) and the polybasic cleavage site (amino acids 682-685) (Boddy et al., 2007), which regulates the capability of SARS-CoV-2 to bind to the human host ACE2 receptor or is involved in other steps related to the invasion of host cells (Andersen et al., 2020; X. Ou et al., 2020). This might explain the rapid spread of infections in the eastern region at the beginning of the pandemic. Except for OV091533.1 and OV079467.1, the D614G mutation in the spike protein was observed in all genomes, among the other 428 aa mutations, with almost 50% of them unique based on GISAID.

A rare mutation, Spike-I472V, was also recorded in both genomes OV079467.1 and OV090001.1, which is known to work in favor of the virus by increasing both infectivity and resistance to neutralizing antibodies (Li et al., 2020). The current study also includes some deletion mutations at glycosylation sites in the spike proteins. These types of spike mutations are known to reduce infection, revealing the importance of glycosylation for viral infectivity (Guruprasad, 2021). A total of 22 deletion mutations were recorded in both genomes OV079467.1 and OV090001.1, and all were located on the spike protein. In addition, only one mutation (N-A313V) was recorded in the nucleocapsid (N) phosphoprotein in this study, which likely involves cooperative interactions between the dimerization domain and other regions of the protein, as well as the bound RNA (Surjit et al., 2004). However, this has yet to be confirmed, as patient antibodies targeting this domain may not be reliably detected with tests using the reference N protein (Ye et al., 2020).

The current study may enhance our understanding of COVID-19, especially during the ongoing pandemic, when the scientific community is learning about this new viral pathogen. This can be achieved through a better understanding of the main drivers of pathogen emergence, spread, and dominance over human defenses, as these mutations could adversely affect all efforts at drug repurposing. The SARS-CoV-2 S protein is an important component that determines virus virulence, tissue tropism, and host range, as well as a major target for neutralizing antibodies and vaccine development. Mutations at the interface between the spike protein and the ACE-2 receptor could affect vaccine performance and the efficacy of drugs targeting protein-protein interactions. Therefore, the mutations identified in this study should be considered in antibody, vaccine, and drug development.

5. Limitations

This study should be interpreted within the context of its scope and design. As a descriptive genomic surveillance analysis based on 18 publicly available sequences, the findings offer preliminary insights into the evolutionary relationships among circulating SARS-CoV-2 isolates in the Eastern Region of Saudi Arabia, rather than population-level epidemiological conclusions. Additionally, as the analysis relied on sequences deposited in NCBI, individual patient clinical and demographic metadata (such as age, sex, disease severity, and vaccination status) were not accessible, which is a common constraint of public sequence repository-based studies. Future work incorporating larger, longitudinal datasets with linked clinical annotation would help extend these findings and further clarify potential associations between genomic variation and clinical outcomes in this part of the world.

1. Consent for publication

- Not applicable.

2. Competing interests

- The authors declare that they have no competing interests.

3. Funding

- This work was not funded.

4. Authors' contributions

- The author prepared, analyzed, read, and approved the final manuscript.

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High Aspect Ratio CeO_2 Nanocrystals Decorated Polyaniline Heterostructure for Dual Function: Green Remediation of Water Pollutants and Microbial Pathogens

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Abstract
The textile production companies are main tracks to water contamination owing to massive utilization of synthetic colorants, which are often resistant to degradation and pose significant environmental and health risks. Rhodamine 6G (R6G) dyes which are one of the significant water pollutants, have a complex structure and are lethal if ingested or inhaled in substantial amounts. Similarly, food-borne infections are also key concerns of community well-being, internationally. This study introduces a novel method to boost antimicrobial effectiveness of CeO_2 decorated PANI composite against food pathogens and simultaneously aid in removing hazardous effluents such as R6G from wastewaters. The CeO_2 decorated PANI heterostructure, therefore, grips enormous potential in preserving two essential pillars of sustenance viz., water and food. CeO_2 decorated PANI heterostructure have been amalgamated via in situ deposition oxidative polymerization method. Samples were characterized in detail using sophisticated procedures, such as XRD, SEM-EDX, FT-IR and UV-Vis. The CeO_2-PANI heterostructure exhibit enhanced photocatalytic performance under visible light. The composite also showed strong antimicrobial activity against representative bacteria and fungus, mainly through ROS generation and cell membrane disruption. These nanocomposites offer a cost-effective, scalable approach for advanced photocatalytic destruction of bacteria and fungi which is desirable in diverse healthcare applications.

Keywords: Nanocomposite; Water pollutants; Antimicrobial; Pathogens; Photocatalyst

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1. Introduction

Globally water pollution is a perilous problem, imposing incessant appraisal and upgrading water resources. It is one of the major contributors to sickness and mortality. Both developed and developing countries experience momentous trials in sustaining water quality. Water worth is spoiled by various of natural and human activities (Chaudhry & Malik, 2017). In this direction the textile industry significantly contributes to water pollution via artificial colorants, resulting environmental instabilities, hazardous impact on marine flora and fauna, and abridged water eminence from dye-loaded wastewater emancipation. Nonetheless, the textile industry contributes considerably to environmental pollution, principally owing to excessive use of synthetic dyes which impart vivacious colors to textiles, often very complicated to disintegrate, therefore, retain in atmosphere, resulting hazardous consequences (Kumbhar, Shingare, Bagal, Suryawanshi, & Mane, 2025). Heterogeneous photocatalysis is a progressive oxidation procedure and is topic of rigorous investigations subjected to air and water cleansing. However, application of light energy for translation into chemical vigor and safeguarding environmental sterility is a challenge. A lot of investigations are being carried out to expand photocatalytic process established on semiconductor (Algethami et al., 2023; Hassan et al., 2022). So, nowadays, considerable attention has been given to conducting polymers as they fulfil anticipated standards which brand them perfect for an active catalyst matrix (Q. Wang et al., 2013). Nanoceria, one of the significant rare earth oxides has broadly been exploited in catalytic and biological fields owed to its inimitable redox (Ce^{3+} and Ce^{4+}) and robust buffering characteristics (Phanichphant, Nakaruk, & Channei, 2016; Samai & Bhattacharya, 2018). Moreover, nowadays considerable attention has been given to conducting polymers as they fulfil anticipated standards which brand them perfect for an active catalyst matrix (Q. Wang et al., 2013). The mortality frequency is intensifying worldwide owing to swift development of bacterial and fungal infections, as well as prevalent occurrence of resistant microorganisms. It has been foretold that approximately 10 million people will expire yearly from these infections, by 2050, and treatment expenses may reach USD 100 trillion. Nonetheless, during the year 2014, World Health Organization (WHO) acknowledged advancement of antimicrobial resistant microorganisms as a grave peril to universal well-being (Ghodake, Koyale, Patil, Patil, & Delekar, 2025). Salmonellosis is one of the most predominant foodborne sicknesses causing roughly 93.8 million food related infections and 155,000 losses globally on yearly basis. The transmission of non-typhoid Salmonella contagion to beings can happen via incorporation of foodstuff or water soiled with excreta of infested fauna, interaction with diseased fauna or by ingesting food of diseased creatures (Eng et al., 2015). The genera Salmonella is an adherent of Enterobacteriaceae family, and it comprises Gram-negative, whipped, non-sporulating, and facultative bacteria that normally grow from 35-37 °C. S. Typhimurium is pre-dominant serovar in environment, allied with foodborne epidemics equally in developing and developed nations (Mohammed, 2017). Similarly, Staphylococcal food related disease (SFD) is also most prevalent food-borne ailments resultant of infection of foodstuffs by S. aureus enterotoxins. Additionally, it is most common source of testified food-borne illnesses in USA. Even though numerous Staphylococcal enterotoxins (SEs) have been recognized, however, SEA, an extremely heat resistant, is prevalent basis of SFD internationally. Epidemic surveys have initiated that inappropriate food management in retail industry justify most of SFD outbursts (Kadariya, Smith, & Thapaliya, 2014). Staphylococcus aureus is a commensal and an opportunistic pathogen as well proficient to spread wide-ranging infestations, for instance; insignificant dermal infections to acute life-threatening hostile illnesses (Kadariya et al., 2014; Lowy, 1998). Currently, nanotextured fibers and tubes inherited with antimicrobial potential are of tremendous demand owing to their extensive antibiotic resistance for diverse pathogens. These nanotextured materials are usually based on metal or metal oxide nanoparticles that have been in practice since centuries (Maliszewska & Czapka, 2022). Furthermore, in this direction, the cerium oxide (CeO_2) and polyaniline (PANI) are two important materials that have attained noteworthy consideration due to their exceptional assets and impeding usage in diverse arena. CeO_2 is a rare earth metal oxide that displays outstanding catalytic, optical, and electronic properties, while PANI is a conductive polymer that possesses good mechanical strength, thermal stability, and electrical conductivity. The amalgamation of these two materials in a heterostructure has shown promising results in photocatalysis and antimicrobial applications in present study. Therefore, this newly designed heterostructure not only constrains foodborne pathogens but can also prevent biofilm formation on surfaces, also a key factor in reducing chemical and biological long-term contamination in water systems.

2. Experimental

2.1 Chemicals

Aniline monomer, ammonium per-sulfate (APS) and Oleylamine (70%) were procured from Sigma-Aldrich and citric acid were brought from Showa Chemicals Ltd., Japan. Cerium (III) nitrate hexahydrate (99%) and Diphenyl ether (99%) were purchased from Samchun chemicals, South Korea.

2.2 Synthesis of samples

2.2.1 Synthesis of CeO_2 Nanocrystals

CeO_2 Nanocrystals were synthesized using previously

established methodology (Hassan et al., 2016) with desired alterations. Cerium nitrate hexahydrate (1.7 g) was combined with oleylamine (20 ml) at room temperature in a three-neck flask with stirring at 400 rotation per minute (RPM). After raising the temperature to 90 °C, a clear solution was occasionally obtained (pH~9). At 90 °C, diphenyl ether (3.0 ml) was added to the same solution. After two hours, the solution temperature increased 320 °C and it was allowed to age for two hours. A colloidal black fluid is produced. To precipitate the solution, 100 mL of ethanol was added after the solution had cooled down. Finally, the solution was centrifuged, the finished product was dispersed into toluene or hexane.

2.2.2 Synthesis of PANI NTs

Typically, 500 ml of distilled water was combined with 0.1 M of aniline, and then 4.0 g of citric acid was supplemented to make solution. Then, in a 1:1 weight percentage ratio, the CeO_2 NCs were added to the mixture. Simultaneously, a 0.1M APS aqueous solution was stirred into the previous solution (Jeong et al., 2014). After that, the sample was refrigerated 24 hours at 4 °C. High-suspended stability PANI-CeO_2 composite suspension was created. After filtration the composite suspension washed three times with distilled water and one time with ethanol to get rid of any remnants, the finished product was vacuum-dried overnight at 60 °C.

2.2.3 Synthesis of CeO_2 NCs-PANI NTs composite

For the synthesis of composite sample, CeO_2 NCs were added (1:1 w/w) to the mixture of aniline and citric acid, then APS was added for polymerization. Rest of the process was identical as described above for pure PANI nanotubes synthesis.

