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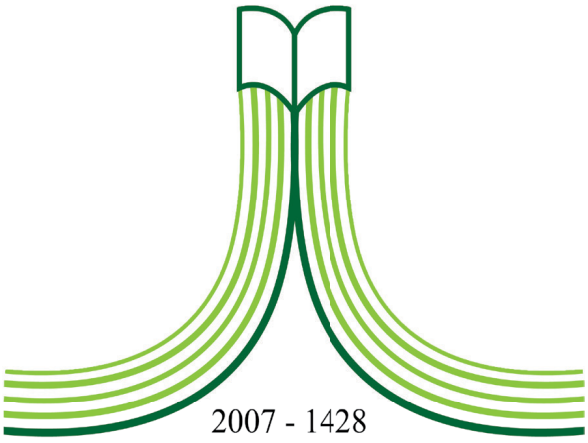
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Effect of Ginger Supplementation on Waist Circumference and Body Composition in Overweight and Obese Adults in Jazan, Saudi Arabia: A Quasi-Experimental Trial

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Abstract
Overweight and obesity are major public health challenges associated with increased cardiometabolic risk. This quasi-experimental trial investigated the short-term effects of ginger supplementation on waist circumference, body weight, and body composition among overweight and obese adults living in Jazan, Saudi Arabia. Fifty participants received 3 g/day powdered ginger in capsule form for 4 weeks while maintaining their usual diet and physical activity. Anthropometric and body composition parameters were assessed at baseline and after the intervention. Waist circumference decreased significantly after supplementation ($p = 0.024$), whereas body weight, body mass index, body fat percentage, fat mass, lean mass, and basal metabolic rate did not change significantly (all $p > 0.05$). These findings suggest that short-term ginger supplementation may preferentially influence central adiposity rather than overall body weight. Longer controlled trials are needed to confirm these findings and clarify their clinical relevance.

Keywords: supplementation; central adiposity; metabolic health; anthropometry; phytotherapy.

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1. Introduction

Obesity has emerged as one of the most pressing global health challenges of the twenty-first century and is associated with substantial cardiometabolic morbidity and mortality (World Health Organization, 2024; Ward et al., 2019). In Saudi Arabia, the burden of overweight and obesity remains high, underscoring the need for safe and acceptable interventions that can be integrated into routine care (Al-Omar et al., 2024). Lifestyle modification through dietary control and physical activity remains the cornerstone of obesity management; however, there is increasing interest in functional foods, herbs, and phytochemical-based adjuncts that may support weight management and metabolic health (Das et al., 2025; Payab et al., 2020; Ofoezie et al., 2025). Ginger (Zingiber officinale) is among the most widely studied medicinal plants in this context because of its bioactive compounds and proposed anti-inflammatory and metabolic effects (Dissanayake, 2020; Ballester et al., 2022).

Recent human trials and evidence syntheses suggest that ginger supplementation may improve selected obesity-related outcomes, particularly central adiposity indices, although findings for body weight and BMI remain inconsistent across studies (Rafieipour et al., 2024; Rjabi et al., 2025; Maharlouei et al., 2019). This inconsistency may reflect differences in dose, intervention duration, participant characteristics, and concomitant lifestyle measures (Ebrahimzadeh Attari et al., 2018; Park et al., 2020).

Accordingly, the present quasi-experimental trial was conducted to investigate the short-term effect of ginger supplementation on waist circumference, body weight, and body composition among overweight and obese adults living in Jazan, Saudi Arabia, with particular attention to whether a 4-week intervention might influence central adiposity.

2. Methods

Study design. This quasi-experimental trial was conducted in Jazan, Saudi Arabia. The study examined the effect of 4 weeks of ginger supplementation on anthropometric and body composition outcomes in a single-group pre–post treatment.

Participants. Fifty overweight and obese male and female adults aged 18–50 years were enrolled. Eligibility was based on a body mass index (BMI) of 30 kg/m² or higher. The sample size was estimated with reference to a previous intervention study on ginger supplementation in obesity-related outcomes (Ebrahimzadeh Attari et al., 2015).50 participants were recruited through a social media announcement distributed across Jazan city.