2.3 Characterization and Photocatalysis

The XRD of produced heterostructure was documented on a Rigaku/Max-3A X-ray diffractometer with CuK radiation (λ=1.5418 Å), operational voltage and current has been insisted at 30 kV and 40 mA, correspondingly (Amna et al., 2012). To inspect the structural features and chemical composition, the composite was homogeneously squirted on aluminum foil and imaging was carried out at diverse intensifications by field (FESEM-EDX, JEOL JSM6700, Japan) and transmission electron microscopy (TEM, H-7650, Hitachi, Japan). The Fourier transform infrared (FTIR) spectra using KBr pellet technique (Varian FTS 1000) was acquired. The light absorbance of heterostructures was determined by UV-Vis diffused reflectance spectrum (UV-DRS, 525 Shimadzu).

To perform photocatalytic degradation, 2.5 mg of materials were continuously stirred into 250 mL of R6G solution (10 ppm). Before irradiating slurry with visible light ($\lambda > 400$ nm), it was aerated for 30 min to accomplish adsorption equilibrium. Photocatalytic studies were conducted at room temperature. At predetermined intervals, representative samples were captured from suspension and centrifuged right away at 12,000 rpm. With the help of UV-Vis spectrophotometer (Shimadzu UV-3101) absorbance of the R6G solution was assessed.

2.4 Growth inhibition studies of CeO_2-PANI NTs

The antibacterial efficacy of CeO_2-PANI NTs was evaluated through growth inhibition assays, based on previously described methodologies (Amna, 2023; Amna et al., 2013) with applicable amendments against two representative foodborne bacteria, S. aureus KCCM 11256 and S. typhimurium KCCM 11862, procured from KCCM, South Korea. To begin with, axenic bacterial cultures were made to proliferate by colonies from Tryptic Soy Agar (TSA) into Tryptic Soy Broth (TSB; pH 7.3) and incubated at 37 °C for 18 h. Bacteriological advancement was monitored at specific intervals using a UV visible spectrophotometer (UV-2550, Shimadzu, Japan) via optical density (OD). For antibacterial assay, 1 mL of homogenous revived bacterial inocula was added to fresh broth augmented with variable concentrations of CeO_2-PANI NTs (0, 100, 200, and 400 µg/mL). All experimental flasks were upheld as aforementioned under constant agitation at 150 rpm. The influence of CeO_2-PANI NTs on bacterial propagation/inhibition was administered spectrophotometrically as a function of time, aiding quantitative assessment of growth inhibition(Shamshi Hassan et al., 2024).

2.5 Antimycotic activity of CeO_2-PANI NTs

A clinical isolate of Candida albicans (ATCC 10231) used in this study was maintained and cultured according to previously established protocols (Jalal, Ansari, Ali, Khan, & Rehman, 2018). The antifungal activity of CeO_2-PANI NTs was evaluated using a range of concentrations. Minimum fungicidal concentrations (MFCs) were determined on Sabouraud Dextrose Agar (SDA) plates, following method described by (Alghamdi et al., 2024; Jalal et al., 2016) with appropriate adjustments. Fungal growth was monitored after a 72h incubation period, using a two-fold serial dilution of CeO_2-PANI ranging from 0 to 800 µg/mL.

3. Results and discussion

The X-ray diffractograms of PANI, CeO_2 and PANI@CeO_2 composite are referred in Fig. 1. The broad characteristic apices at 20-25 degree indicate amorphous polyaniline phase (Fig. 1a) (Jeong et al., 2014). The diffraction peaks at 28.31, 32.91, 47.31, 56.01, 59.61 and 69.01 correspond to cubic configuration of CeO_2 (Hassan et al., 2016).

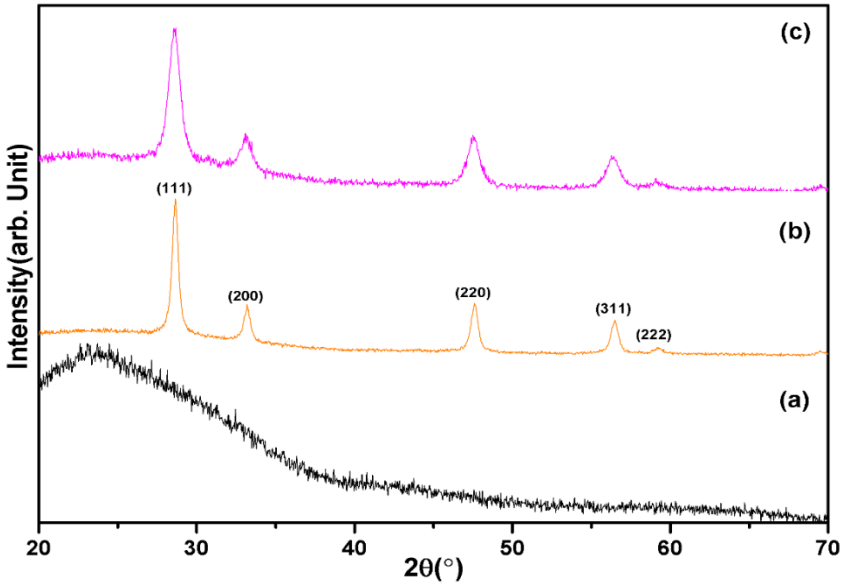


Figure 1. XRD pattern of (a) PANI (b) CeO_2 and (c) CeO_2-PANI heterostructure

High intensity of peaks proved crystallinity of CeO_2 (Fig. 1b). On the other hand, PANI@CeO_2 composite is composed of all the characteristic peaks of phase CeO_2 whereas distinguishing peaks of PANI were not detected in composite due to amorphous nature of PANI (Fig. 1c). The crystallite sizes of pristine CeO_2 and the CeO_2-PANI heterostructure were estimated using the Debye-Scherrer equation based on the prominent CeO_2 (111) diffraction peak. The calculated crystallite sizes were approximately 7.98 nm for CeO_2 and 13.65 nm for the CeO_2-PANI heterostructure, indicating that the incorporation of PANI did not significantly alter the crystallite size of CeO_2. During heterostructure formation, PANI may modify the local chemical environment around CeO_2 particles, allowing smaller CeO_2 crystallites to grow or reorganize into larger crystalline domains. The surface morphology of the composite powders can be observed by FESEM analysis. Figure 2a determines SEM views of pure PANI having tubular structures. As shown in Figure 2b, pure CeO_2 is rounded in shape and exhibited nano-size. Whereas Fig 2(c, d) shows the images of CeO_2-PANI, it clearly demonstrated the heterostructure having CeO_2 nanocrystals distributed over the PANI nanotube.

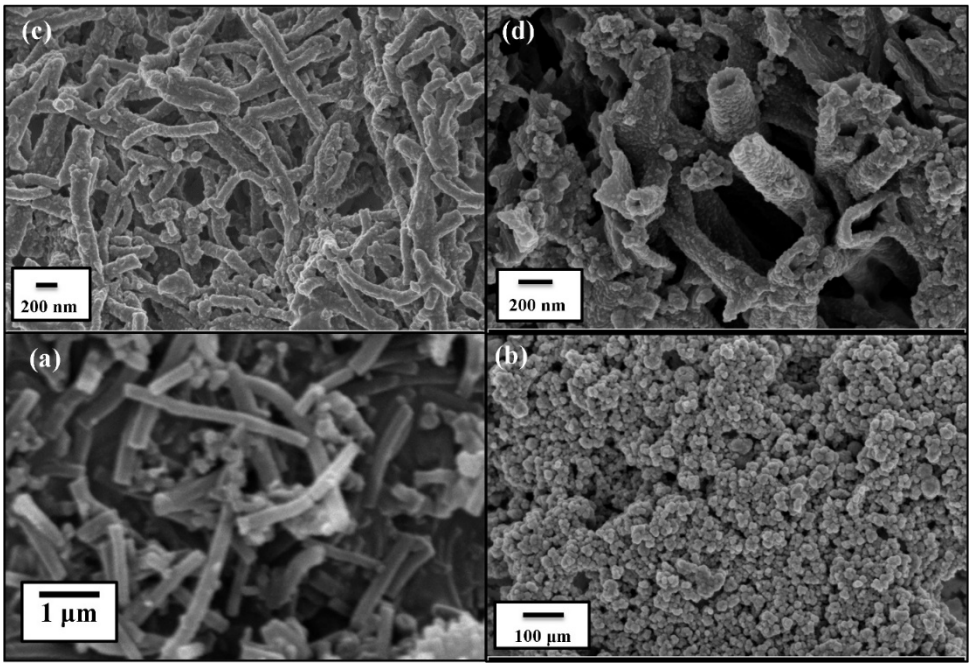


Figure 2. FESEM images of (a) pure PANI (inset shows high magnification), (b) CeO_2 and (c, d) CeO_2-PANI NTs at different magnifications

These results were further explained and confirmed by TEM images (Fig. 3). Fig. 3a shows TEM micrograph of CeO_2 sample which clearly shows the formation of spherical nanocrystals having diameters around 7-8 nm. Whereas PANI shows the tubular structure having diameter of the nanotube, ranges between 100 to 200 nm (Inset Fig. 3a). Fig. 3 (b, c) shows the high-resolution TEM appearance of CeO_2-PANI heterostructure. Microstructures reflected two distinct pictures, one having dark crystalline structure of CeO_2 and another image shows amorphous PANI. The SAED pattern of composite displays the multi-crystalline nature of composite (Fig. 3d).

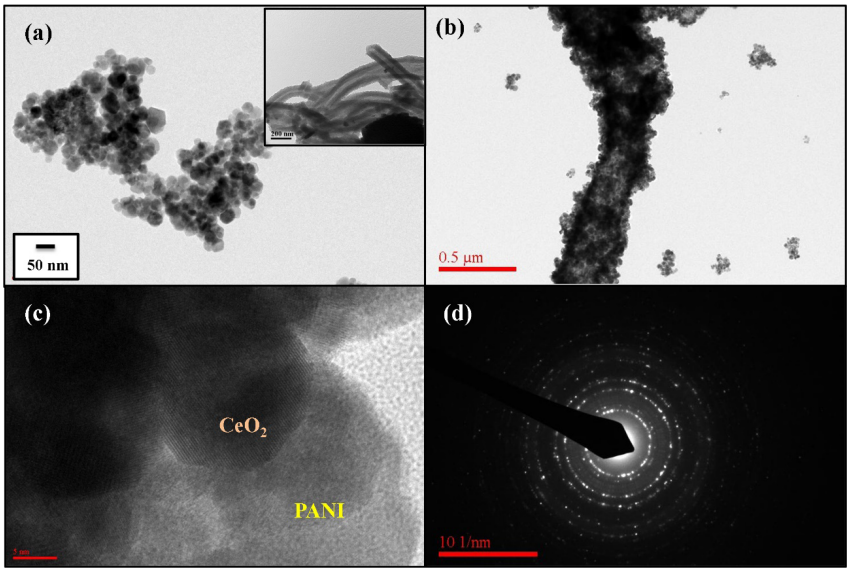
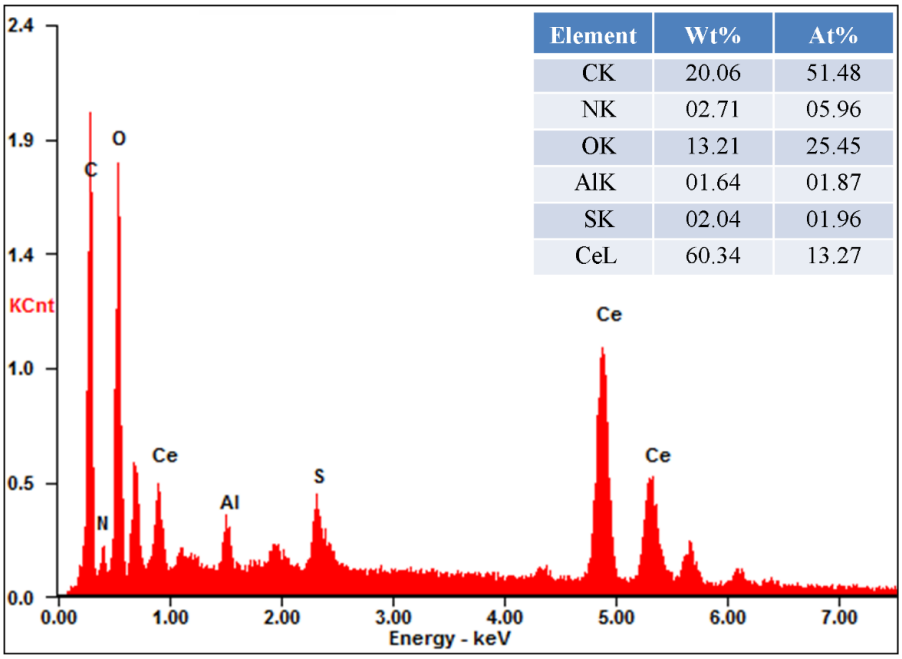


Figure 3. TEM image of (a) CeO_2 NCs (Inset shows image of PANI NTs) (b) CeO_2-PANI heterostructure (c) HR-TEM image and (d) SAED pattern of CeO_2-PANI

EDS analysis was employed to determine the composition of heterostructure (Fig. 4). The sample contains Ce, C, N and O elements, which further authorizes the presence of CeO_2 particles on exterior of PANI nanotubes. Appearance of Sulphur is ascribed to remnants of ammonium peroxodisulphate, utilized as an oxidant in preparation of PANI. Aluminum peak is due to the sampling of EDX was done on aluminum foil.



Element	Wt%	At%
CK	20.06	51.48
NK	02.71	05.96
OK	13.21	25.45
AlK	01.64	01.87
SK	02.04	01.96
CeL	60.34	13.27

Figure 4. EDX spectrum of CeO_2-PANI heterostructure

FT-IR spectral lines for pure PANI, CeO_2 and CeO_2-PANI heterostructure are revealed in Figure 5. Figure 5a describes representative FTIR of PANI. Characteristic peaks at 1567 cm^{-1} and 1493 cm^{-1} were assigned to C=N widening of quinoid and C=C stretching of the benzoid rings. The stretches at 1240 and 1298 cm^{-1} link to C-N expanding in benzene and quinone rings. The stretch out peak of quinone ring is confirmed by absorption crest (1148 cm^{-1}). Crowning at 820 cm^{-1} is C-H bond-bending vibration of disubstituted benzene ring outward surface (He, Li, & Guo, 2012; Singu, Srinivasan, & Pabba, 2011). Presence of widening band sprinted around 400 cm^{-1} proves development of Ce-O bond (Ho, Yu, Kwong, Mak, & Lai, 2005) (Fig. 5b). Fig. 5c shows the spectrum of composite samples having all the peaks of CeO_2 and PANI with little shift in the peak position to the higher wave number side. All the spectrum demonstrated a wide peak at 3450 cm^{-1}, linking to-OH stretching of water and hydroxyl clusters.

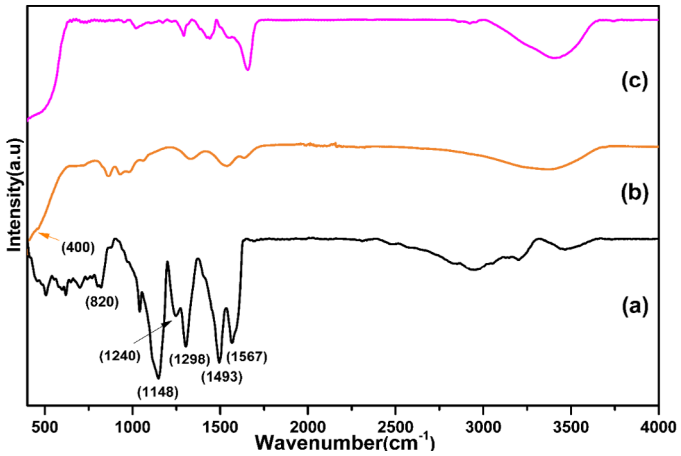


Figure 5. FT-IR spectra of (a) PANI (b) CeO_2 and (c) CeO_2-PANI heterostructure

UV-vis diffuse reflectance spectra of PANI, CeO_2 and CeO_2-PANI heterostructure are illustrated in Fig. 6. PANI (Fig. 6a) indicates two typical crests centered at about 350 and 680 nm wavelengths. The absorption at 380 nm is owed to p-p* transition on polymer and second band at 680 nm attributed to exciton transition (Guo et al., 2013). The spectrum of CeO_2 shows that it has high absorption in UV section and weak absorption in visible light (Fig. 6b). The calculated band gap energy is 3.15 eV (H. Wang, Yang, Yu, & Peng, 2011). Compared to CeO_2, CeO_2-PANI showed absorption to higher wavelength with high intensity (Fig. 6c). The value of band gap energy calculated from spectrum was 3.05 eV. So, the heterostructure showed narrow band gaps and broadened light absorption. The change in absorption of CeO_2-PANI composite is attributed to development of hydrogen bonding between CeO_2 crystals and NAH groups in PANI (Li et al., 2003). These CeO_2-PANI heterostructures have been applied to remove R6G under visible light. Dyes are lethal in nature, but their stoppage is not possible owing to their diverse applications. These dyes possess complicated configurations having multiple functional groups. Furthermore, besides having hazardous impact on marine existence, these dyes are carcinogenic also. Therefore, their eradication from waterbodies is essential. The colored dyes accumulation impedes sunlight penetrating water, thus disturbing the life of water ecosystems significantly. Even these wastewater reservoirs are not suitable for land irrigation. In this regards the photocatalytic dilapidation is believed to be a green approach that transforms photonic energy into useful chemical energy (Haleem et al., 2024).

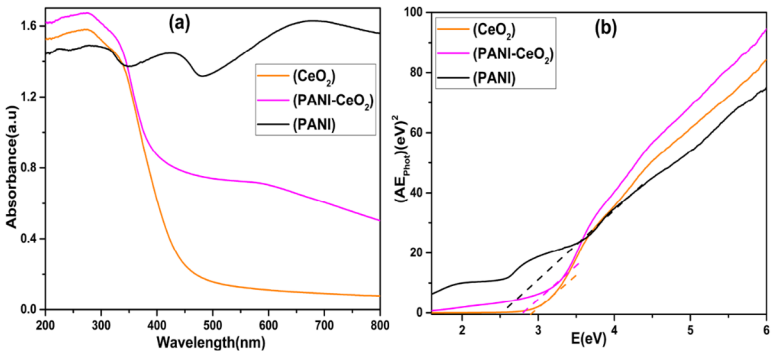


Figure 6. (a) UV-Vis diffuse reflectance spectra and (b) plot of Kubelka-Munk function vs. photon energy of the pure PANI, CeO_2 and CeO_2-PANI heterostructure

The photodegradation of PANI, CeO_2 and CeO_2-PANI materials were assessed via disintegration of R6G in visible light. When irradiated by visible light, PANI and CeO_2 exhibit photocatalytic activity of about 15% and 45% of R6G decomposition in 150 min. Compared with PANI and CeO_2, the CeO_2-PANI composite materials possess better photocatalytic properties (Fig.7a). Approx. 76% R6G can be photodegraded by the composite photocatalyst under the same condition. The high efficiency can be inferred to the parting of photogenerated electron-hole pairs owing to development of a p-n heterojunction between CeO_2 and PANI (Yu et al., 2018). Nonetheless, it has been well identified that semiconductors have a small band gap between conduction and valence bands, thus the electrons could easily be excited from the VB to CB after illumination (Haleem et al., 2024). Furthermore, to investigate the reaction kinetics of R6G degradation, the pseudo-first-order kinetic reaction eqn. (1) was applied in the experiments:

$$\ln(C_0/C) = k_{app}t \quad (1)$$

Where C_0 is original concentration of R6G, C is concentration of R6G at different reaction time and k_{app} is pseudo-first-order rate constant (min^{-1}). The corresponding linear transforms in $\ln(C_0/C)$ as a function of illumination time are given in Fig. 7b. The value of calculated k_{app} for PANI, CeO_2 and CeO_2-PANI composite were 0.0007 min^{-1}, 0.004 min^{-1} and 0.01 min^{-1}, respectively. The degradation rate constant of CeO_2-PANI was around 14.2 and 2.5 times higher than those of PANI and CeO_2, respectively.

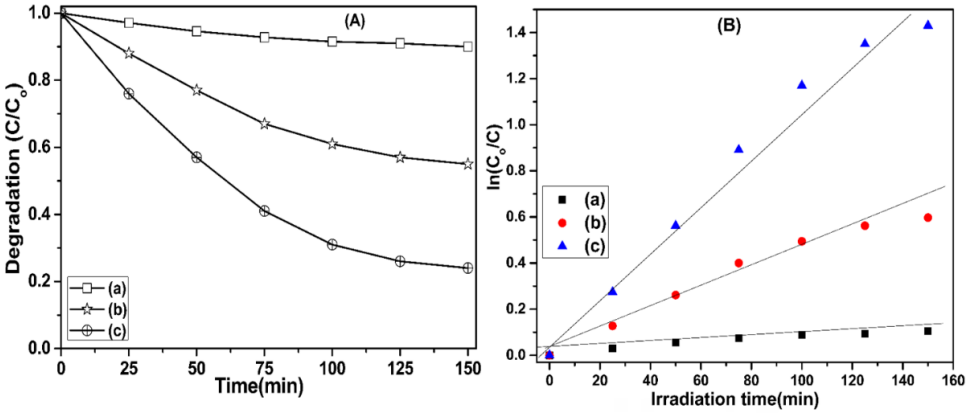


Figure 7. (A) Photocatalytic degradation and (B) Fitted pseudo first-order kinetics for degradation of R6G dye by (a) PANI (b) CeO_2 (c) CeO_2-PANI heterostructure

To investigate the recyclability of optimized photocatalysts, CeO_2-PANI were used for five photocatalytic cycles of degradation of R6G in aqueous solution. After each photocatalytic degradation, the photocatalyst was separated, washed and dried, and used for further run without any treatment. Fig.8 shows the recycling test of CeO_2-PANI heterostructure for degradation of R6G. The R6G degradation shows a bit decrease in efficiency with increase in cycle number but still efficiency was good even after 5 cycles. The R6G degradation rates were 76%, 75%, 74%, 73% and 73%, respectively showing better stability of photocatalyst.