Inclusion and exclusion criteria. Adults aged 18–50 years with overweight or obesity who agreed to participate were eligible. Exclusion criteria included age younger than 18 years or older than 50 years, BMI greater than 40 kg/m², clinically diagnosed diabetes mellitus, cardiovascular disease, hypo- or hyperthyroidism, gallstones, severe depression, pregnancy, breastfeeding, current weight-reduction dieting, medications that could influence body weight, high physical activity levels, smoking, use of nutritional supplements, and hypersensitivity to ginger.

Intervention. The active supplement was powdered ginger in capsule form (Natures Aid, Ginger Root, 500 mg, 90 capsules), purchased from Alnahdi Pharmacy in Jazan, Saudi Arabia. Each participant received one container and was instructed to take two capsules after each of the three main meals daily, equivalent to 3 g/day of ginger, for 4 weeks. Participants were also instructed to maintain their usual dietary habits and physical activity levels throughout the intervention period.

Outcome measures. Anthropometric measurements were obtained by the same technician. Height, body weight, waist circumference, and hip circumference were measured with the participants barefoot. Waist circumference was measured at the midpoint between the lower border of the rib cage and the iliac crest. BMI was calculated as weight in kilograms divided by height in meters squared. Body composition variables, including fat percentage, fat mass (kg), lean percentage, lean mass (kg), and basal metabolic rate (BMR), were assessed using a body fat analyzer. All outcomes were measured at baseline and after 4 weeks of supplementation.

Ethical considerations. Each participant received an information sheet and provided informed consent before participation. Participants were informed of the study purpose, confidentiality procedures, and their right to withdraw at any time without penalty. Ethical approval was obtained from the Standing Committee for Scientific Research, Jazan University (HAPO-10-Z-001), Reference No. REC-44/07/538.

Statistical analysis. Data were analyzed using SPSS version 20 (SPSS Inc., Chicago, IL, USA). Descriptive statistics were expressed as mean ± standard deviation (SD). Because the study used a single-group pre–post design, within-group comparisons were performed using paired-sample t-tests. Participant-reported symptoms were summarized as frequencies and percentages. Statistical significance was set at $p < 0.05$.

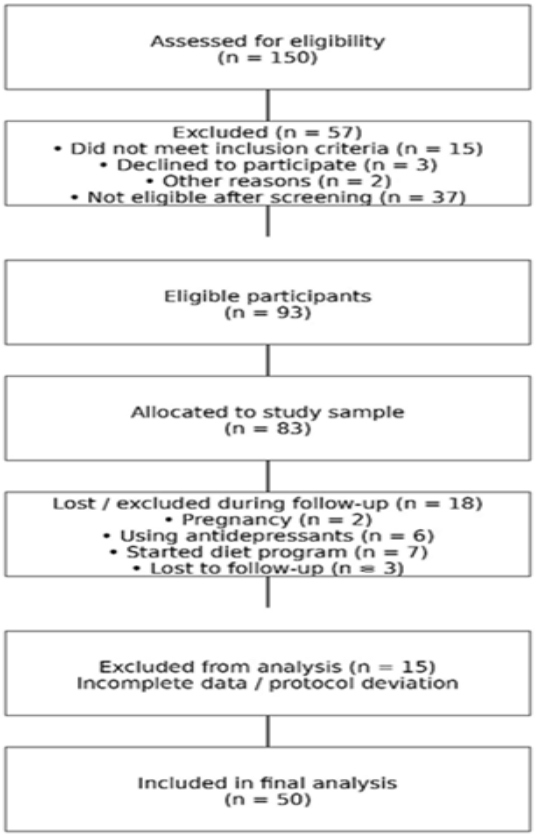


Figure 1. CONSORT flowchart summarizing participant enrollment and study progression.