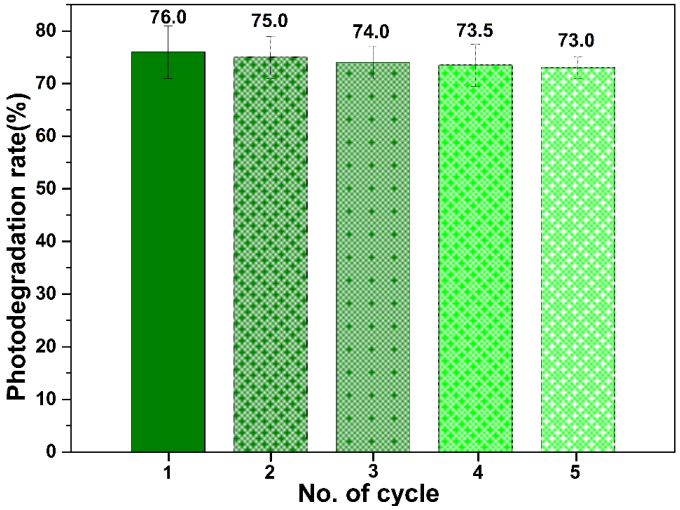


Figure 8. Photocatalytic efficiency of R6G dye by CeO_2-PANI heterostructure in cycles

Scheme 1 depicts a proposed hypothesis of charge separation and enhancement of photodegradation of CeO_2-PANI heterostructure (Fig.9). The CB of CeO_2 was lower than LUMO of PANI, so it works as a reservoir for photogenerated electrons in CeO_2-PANI photocatalyst. The VB CeO_2 was lower than HOMO of PANI, so the later could act acceptor for photogenerated holes (Cho, Park, Hwang, & Choi, 2004; Lotfi, Ouardi, Ahsaine, & Assani, 2022; Sharma & Khare, 2018; Turkten, Karatas, Kurumoglu, & Gurkan, 2025). Therefore, the CeO_2 and PANI can be excited by visible light and the electrons from PANI may be transferred to CeO_2 CB. Simultaneously, holes in VB of CeO_2 can spontaneously injected to HOMO of PANI. Consequently, the photogenerated electrons and holes rolled in opposite ways, reducing the chances of recombination, Therefore, reaction triggers development of super oxide radical ion and hydroxyl radical, ultimately ensuing high photodegradation efficiency which leads to degradation of dye (Turkten et al., 2025).

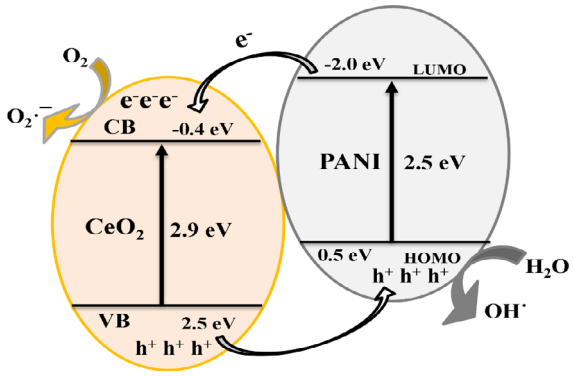


Figure 9. Schematic diagram illustrating mechanism of charge transfer and separation of CeO_2-PANI under visible-light irradiation

To evaluate antibacterial efficacy of CeO_2-PANI, a range of concentrations were systematically investigated, as illustrated in Fig.10. Experimental results revealed that the minimum inhibitory concentration for foodborne bacterial strains was determined to be 100 µg/mL. A concentration dependent increase in antibacterial activity was detected, with momentous inhibition of bacterial proliferation, particularly during exponential growth stage. Conspicuously, at highest concentration tested (400 µg/mL), complete bacterial growth inhibition was accomplished (Fig.10a, b). CeO_2-PANI confirmed persistent antimicrobial potential against foodborne bacteria, emphasizing their broad-spectrum effectiveness. Perceptibly these results indicate that antimicrobial performance is closely linked to both concentration of heterostructure and successful incorporation of CeO_2 NCs within the PANI NT matrix. Mechanistically, antibacterial activity of CeO_2-PANI is accredited to a synergistic interaction of physicochemical progressions. It is anticipated that upon introduction to aqueous environments, the CeO_2 NCs produce reactive oxygen species (ROS), for instance, hydroxyl radicals (•OH), superoxide anions ($O_2•^-$), and hydrogen peroxide (H_2O_2). These ROS induce oxidative stress within bacterial cells, ensuing in lipid peroxidation, protein denaturation, and nucleic acid degradation, eventually triggering cell death. Furthermore, the high aspect ratio structure of CeO_2-PANI heterostructure enables physical distraction of bacterial sheaths, leading membrane penetrability, therefore triggering cytoplasmic seepage. Additionally, the discharge of Ce^{3+}/Ce^{4+} ions interfere with enzymatic activity, bind to vital molecules, impair important metabolic and replication paths, thus collectively contribute to bacteriostatic and bactericidal activity (Ghodake et al., 2025).

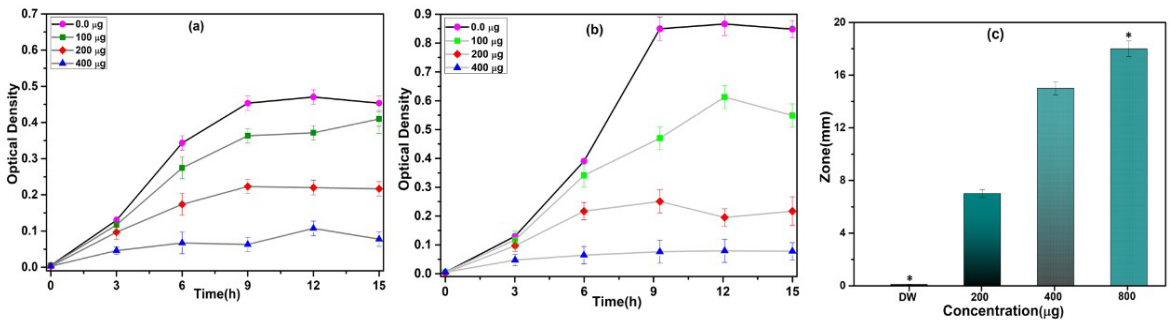


Figure 10. Antimicrobial sensitivity of (a) S. aureus (b) S. typhimurium after 20 h (c) C. albicans fungus after 72 h with CeO_2-PANI heterostructure at different concentrations (0-800 µg/mL). Data imply mean ± SD (*p≤0.05). Statistical calculations were done on Origin Pro2016 software

The matrix of PANI NT provide extra purposeful assistances, such as improved dispersion and equilibrium of CeO_2 NCs, electrochemical reactivity, environmental resilience, and effortlessness of surface amendments. These features style CeO_2-PANI heterostructure a versatile and promising candidate for assimilation into progressive antimicrobial material, such as filtration membranes, protective coatings, or water purification systems. In analog, the anticandidal activity of CeO_2-PANI heterostructure was evaluated by means of broth dilution technique against Candida albicans, designated as an illustrative fungal strain. The MIC was determined to be 100 µg/mL, while a pronounced antifungal effect was detected at higher concentrations, predominantly at 800 µg/mL, as portrayed in Figure 10c. The antifungal mechanism, parallel to antibacterial action, is predominantly driven by ROS production enabled by redox-active Ce^{3+}/Ce^{4+} species under aqueous settings. Likewise, it is expected that these species will dislodge fungal cell membranes, disintegrate crucial proteins, and produce DNA destruction (Fig.11). Amalgamation with PANI NT not only expands bioavailability of CeO_2 NCs but also augments interaction with fungal surfaces due to high aspect ratio and intrinsic electroactivity.

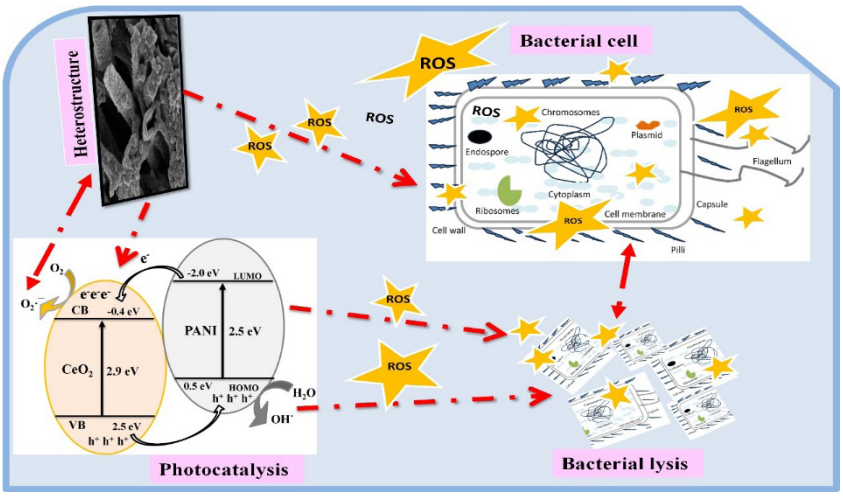


Figure 11. Proposed schematic overview of antimicrobial activity mechanism of CeO_2-PANI heterostructure

Conclusively, the CeO_2-PANI NTs exhibits robust antimicrobial properties via manifold harmonizing mechanisms. Nevertheless, its exclusive physicochemical features, united with exceptional biocidal competence, place them as a next generation nanotextured material for mitigating microbial contamination and ensuring safe, clean water.

4. Conclusion

To sum up, the untreated dye-containing effluents can pollute waterways, damage aquatic ecosystems, and degrade overall water quality. Likewise, pathogenic bacteria will continue to cause outbreaks and fatalities worldwide, as no effective interventions have yet succeeded in eliminating them completely from food supply. Herein the CeO_2-PANI NTs were effectively primed via in situ deposition oxidative polymerization of aniline monomer. The microstructure has been investigated and discussed in detail. The FT-IR results confirmed the interaction between PANI and CeO_2 in heterostructure. This demonstrated compelling absorption in visible light region and exhibited enhanced photocatalytic efficiency for the degradation of Rh6 G dye. A possible photocatalytic and antimicrobial mechanism is proposed. Additional studies are obligatory to progress effective approaches which could be blend of existing practices and those being developed. In this direction, CeO_2-PANI have shown great potential in photocatalysis and antimicrobial applications. This hybrid material synergistically combines redox-active properties of CeO_2 NCs with high surface area and conductive polymer matrix of PANI nanotubes, resulting in enhanced antimicrobial performance. The heterostructure not only inhibits microbial growth but can also prevent biofilm formation on surfaces, a key factor in reducing long-term contamination in water systems. The development of new materials and exploration of their applications in various fields are expected to further enhance their potential and impact in environmental and health sectors.

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4. **Ethical approval:** Not applicable.
5. **Compliance with ethical standards:** Not applicable

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Perceived Burden of Caring for Children with Disabilities and Its Impact on Caregivers' Quality of Life Domains: A Cross-Sectional Study

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Abstract
Background: Caring for children with disabilities imposes multidimensional demands on caregivers, affecting their physical, psychological, social, and environmental quality of life (QoL). Evidence from southern Saudi Arabia across all QoL domains remains limited.

Objective: This study examined the association between caregiver burden and sociodemographic factors with QoL across four domains among caregivers of children with disabilities in Jazan, Saudi Arabia.

Methods: A cross-sectional study was conducted from June to November 2023 among 120 caregivers recruited from rehabilitation centers in Jazan. Data were collected using the Arabic WHOQOL-BREF and the Arabic Short Form Zarit Burden Interview (ZBI-12). Multiple linear regression analyses were performed.

Results: Caregivers reported moderate QoL; 50% moderate, 25% low, and 25% high. Higher caregiver burden was significantly associated with lower QoL across all domains ($p < 0.001$). Employment was positively associated with physical, psychological, and social QoL. Older age negatively affected social and environmental QoL, while education was positively associated with social QoL. Marital status and disability type were not significant predictors. Models explained 14%–24% of variance.

Conclusion: Caregiver burden is the main determinant of QoL, while age and employment affect specific domains. Integrating caregiver support into rehabilitation services is recommended..

Keywords: Caregiver burden, quality of life, disability, caregivers, Saudi Arabia.

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1. Introduction

Quality of life (QoL) is widely recognized as a multidimensional construct encompassing physical, psychological, social, and environmental domains(Group, 1996; Skevington et al., 2004). Among caregivers of children with disabilities, QoL is influenced by multiple factors, including the child's characteristics, type and severity of disability, family stress levels, and the availability of social and environmental support (Almulla et al., 2024; Asiri et al., 2023; Sulaimani et al., 2023). In this context, QoL reflects not only caregivers' physical well-being but also their emotional resilience, social participation, and access to supportive services, highlighting the need for a comprehensive framework to understand caregivers' overall well-being.

Caring for children with physical, developmental, or sensory disabilities has challenges and demands long-term responsibilities, which reflect on the lives of caregivers. The caregiving demands are increased by continuous monitoring, interventions, and support needed for children with disabilities such as cerebral palsy or autism(Dlamini et al., 2023; Rizzo et al., 2024). Research has demonstrated that caring responsibilities can be both rewarding and challenging, with subsequent effects on parents' well-being (Organization & Fund, 2023). Caregiver's quality of life (QoL) is influenced by the child's personality, the nature of disability, parenting style, stress level in the family, the environment of the child, the society in which they live, and the help they received(Almulla et al., 2024).

The concept of caregiver burden is defined as "the level of multifaceted strain perceived by caregiver from caring for a family member and/or loved one over time"(Liu et al., 2023). The perceived burden is consistently associated with QoL across all four dimensions, making it an area to explore when studying caregivers of children with disabilities(Sulaimani et al., 2023; Tedla et al., 2023).

Caring for children with disabilities often involves intense physical demands, for example, carrying, feeding, mobility assistance, and continuous medical monitoring. Shahali et al. (2024) have reported that parents frequently report sleep deprivation, chronic fatigue, and musculoskeletal pain(Shahali et al., 2024). The psychological burden is equally substantial, with elevated levels of stress, anxiety, melancholy, and emotional exhaustion associated with the severity of the child's disability and the uncertainty surrounding long-term outcomes(Almulla et al., 2024). The social domain highlights problems such as social stigma, limited leisure and career options, and strained family relationships, all of which reduce caregivers' social involvement and support(Alnahdi, 2024). In terms of the environment, caregivers face challenges such as accessing health services, financial strain related to care expenses, transportation issues, and limited community resources(Organization & Fund, 2023). These pressures affect caregivers' health and quality of life, underscoring the seriousness of the issue.

In Saudi Arabia, studies have reported a similar pattern of multidimensional challenges among caregivers of children with disabilities. For instance, research on parents of children with autism spectrum disorder (ASD) and cerebral palsy (CP) indicates considerably lower QoL scores, especially in the psychological and social categories(Al-Jabri et al., 2022; Tedla et al., 2023). A study conducted among Saudi mothers reported that psychological stress, social isolation, and role constraints, especially among single or divorced mothers, were significant (Alsamiri et al., 2024). Another study found that caregiver stress, insufficient social support, and fragmented services increase caregiving burden and lower overall QoL(Al-Otaibi et al., 2024). These findings underscore the critical need to better identify and manage caregivers' well-being in Saudi Arabia, particularly given cultural norms that place caregiving tasks predominantly on family members.

Although international and regional studies have examined QoL across the physical, psychological, social, and environmental domains, there is still a lack of research in Saudi Arabia that comprehensively examines these four domains while accounting for both mental and physical disabilities and sociodemographic factors. Existing Saudi research has frequently focused on specific disabilities, for example, ASD or CP (Al-Jabri et al., 2022; Al-Otaibi et al., 2024) or aspects of caregiver well-being(Alsamiri et al., 2024). However, few have examined the overall relationship between perceived caregiver burden and its impact on four core domains of QoL. Furthermore, most available studies have been conducted in the north(Alsamiri et al., 2024), central (Al-Otaibi et al., 2024), or west (Al-Jabri et al., 2022) regions of Saudi Arabia, where health services and social support systems differ from those in the southern region. The southern region is characterized by more rural areas and limited access to specialized rehabilitation and mental health services(Lin & Yao, 2022). These contextual factors may influence caregivers' experiences, burden levels, and QoL. There is limited research in southern Saudi Arabia that examines all four QoL domains (physical, psychological, social, and environmental) simultaneously among caregivers of children with different types of disabilities. This gap limits a comprehensive understanding of caregivers' overall quality of life in this region.

2. Research Questions:

This study was guided by the following research questions:

1. What is the level of quality of life (QoL) across the four domains (physical, psychological, social, and environmental) among caregivers of children with disabilities?
2. What is the level of perceived caregiver burden among caregivers of children with disabilities?
3. Is there association between perceived caregiver burden and the four domains of QoL?
4. Is there association between caregiver's sochiodemographic characteristics and their Quality of life across the four domains?
5. Is there association between burden of QOL domains and their sociodemographic characteristics among caregivers of children with disabilities?

3. Operational Definitions:

A caregiver was defined as an adult who is a parent, legal guardian, or other adult providing care for a child with a disability.

4. Methods

4.1 Study Design

This study was a cross-sectional study conducted from June 2023 to November 2023.

4.2 Participants and Setting

The study population included male and female caregivers of children aged 0–18 years with physical, developmental, or sensory disabilities who were receiving services from multiple rehabilitation centers in Jazan, Saudi Arabia

Inclusion criteria were adults aged 18 years and above, male and female caregivers, Arabic speakers, and those providing care for at least one child with a physical, developmental, or sensory disability. Information regarding the number of children with disabilities under each caregiver's responsibility was also collected, as it may influence caregiver burden.

A convenience sampling technique was used to recruit participants from rehabilitation centers in Jazan, Saudi Arabia.

4.3 Sample Size

Sample sizes were determined using G*Power version 3.1 for multiple linear regression analysis, assuming a medium effect size ($f^2 = 0.15$), a statistical power of 0.80, and a significance level of 0.05. The minimum required sample size was 98 participants. To account for potential non-response or dropout, an additional 20% was added, resulting in a final target sample size of approximately 120 participants.

4.4 Instruments and Data Collection

Data were collected using online self-structured questionnaires.

- Sociodemographic questionnaire: A structured questionnaire was developed by researchers based on previous literature and standardized sociodemographic instruments used in caregiver research, such as the Sociodemographic Variables Questionnaire (Q-SV)(Toledano-Toledano et al., 2019). It included items on caregivers' age, gender, educational level, occupation, marital status, relationship to the child, and type of child disability.
- Environmental factors such as accessibility of rehabilitation services, transportation, and home environment were considered as contextual factors influencing caregiving burden rather than a separate category of disability.
- Employment status was categorized as student, employed, and unemployed. However, detailed occupational sectors (e.g., governmental, private, or self-employed) were not collected due to limitations in the data collection tool.
- The general health items represents a single overall perception of health and is not considered a separate QoL domain.

4.4.1 WHOQOL-BREF questionnaire-Arabic version:

The WHOQOL-BREF, adopted from the World Health Organization (1996), was used to assess caregivers' quality of life across four domains: physical health, psychological health, social relationships, and environmental health. The validated Arabic version of the instrument was employed in this study.

The WHOQOL-BREF consists of 26 items rated on a 5-point Likert scale. Domain scores were calculated and transformed to a 0–100 scale, with higher scores indicating better quality of life. The Arabic version has demonstrated good validity and acceptable internal consistency in Arabic-speaking populations, with Cronbach's alpha coefficients ≥ 0.70, as reported by Ohaeri and Awadalla.(Ohaeri & Awadalla, 2009).

For interpretation purposes, total quality of life scores were categorized into three levels (low, moderate, and high) based on the quartile distribution of the sample scores. Scores at or below the first quartile were classified as low quality of life, scores between the first and third quartiles were classified as moderate quality of life, and scores at or above the third quartile were classified as high quality of life.

4.4.2 Zarit Burden Interview (ZBI-12, Arabic version)

The ZBI-12 was used to measure caregivers perceived burden. It consists of 12 items rated on a 5-point Likert scale (0 = never to 4 = nearly always), with total scores ranging from 0 to 48. Higher scores indicate greater perceived caregiver burden.

The Arabic version of the ZBI-12 has demonstrated good psychometric properties, with acceptable internal consistency (Cronbach's alpha reported in previous studies > 0.80) (Alshammari et al., 2023). It has been widely used in caregivers of individuals with chronic conditions and disabilities.

4.5 Data Analysis

Data were analyzed using SPSS version 31. Descriptive statistics, including frequencies, means, and standard deviations, were used to summarize sociodemographic characteristics and study variables.

Multiple linear regression analyses were performed to identify predictors of caregivers' quality of life. The independent variables included caregiver age, gender, marital status, education level, employment status, relationship to the child, type of child disability, and caregiver burden score (ZBI-12).

Four separate regression models were conducted, with each model corresponding to one WHOQOL-BREF domain: physical health, psychological health, social relationships, and environmental health. A p-value of < 0.05 was considered statistically significant.

4.6 Ethical Considerations:

Ethical approval was obtained from the Standing Committee for Scientific Research, Jazan University (HAPO-10-Z-001; REC-44/11/673) on 28 May 2023. The study was conducted in accordance with the Declaration of Helsinki. Informed consent was obtained electronically from all participants prior to participation, and confidentiality, anonymity, and voluntary participation were ensured.

5. Results

A total of 120 caregivers of children with disabilities participated in the study, the majority of whom were mothers (97.5%). Over half were younger than 25 years (52.5%), and 70.0% were married. Most caregivers had tertiary education (57.5%), while nearly half were unemployed (47.5%). The most common types of disabilities were sensory (35.0%), followed by physical and developmental disabilities (32.5% each).

Caregivers reported overall moderate quality of life. The mean total QoL score was 80.4 ± 19.8. Environmental health had the highest mean score, whereas social relationships had the lowest. Physical and psychological domains showed similar scores. The general health score (7.0 ± 2.5) also indicated moderate perceived health. The mean caregiver burden score was 19.3 ± 13.4 (Table 1).

Table 1. Distribution of caregivers according to their sociodemographic characteristics, quality of life, and caregiver burden (N = 120)

Variables	Categories	n (%) / Mean ± SD
Relation to the child	Mother	117 (97.5)
	Father	3 (2.5)
Age	<25 years	63 (52.5)
	25–45 years	42 (35.0)
	>45 years	15 (12.5)
Marital status	Married	84 (70.0)
	Divorced/Separated	36 (30.0)
Educational level	Secondary or below	51 (42.5)
	Tertiary (College/ University)	69 (57.5)
Employment status	Student	21 (17.5)
	Employed	42 (35.0)
	Unemployed	57 (47.5)
Type of disability	Physical	39 (32.5)
	Developmental	39 (32.5)
	Sensory	42 (35.0)
Quality of life domains (Mean ± SD)	Physical health	19.3 ± 4.6
	Psychological health	19.3 ± 4.2
	Social relationships	10.4 ± 3.7
	Environmental health	24.2 ± 7.5
	General health	7.0 ± 2.5
	Total QoL	80.4 ± 19.8
Caregiver burden	ZBI-12 score	19.3 ± 13.4

Note: General health refers to the single-item overall perception of health in the WHOQOL-BREF and is not a separate domain score.

5.1 Distribution of Quality-of-Life Levels

Caregivers' quality of life was categorized into three levels (low, moderate, and high) based on quartile distribution. Half of the caregivers (50.0%) reported a moderate level of QoL, while 25.0% had low QoL and 25.0% had high QoL (Table 2).