3. Results

Baseline characteristics of the participants are presented in Table 1. The mean age of the participants was 31.58 ± 10.25 years. At baseline, the mean body weight was 86.54 ± 17.08 kg, the mean waist circumference was 95.01 ± 13.76 cm, and the mean BMI was 32.93 ± 5.09 kg/m².

Table 1. Baseline characteristics of the participants.

Variable	n	Mean	SD
Age	50	31.58	10.25
Body weight (kg)	50	86.54	17.08
Waist circumference (cm)	50	95.01	13.76
BMI (kg/m²)	50	32.93	5.09
Body fat (%)	50	39.51	7.81
Lean percentage (%)	50	60.40	7.43
Lean mass (kg)	50	50.94	12.76
Fat mass (kg)	50	34.20	12.24
BMR (kcal/day)	50	1564.44	401.04

Note. Values are expressed as mean ± SD. Baseline data are shown for participants who completed the study.

Changes in anthropometric and body composition outcomes after 4 weeks of supplementation are shown in Table 2. A statistically significant reduction was observed only in waist circumference (95.01 ± 13.76 cm at baseline vs. 89.03 ± 12.95 cm after intervention; mean change = −5.98 cm; $p = 0.024$). In contrast, body weight, BMI, body fat percentage, fat mass, lean percentage, lean mass, and basal metabolic rate did not change significantly (all $p > 0.05$).

Table 2. Pre–post changes in anthropometric and body composition outcomes after ginger supplementation.

Outcome	Baseline, mean ± SD	Post-intervention, mean ± SD	Mean change	p value
Body weight (kg)	86.54 ± 17.08	86.51 ± 17.06	−0.03	0.857
Waist circumference (cm)	95.01 ± 13.76	89.03 ± 12.95	−5.98	0.024
BMI (kg/m²)	32.93 ± 5.09	32.91 ± 5.02	−0.02	0.789
Body fat (%)	39.51 ± 7.81	39.35 ± 9.27	−0.16	0.811
Fat mass (kg)	34.20 ± 11.21	34.48 ± 12.49	+0.28	0.588
Lean percentage (%)	60.40 ± 7.43	60.28 ± 9.18	−0.12	0.874
Lean mass (kg)	50.94 ± 10.63	52.05 ± 11.65	+1.11	0.273
BMR (kcal/day)	1564.44 ± 401.32	1592.64 ± 332.94	+28.20	0.472

Note. Within-group pre–post comparisons were performed using paired-sample t-tests. Mean change was calculated as post-intervention minus baseline. Statistical significance was set at $p < 0.05$. BMI, body mass index; BMR, basal metabolic rate; SD, standard deviation.

Participant-reported gastrointestinal and appetite-related symptoms are summarized in Table 3 as frequencies and percentages. Satiety was reported by 22 participants (44%), whereas nausea was uncommon. Improvement in digestion was reported by 32 participants (64%). Heartburn was the most frequently reported gastrointestinal complaint, occurring in 20 participants (40%), while diarrhea was reported by 10 participants (20%).

Table 3. Participant-reported symptoms during the intervention period, n (%).

Symptom	Yes, n (%)	Sometimes, n (%)	No, n (%)
Satiety	22 (44)	13 (26)	15 (30)
Nausea	3 (6)	3 (6)	44 (88)
Heartburn	20 (40)	18 (36)	12 (24)
Diarrhea	10 (20)	6 (12)	34 (68)
Constipation	7 (14)	0 (0)	43 (86)
Gas	6 (12)	4 (8)	40 (80)
Improved digestion	32 (64)	5 (10)	13 (26)

Discussion

The present quasi-experimental study examined the short-term effects of ginger supplementation (3 g/day for 4 weeks) on anthropometric and body composition outcomes in overweight and obese adults living in Jazan, Saudi Arabia. The principal finding was a statistically significant reduction in waist circumference. In contrast, body weight, body mass index (BMI), body fat percentage, lean mass, and basal metabolic rate (BMR) did not change significantly. This pattern suggests that ginger supplementation may exert a more detectable effect on central adiposity than on total body weight during short intervention periods. From a clinical perspective, this observation is relevant because waist circumference is more closely linked to visceral adiposity and cardiometabolic risk than body weight alone (Rafieipour et al., 2024; Rjabi et al., 2025).