Table 2. Distribution of caregivers according to levels of total quality of life (N = 120)

QoL Level	Score Range	n	%
Low QoL	≤ 68	30	25.0
Moderate QoL	69 – 98	60	50.0
High QoL	≥ 99	30	25.0
Total	120	100%	

Association Between Quality-of-Life Levels and Sociodemographic Characteristics

A statistically significant association was observed between QoL levels and both educational attainment and employment status ($p < 0.05$), indicating that caregivers with higher education and those engaged in employment demonstrated better quality of life. However, no significant associations were identified between QoL levels and age, marital status, or type of disability ($p > 0.05$), suggesting that these variables did not influence perceived quality of life in this sample (Table 3).

Table 3. Association between levels of quality of life and sociodemographic characteristics (N = 120)

Variable	Category	Low N (%)	Moderate N (%)	High N (%)	χ^2	p-value
Age	<25 years	18 (28.6)	30 (47.6)	15 (23.8)	4.21	0.38
	25–45 years	9 (21.4)	24 (57.1)	9 (21.4)		
	>45 years	3 (20.0)	6 (40.0)	6 (40.0)		
Marital status	Married	18 (21.4)	48 (57.1)	18 (21.4)	3.89	0.14
	Divorced/ Separated	12 (33.3)	12 (33.3)	12 (33.3)		
Educational level	Secondary or below	18 (35.3)	24 (47.1)	9 (17.6)	6.52	0.038*
	Tertiary	12 (17.4)	36 (52.2)	21 (30.4)		
Employment status	Student	6 (28.6)	12 (57.1)	3 (14.3)	7.11	0.029*
	Employed	6 (14.3)	24 (57.1)	12 (28.6)		
	Unemployed	18 (31.6)	24 (42.1)	15 (26.3)		
Type of disability	Physical	9 (23.1)	21 (53.8)	9 (23.1)	2.34	0.67
	Developmental	12 (30.8)	18 (46.2)	9 (23.1)		
	Sensory	9 (21.4)	21 (50.0)	12 (28.6)		

Note: $p < 0.05$ indicates statistical significance

5.2 Regression Analysis

Multiple linear regression analyses were performed to identify predictors of caregivers' QoL across different domains. Caregiver burden was a significant negative predictor across all domains ($p < 0.001$). Employment status showed a positive association with physical, psychological, social, and general health Item. Older age was negatively associated with social relationships and environmental health, while higher educational level was positively associated with social relationships. Marital status and type of disability were not significant predictors (Table 4).

Table 4. Multiple regression analysis to examine the association between caregivers' perceived burden and their QoL domains

Variables	Physical Health β (p)	Psychological Health β (p)	Social Relationship β (p)	Environmental Health β (p)	General Health β (p)
Caregivers' age	-0.18	-0.18	-0.32*	-0.33**	-0.21
Marital status	0.08	0.08	0.02	0.10	0.05
Educational level	0.09	0.09	0.24*	0.06	0.12
Employment status	0.19*	0.19*	0.20*	0.16	0.18*
Type of disabilities	-0.01	-0.01	-0.06	-0.08	-0.04
Caregiver burden	-0.33**	-0.33**	-0.27*	-0.38**	-0.30**

Note: β: standardized coefficient, * $p < 0.05$, ** $p < 0.001$

5.3 Domain-specific regression results

The regression models for all QoL domains were statistically significant. Caregiver burden consistently emerged as a significant negative predictor across all domains ($p < 0.001$). Employment status showed a positive association with physical, psychological, social, and general health items.

Specifically, the physical and psychological health models explained 16% of the variance ($R^2 = 0.16$), while the environmental health model explained a higher proportion ($R^2 = 0.24$), with caregiver burden and older age identified as significant negative predictors. The social relationships model explained 14% of the variance ($R^2 = 0.14$), where caregiver burden and age were negatively

associated, whereas educational level and employment status were positively associated.

6. Discussion

This study examined the predictors of quality of life (QoL) among caregivers of children with disabilities across five domains: physical, psychological, social, environmental, and general health. Overall, caregivers reported moderate levels of QoL, which is consistent with previous studies conducted in Saudi Arabia indicating that caregivers often maintain a moderate level of well-being despite ongoing caregiving challenges (Alnahdi & Schwab, 2024).

The predominance of mothers in this study highlights the culturally embedded role of maternal caregiving within Saudi families. This finding aligns with prior research indicating that mothers are more likely to assume primary caregiving responsibilities, which may expose them to higher levels of physical and emotional burden (Sulaimani et al., 2023).

A key finding of this study is that caregiver burden was a strong and consistent negative predictor across all QoL domains, including general health. This suggests that increased caregiving demands are associated with poorer physical condition, emotional distress, reduced social interaction, and lower overall health perception. These findings are in line with previous research showing that caregiving burden contributes to fatigue, stress, and reduced life satisfaction (Shahali et al., 2024). The inclusion of general health further strengthens this evidence, indicating that burden affects not only domain-specific outcomes but also caregivers' overall health perception.

Employment status emerged as a significant positive predictor of QoL across multiple domains, including physical, psychological, social, and general health. This may be explained by the benefits of financial stability, social engagement, and enhanced self-efficacy associated with employment (Watson et al., 2021). In contrast, unemployment may exacerbate financial strain and social isolation, negatively influencing caregivers' well-being.

Interestingly, although a considerable proportion of caregivers had higher education, education had a limited domain-specific effect rather than being a consistent predictor . This suggests that education alone may not mitigate the complex burden of caregiving. Instead, access to support systems and coping resources may play a more crucial role (Cejalvo et al., 2021).

Age was found to be negatively associated with social and environmental QoL domains, indicating that older caregivers may experience more challenges related to social participation and access to supportive resources. This may be due to increased physical fatigue and long-term caregiving strain (Abeasi et al., 2024).

Consistent with earlier findings, the type of child disability was not significantly associated with QoL outcomes. This suggests that caregiving challenges may be similar across different disability types, particularly in terms of emotional and practical demands. It may also reflect improved healthcare access and support services in Saudi Arabia, reducing disparities between disability categories (Sulaimani et al., 2023).

Furthermore, the analysis of QoL levels indicated that most caregivers fell within the moderate category, with fewer participants reporting high or low QoL. This distribution reinforces the overall pattern observed in the mean scores and highlights the need for targeted interventions to shift caregivers toward higher well-being levels.

Overall, the findings emphasize that caregiver burden and employment status are the most influential factors affecting QoL, while sociodemographic variables play a secondary role.

These results underscore the importance of implementing supportive interventions such as psychological counseling, caregiver support programs, financial assistance, and flexible employment opportunities.

The regression models demonstrated moderate explanatory power, explaining between 14% and 24% of the variance across QoL domains.

Overall, the regression models demonstrated modest explanatory power, suggesting that additional unmeasured psychosocial and environmental factors may influence caregivers' quality of life.

Healthcare providers play a critical role in improving caregiver outcomes by facilitating access to rehabilitation services, offering health education, and integrating psychosocial support into routine care. Addressing caregiver burden through structured interventions may lead to meaningful improvements in both domain-specific QoL and overall health.

7. Limitations

This study has several limitations that should be acknowledged. First, the cross-sectional design limits the ability to establish causal relationships between caregiver burden and quality of life outcomes. Second, data were collected within a relatively short period, which may not fully capture fluctuations in caregivers' experiences over time.

In addition, challenges in reaching caregivers with high caregiving burden or limited availability may have introduced selection bias. The use of convenience sampling may limit the generalizability of the findings to the broader population of caregivers in Saudi Arabia. Furthermore, the use of a non-random sampling approach may introduce selection bias.

The use of an online questionnaire may also have excluded caregivers with limited digital literacy, potentially affecting sample representativeness. Moreover, the study did not include detailed classification of occupational sectors and some contextual variables, which may have limited a more comprehensive understanding of socioeconomic influences. Finally, the study was conducted in rehabilitation centers within one region of Saudi Arabia, which may further limit generalizability.

7.1 Implications for practice

The findings of this study have important implications for clinical practice and health service planning. The predominance of mothers as caregivers highlights the need for family-centered and gender-sensitive interventions, with a focus on providing psychosocial support, caregiver education, and counseling services.

Given that employment was identified as a protective factor for quality of life, policies that promote flexible working conditions, caregiver-friendly workplace environments, and social protection programs are essential to enhance caregivers' financial stability and well-being.

The strong association between caregiver burden and reduced quality of life across all domains, including general health, emphasizes the importance of routine caregiver burden screening in clinical and rehabilitation settings. Nurses and healthcare providers should integrate caregiver assessment into standard care pathways and facilitate timely referral to mental health and social support services. Older caregivers were found to have lower quality of life in specific domains, suggesting the need for age-sensitive support strategies to address their increased vulnerability and caregiving strain. Strengthening multidisciplinary collaboration between healthcare providers, social workers, and community-based organizations is essential to ensure comprehensive and continuous caregiver support.

8. Conclusion

In conclusion, this study demonstrates that caregiver burden, employment status, and age are key determinants of quality of life among caregivers of children with disabilities in southern Saudi Arabia. Higher caregiver burden and older age were associated with poorer quality of life across multiple domains, while employment served as a protective factor.

These findings highlight the importance of integrated, multidisciplinary support systems that address the psychological, social, and economic challenges faced by caregivers. Embedding caregiver support within rehabilitation and primary healthcare services may contribute to improved caregiver well-being and better family health outcomes.

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Knowledge, Attitudes, and Determinants of HPV Infection and Vaccination among Female University Students at Jazan University, Saudi Arabia

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Abstract

Background: Human papillomavirus (HPV) is a sexually transmitted infection that can result in many epithelial lesions and cancers. Worldwide, cervical cancer is the fourth most common type of cancer in women. Although HPV vaccines are readily available and have been shown to be effective, vaccination uptake remains insufficient.

Methods: A cross-sectional community-based study was carried out with 445 female students at Jazan University, Saudi Arabia, from April to September 2025, to assess knowledge, attitudes, practices, and factors influencing HPV vaccination. The Participants were selected through stratified and convenience sampling through an online questionnaire, and the data were analyzed by descriptive statistics and regression analyses.

Results: The study revealed that only 160 (43%) participants had previously heard of HPV. Knowledge of HPV transmission, related diseases, and vaccination rate was low. HPV vaccination uptake was limited (11%). Medical college students had significantly higher knowledge and more positive attitudes than non-medical students.
Vaccination uptake was significantly associated with college type, age, marital status, good knowledge, prior health education, and belief in vaccine effectiveness. Overall, knowledge was low, attitudes were negative, and HPV vaccination uptake was low among female university students.

Conclusion: HPV knowledge, attitudes, and vaccination were low; Health Belief Model strategies support Vision 2030 prevention goals.

Keywords: Human papillomavirus; Papillomavirus vaccines; Health knowledge, attitudes, and practice; Female students; Saudi Arabiad.

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1. Introduction

Human papillomavirus (HPV) is a sexually transmitted infection that can result in many epithelial lesions and cancers. Numerous genotypes have been found; the most prevalent ones are 6, 11, 16, and 18. Low-risk genotypes like 6 and 11 are linked to benign genital warts [1]. On the other hand, 16 and 18 are regarded as high-risk genotypes linked to genital tract cancers, particularly cervical cancer, and ovarian and endometrial cancers on occasion [1].

According to estimates, there were 36,068 new cases and 13,211 deaths from penile cancer and 604,000 new cases and 342 fatalities from cervical cancer globally in 2020. Worldwide, cervical cancer is the fourth most common type of cancer in women [2,3]. Saudi Arabia reported four new instances of penile cancer and two fatalities from the disease in 2020, along with 358 new cases of cervical cancer and 179 deaths from its consequences. In addition, penile cancer is the 35th most prevalent cancer in Saudi Arabia, and cervical cancer is ranked seventh [4].

The HPV vaccine could prevent more than 4 million female deaths in low- and middle-income countries over the following decade. Furthermore, WHO guidelines recommend a two-dose vaccination schedule for both girls and boys aged 9 to 14 years, while for older adolescents and any young adult who was not previously immunized, a three-dose catch-up series [5,6].

Multiple studies have demonstrated that HPV vaccination significantly reduces the infection caused by types 6,11, and 18, as well as the genital warts, by approximately 90% and reduces the rate of high-grade cervical lesions by up to 85% [5,7]. In Saudi Arabia, human papillomavirus vaccines have been incorporated into the national immunization program for females aged 11–26 years [8].

Although HPV vaccines are readily available and have been shown to be effective, the change of positive attitudes and knowledge into appropriate preventive measures remains less than its best. Adherence to suggested preventative behaviors, timely involvement in cervical cancer screening, and vaccination uptake are preventive measures associated with HPV. Studies show that actual HPV prevention measures are frequently insufficient even among groups with major awareness, especially among young adults and women [9]. In order to better understand obstacles to effective HPV prevention, it is essential to adopt a comprehensive Knowledge, Attitudes, and Practices (KAP) approach. Studies carried out in Saudi Arabia and other Arab countries have consistently reported gaps not only in knowledge and attitudes toward HPV infection and vaccination, but also in preventive practices [9,10,11,12].

The objective of this study was to assess the Knowledge, attitudes, and practices of female students at Jazan University towards human papillomavirus infection and its vaccine. The study hypothesized that female students have inadequate knowledge, attitudes, and practices regarding HPV infection and vaccination, and that HPV vaccine uptake varies by age, marital status, and source of information.

2. Materials and Methods

2.1 Study design and setting

A cross-sectional community-based descriptive study was conducted to assess the Knowledge, attitudes, and practices of female students regarding human papillomavirus infection and vaccination at Jazan University, from April to September 2025.

The target population includes all female undergraduate students enrolled at Jazan University during the 2024-2025 academic year.

2.2 Study participants and sampling

The study population consists of female students at Jazan University, Saudi Arabia, with the inclusion criteria of being registered students, agreeing to participate, and providing informed electronic consent. Both medical and non-medical college students were included to ensure adequate representation of different academic disciplines.

The sample size was calculated using Cochran's formula:

$$n0 = (Z^2 \times p \times (1-p)) / e^2$$

Where Z = 1.96 corresponds to a 95% confidence level, p = 0.5 represents the estimated population proportion, and e = 0.05 the margin of error. 384 participants. This was increased to 445 to account for an anticipated non-response rate.

An online self-administered questionnaire, distributed through university email, student leaders, and student social media platforms, was used to collect data. Most responses were from the Students' University email. A stratified sampling approach was used based on college type (medical and non-medical), and a convenience sampling technique was applied to recruit the participants.

Among survey respondents, female students who agreed to participate and completed the questionnaire were included in the study. In contrast, those who declined participation or submitted incomplete responses were excluded. Among participants, students who reported prior awareness of Human Papillomavirus (HPV) were included in the detailed analysis of knowledge-related items.

3. Method of data collection

A self-administered standardized questionnaire was built based on relevant literature, including previous KAP studies on HPV among Saudi university students and women [13.14,15]. The questionnaire was initially designed in English, then translated into Arabic, and subsequently back-translated into English by independent specialists to ensure the language and concept reliability. Content validity was assessed by three academic experts in public health, who reviewed the questionnaire for relevance, clarity, and comprehensiveness.

A pilot study was conducted among 20 participants to evaluate the clarity, accuracy and reliability of the questionnaire. Minor modifications included rephrasing unclear questions and improving the sequence of items for better comprehension. Internal consistency was assessed using Cronbach's alpha, which demonstrated acceptable reliability, with a value of 0.75.

3.1 The questionnaire consisted of five sections:

The first section aimed to inform participants about the study objectives, confidentiality, and voluntary participation, with electronic informed consent obtained. The second section collected demographic data, including age, marital status, and college type. The third section about the assess knowledge regarding HPV infection. HPV knowledge using a scoring system. Each correct answer was scored 1 point, with total scores ranging from 0–14, categorized as:

- Poor (0–6)
- Moderate (7–9)
- Good (10-14)

The fourth section aimed to evaluate the attitudes toward HPV vaccination, including perceptions of vaccine safety and efficacy, protection against HPV infection and cervical cancer, and willingness to receive or recommend the vaccine. Each correct answer was scored 1 point, with total scores ranging from 0–10), categorized as:

- Negative (0–5)
- Positive (6- 10)

The fifth section aimed to determine HPV vaccination uptake and the reasons influencing vaccination decisions. It included items on whether participants had received HPV vaccination or health education, reasons, and barriers to vaccination. This section was analyzed descriptively using frequencies and percentages.

3.2 Method of data analysis

Data were entered into Microsoft Excel and analyzed using the Statistical Package for Social Sciences (IBM SPSS Statistics version 29). Descriptive statistics, including frequencies and percentages, were computed and reported. Multiple linear regression was used to examine associations between students' sociodemographic characteristics and their knowledge, attitudes, and practices regarding HPV infection. In contrast, logistic regression was used to predict HPV vaccination status. A p-value < 0.05 was considered statistically significant.

4. Results

4.1 Knowledge about HPV infection and HPV Vaccination

Of 445 approached students, 384 completed the survey, resulting in a response rate of 86%. Only 160 (43%) had heard of Human Papillomavirus (HPV among them, the knowledge was limited. (41%) said the virus is transmitted sexually and (23%) linked it to cervical cancer. Regarding vaccination, only (20%) knew about the availability of the vaccine, and (14%) recommended HPV vaccination for those aged 9-25 years. 19% said the vaccine should be administered in multiple doses. Furthermore, 31% of respondents agreed that routine Pap screens are the best way to prevent HPV- related complications [Table 1].

Table 1: Knowledge about HPV infection and HPV Vaccination among Female University students who had ever heard of HPV (n = 160)

Items	n(%)
HPV is transmitted through sexual contact	66 (41%)
Diseases can cause Cervical cancer	37 (23%)
Diseases cause Genital warts	33 (21%)
Skin warts	28 (18%)
Penile cancer	22 (14%)
Both males & females can get infected with HPV	57 (36%)
HPV infection is not rare	110 (69%)
The highest incidence occurs during the 20s -30s	90 (56%)
People with genital HPV develop symptoms	70 (44%)
HPV is curable	83 (52%)
Availability of the HPV vaccination	32 (20%)
Recommended HPV vaccination aged (9-25 years)	24 (15%)
The vaccine is given in multiple doses	30 (19%)
Pap smears preventive	50 (31%)

4.2 Attitudes toward HPV Infection and Vaccination

Students showed limited positive attitudes toward HPV vaccination. Only 13% believed it was effective, and 15% considered it safe, while 21% thought screening was unnecessary after vaccination. However, 42% agreed to vaccinating males, and 77% were interested in learning more about HPV vaccination [Table 2].

Table 2: Attitudes toward HPV Infection and Vaccination among Female University Students (n = 160)

Item	n(%)
Cervical screening is unnecessary after receiving the vaccine	33 (21%)
HPV vaccination is effective in preventing cervical cancer	20 (13%)
The HPV vaccine is safe	24 (15%)
Should males/boys also be vaccinated	68 (42%)
Interest in learning more about HPV vaccination	123 (77%)

4.3 HPV Vaccination Status and Barriers

13% of participants reported having previously received health education about the HPV vaccine, with only 11% vaccinated, and the uptake was mainly due to perceived safety, effectiveness, and family history. Among the unvaccinated participants, the main barriers included lack of information, fear of side effects, perceived lack of necessity, and cultural reasons [Table 3].

Table 3: HPV Vaccination Status and Barriers among Female University Students(n = 160)

Item	%
Received HPV vaccine health education	21 (13%)
Received HPV vaccination	18 (11%)
Reasons for receiving HPV vaccination: safe and effective	8 (5%)
Reasons for receiving HPV vaccination: family history of cervical cancer	10 (6%)
Reasons for not receiving HPV vaccination: lack of information	86 (53%)
Reasons for not receiving HPV vaccination: fear of side effects	48 ()30%
Reasons for not receiving HPV vaccination: not necessary	6 (4%)
Reasons for not receiving HPV vaccination: cultural reasons	2 (1%)

4.4 Sociodemographic factors associated with the general score of knowledge of HPV infection and vaccination

Age and college type were significant predictors of general knowledge scores. Knowledge was positively associated with age, indicating higher scores among older students. A strong positive correlation was also found with college type, with medical students scoring significantly higher than non-medical students. Marital status showed no significant association with knowledge scores [Table 4].

Table 4: Linear Regression Analysis of sociodemographic factors associated with the general score of knowledge of HPV infection and vaccination

Sig.	T	Beta	Std. Error	B	Variables
.0000	4.986	-	0.139	0.691	(Constant)
<0.000	3.897	0.131	0.032	0.126	Age
0.000	22.914	0.769	0.033	0.748	College types
.7070	-.376	-.013	0.063	-.024	Marital status

4.5 Sociodemographic factors associated with the general Attitudes of HPV infection and vaccination

College type was a significant predictor of attitudes toward HPV infection and vaccination, with medical students showing more positive attitudes than non-medical students. However, no significant associations were found with age or marital status [Table 5].

Table 5: Linear Regression Analysis of sociodemographic factors associated with the general Attitudes of HPV infection and vaccination

p-value	T	Beta	Std. Error	B	Variables
0.000	11.704	-	0.149	1.743	(Constant)
0.937	-0.080	-0.004	0.035	-.0003	Age
0.000	6.532	0.322	0.035	0.229	College types
.0620	-1.871	-0.0092	0.068	-0.127	Marital status

4.6 Multivariate binary logistic regression analysis of factors associated with the HPV vaccination status

The study showed that HPV vaccination status was significantly associated with several factors. Non-medical students were less likely to be vaccinated compared to medical students. Younger students had lower odds of vaccination than those

aged ≥24 years. Married students were more likely to be vaccinated than single students. Higher knowledge, prior health education, and belief in vaccine effectiveness were associated with increased vaccination uptake. However, attitudes and social media as the main information source were not significantly associated with vaccination status [Table 6].

Table 6: Multivariate binary logistic regression analysis of factors associated with the HPV vaccination status among female university students

Variables	Category	OR	95% CI	P-value
College type	Medical college	-	-	-
	Non-medical college	0.41	0.22 - 0.77	0.005
Age (Years)	≥ 24	-	-	-
	18-20	0.18	0.19 - 0.90	0.027
	21-23	0.27	0.10 -0.69	0.001
Marital status	Single	-	-	-
	Married	3.22	1.81- 6.11	0.0001
Knowledge score	Poor	-	-	-
	Good	1.12	1.05 -1.20	0.001
Attitude	Negative	-	-	-
	Positive	1.05	0.98 -1.12	0.145
Received Health Education	No	-	-	-
	Yes	1.68	1.27 - 2.22	0.001
Belief in vaccine effectiveness	No	-	-	-
	Yes	1.84	1.32-2.57	0.001
Social media is a source of information	Health Care Provider	-	-	-
	From social media	0.64	0.29-1.42	0.273

5. Discussion

This study examined awareness, attitudes, and practices related to HPV infection and HPV vaccination among female students at Jazan University. Overall awareness was low, as less than half of the participants had previously heard of HPV. This result is consistent with studies conducted in other regions of Saudi Arabia, including Abha, Makkah, Qassim, and Riyadh, which have also reported low HPV knowledge among women in the general population [11,12, 13,16]. This low level of awareness might be the result of both a lack of ongoing awareness initiatives targeted at young women and limited integration of HPV- related content within the university curriculum

Even among those aware of HPV, understanding remained incomplete. Less than half correctly identified HPV as a sexually transmitted infection, and only a small proportion recognized its established role as the primary cause of cervical cancer [1,2]. Awareness of other HPV-related conditions, such as genital warts and penile cancer, and recognition that HPV affects both males and females, was also low. This misconception has been widely reported in Saudi studies [9,14,17]. These gaps suggest limited depth of health knowledge, where students may have heard about HPV but lack accurate understanding of its transmission and complications, indicating ineffective health communication strategies.

Although most participants correctly stated that HPV infection is common and most prevalent in individuals aged 20–30 years, more than half believed that the infection is curable. This misconception has been repeatedly reported in Saudi research and highlights ongoing gaps in accurate HPV-related knowledge [9,18]. Awareness of the recommended age for HPV vaccination and dosing schedules among female students was low, despite the vaccine being included in the Saudi Arabia national immunization program for eligible age groups [8]. Additionally, limited recognition of the preventive role of Pap smear screening indicates an inadequate understanding of comprehensive cervical cancer prevention strategies, consistent with previous Saudi findings [13]. This suggests weak dissemination of preventive health guidelines and limited integration of reproductive health education into student health programs.

Together, these gaps underscore the need for strengthened health education initiatives that align with Saudi Vision 2030 and the National Transformation Program (NTP), which emphasize improving preventive health services, promoting health education, and increasing vaccination uptake among youth and university populations [19].

The survey results show that only 11% of female students reported receiving the HPV vaccine, and the main reasons were confidence in its safety, effectiveness, and a family history of cervical cancer. This indicates that perceived risk and trust in the vaccine influence uptake. In contrast, for the unvaccinated students, lack of information was the most frequently reported barrier, followed by fear of side effects. Similar findings were reported in Saudi Arabia and neighboring countries [3,9,11,12]. These findings suggest that vaccine uptake is primarily driven by knowledge and perceived personal relevance rather than general attitudes, highlighting the importance of targeted awareness campaigns It is important that one-fifth of participants believed that cervical cancer screening is unnecessary after vaccination, revealing a serious misconception that threatens the long-term prevention efforts [18,7]. This indicates a critical misunderstanding of the complementary role of screening and vaccination, which could undermine cervical cancer prevention programs if not addressed. Despite these negative attitudes and practices, most students expressed interest in learning more about HPV and its vaccine, highlighting a valuable opportunity for targeted educational interventions within the university [11,12]. This reflects a positive readiness for behavioral change, suggesting that educational interventions are likely to be effective if properly implemented.

Linear regression analysis revealed that age and college type are significant predictors of general knowledge scores. Students enrolled in medical colleges demonstrated higher general and vaccine-specific knowledge than those from non-medical colleges, likely reflecting greater exposure to health-related curricula [20]. This suggests that academic exposure to health sciences plays a key role in shaping accurate HPV knowledge. Knowledge scores also increased with age, suggesting that cumulative educational experience contributes to improved understanding of HPV [12]. College type similarly influenced attitudes toward HPV vaccination, with medical students showing more positive attitudes than their non-medical peers, reinforcing the role of academic background in shaping vaccine perceptions [21,22,23]. This indicates that both maturity and field of study contribute to improved health awareness and more favorable preventive health attitudes.

Vaccination uptake was significantly associated with age, marital status, and knowledge level. Older students were more likely to be vaccinated than the younger students, possibly due to increased health awareness and perceived benefits from the vaccine [22,23]. Married students also showed higher vaccination uptake, indicating that life stage and associated health responsibilities may influence preventive health behaviors [24]. This suggests that personal life experience and perceived vulnerability increase engagement in preventive health actions. Furthermore, vaccination uptake was positively correlated with better knowledge levels, raising the significance of accurate information in converting awareness into action [23,15]. In contrast, attitudes toward HPV vaccination were not significantly associated with vaccination status, indicating that positive perceptions alone may not lead to actual vaccine uptake [25]. This highlights that knowledge is a stronger predictor of behavior than attitudes alone, emphasizing the importance of education over perception change only.

Health education, belief in vaccine effectiveness, and information sources were significant determinants of vaccination behavior. Students who had received structured health education were significantly more likely to be vaccinated, underscoring the role of formal educational interventions in raising awareness and promoting preventive health behaviors [25]. This confirms that structured educational programs have a direct and measurable impact on improving vaccination uptake Similarly, belief in the effectiveness of the HPV vaccine strongly predicted uptake, reflecting the importance of perceived benefits in health decision-making [23,244]. In contrast, reliance on social media as a primary information source was associated with lower vaccination uptake compared with information obtained from medical professionals, indicating that social media may increase awareness but also disseminate misinformation or insufficient information, which can have a detrimental impact on vaccine uptake [25,26].This suggests that credible healthcare providers remain the most influential and reliable source of health information, while unregulated online sources may adversely affect vaccination decisions

The study demonstrates several strengths, including addressing a significant public health issue and providing valuable insights into HPV knowledge, attitudes, and vaccination practices among university students. The inclusion of both medical and non-medical students enhances comparability, and the use of multivariate regression analyses strengthens the findings by allowing identification of independent predictors of HPV knowledge, attitudes, and vaccination behavior.

The study employed a cross-sectional design, which limits the ability to infer causal relationships between knowledge, attitudes, and practices regarding HPV. The research was conducted at a single university, which may limit the generalizability of the findings to other populations. Additionally, vaccination cards were not accessible for verification; the students' immunization status was determined only by self-report. The dependence on self-reporting could have resulted in recall and social desirability bias.

6. Conclusion

This study confirms the hypothesis that female students have suboptimal knowledge, attitudes, and practices regarding HPV infection and vaccination. It also

demonstrates that HPV vaccine uptake varies significantly according to age, marital status, and source of information.

HPV knowledge, attitudes, and vaccination uptake were higher among medical students, revealing disparities in preventive health awareness within the university. Vaccination uptake was significantly influenced by knowledge, health education, and belief in vaccine effectiveness, while reliance on informal information sources was linked to lower uptake. These findings align with Saudi Vision 2030 and the National Transformation Program (NTP), which emphasize enhancing health promotion and disease prevention

Consistent with the Health Belief Model, these factors play a key role in explaining vaccination behavior and supporting cervical cancer prevention efforts among university students.

7. Recommendations

- Organizations must enhance health education to boost awareness of HPV infections and vaccinations. Awareness initiatives, workshops, and incorporation into the curriculum can bridge gaps and foster positive attitudes, especially among non-medical students
- Future studies should use longitudinal or qualitative designs with probability sampling to examine causal relationships and changes over time. Multicenter studies and inclusion of male students would improve generalizability, and adding secondary and preparatory school students would enhance representativeness.
- Public health departments and university must work together on HPV awareness initiatives and effectively provide easily reachable on-campus vaccination services.

8. Ethical considerations

The local Research Ethics Committee at Jazan University (HAPO-10-Z-001) approved this study (Reference No: REC-44/06/463). In accordance with the Helsinki Declaration, informed consent was obtained electronically before participation. Data were collected anonymously without personal identifiers, stored securely, and used only for research purposes. All data will be retained for five years, and then permanently deleted.

1. Author contributions

- Single Author.

2. Funding

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4. Conflict of Interest Statement:

- The author declares that they have no competing interests.

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14) يلتزم الباحث بترجمة (أو رومنة) أسماء المصادر والمراجع العربية إلى اللغة الإنجليزية في قائمة المصادر والمراجع. وعلى سبيل المثال:

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15) تستخدم الأرقام العربية الأصلية (0، 1، 2، 3، ...) في البحث.

16) تؤول جميع حقوق النشر للمجلة في حال إرسال البحث للتحكيم وقبوله للنشر.

ثانياً: الملفات المطلوب تسليمها

1) نسخة إلكترونية من البحث بصيغتي (WORD) و (PDF)، وترسلان على موقع المجلة:

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2) السيرة الذاتية للباحث، متضمنة اسمه باللغتين العربية والإنجليزية، وعنوان البريد الإلكتروني الحالي، ورتبته العلمية.

3) تعبئة النماذج الآتية:

أ - نموذج طلب نشر بحث في المجلة.

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

ثالثاً: تنبيهات عامة

1) أصول البحث التي تصل إلى المجلة لا تردّ سواء أُنْشِرَتْ أم لم تنشر.

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

شروط النشر

أولاً: ضوابط النص المقدم للنشر

1) ألا تزيد صفحاته عن (35) صفحة من القطع العادي (A4).
2) أن يحتوي على عنوان البحث وملخصه باللغتين العربية والإنجليزية في صفحة واحدة، بحيث لا يزيد عن (250) كلمة للملخص، وأن يتضمن البحث كلمات مفتاحية دالة على التخصص الدقيق للبحث باللغتين، بحيث لا يتجاوز عددها (6) كلمات، توضع بعد نهاية كل ملخص.
3) أن يذكر اسم المؤلف وجهة عمله بعد عنوان البحث مباشرة باللغتين العربية والإنجليزية.
4) أن تقدم البحوث العربية مطبوعة بخط (Simplified Arabic)، بحجم (14) للنصوص في المتن، وبالخط نفسه بحجم (12) للهوامش.
5) أن تقدم البحوث الإنجليزية مطبوعة بخط (Times New Roman) بحجم (12) للنصوص في المتن، وبالخط نفسه بحجم (9) للهوامش.
6) كتابة البحث على وجه واحد من الصفحة، مع ترك مسافة سطر واحد بين السطور، وتكون الحواشي 2.5 سم على الجوانب الأربعة للصفحة، بما يعادل 1.00 إنش (بوصة).
7) التزام الترتيب الموضوعي الآتي:

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

العرض: يتضمن التفاصيل الأساسية لمنهجية البحث، والأدوات والطرق التي تخدم الهدف، وترتب المعلومات حسب أولويتها.

النتائج والمناقشة: يجب أن تكون واضحة موجزة، مع بيان دلالاتها دون تكرار.

الخاتمة: تتضمن 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 الببليوغرافية 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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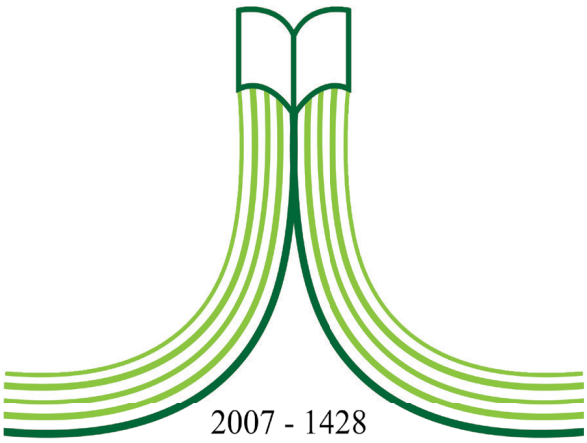
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