The current findings are generally consistent with recent systematic reviews and dose–response meta-analyses showing that ginger supplementation can improve some indices of central obesity, particularly waist circumference, while effects on body weight and BMI are smaller and less consistent across trials (Rafieipour et al., 2024; Rjabi et al., 2025). In the present study, the significant reduction in waist circumference, in the absence of significant changes in overall body weight or body composition, may indicate an early effect on abdominal fat distribution rather than a substantial reduction in total adiposity. Such an interpretation is reasonable because central fat depots are metabolically active and may respond earlier than total body mass to dietary bioactive compounds.

The lack of statistically significant changes in body weight and BMI should be interpreted in light of the design characteristics of the present study. First, the intervention period was only 4 weeks, which may have been insufficient to produce measurable changes in total body mass. Second, the administered dose was moderate compared with some studies that reported broader anthropometric improvements after longer

supplementation periods or different preparations of ginger (Maharlouei et al., 2019; Park et al., 2020). Third, participants were instructed to maintain their habitual diet and physical activity, and no structured caloric restriction or exercise program was introduced. This is important because prior studies suggest that the influence of ginger on weight-related outcomes may be enhanced when supplementation is combined with lifestyle modification or structured exercise (Atashak et al., 2011; Payab et al., 2020).

While previous studies have proposed several biological mechanisms to explain the observed reduction in waist circumference, these remain hypothetical in the context of the present study, as no biochemical markers were measured

Ginger contains bioactive constituents, particularly gingerols and shogaols, that have been linked to thermogenesis, enhanced fat oxidation, modulation of adipocyte metabolism, and improvements in insulin sensitivity (Ballester et al., 2022; Ebrahimzadeh Attari et al., 2018). Experimental and clinical evidence also suggests that ginger may influence appetite regulation and satiety, which could contribute to a gradual reduction in abdominal adiposity even in the absence of marked short-term weight loss (Mansour et al., 2012; Aregawi et al., 2023). Therefore, the present findings may reflect an early metabolic effect of ginger on fat distribution rather than a direct and immediate effect on overall body mass.

In contrast to the significant change in waist circumference, no significant changes were observed in body fat percentage, fat mass, lean mass, or lean percentage. This finding is also in line with previous literature indicating that ginger supplementation alone does not consistently improve whole-body composition over short durations (Ebrahimzadeh Attari et al., 2016; Maharlouei et al., 2019). The slight numerical increase in lean mass observed in the present study should therefore be interpreted cautiously, as it may reflect normal biological variation, device-related measurement variability, or hydration-related changes rather than a true anabolic effect. More pronounced changes in body composition are more likely to occur in studies with longer follow-up, larger samples, and controlled co-interventions such as dietary restriction or resistance training.

The absence of a significant effect on BMR is likewise understandable. Although ginger has been associated with thermogenic and fat-oxidation effects, these responses are often modest and may not be sufficient to produce measurable changes in resting metabolic rate over a short intervention period (Braga Tibaes et al., 2022; Mahluji et al., 2013). The discrepancy between mechanistic expectations and clinical outcomes may be related to dosage, intervention duration, inter-individual metabolic variability, and compensatory physiological responses. Accordingly, the current results support the view that ginger may have subtle metabolic effects, but these effects may not have resulted in statistically significant changes in resting energy expenditure within 4 weeks.

The participant-reported symptom profile provides additional practical insight into tolerability. In the present study, some participants reported increased satiety and improved digestion, findings that are consistent with prior reports suggesting that ginger may enhance gastric motility and promote subjective fullness (Mansour et al., 2012; Aregawi et al., 2023). At the same time, mild gastrointestinal complaints such as heartburn and diarrhea were reported by a subset of participants. These findings should not be ignored; instead, they suggest that ginger was generally acceptable but was associated with mild gastrointestinal side effects in some individuals. This interpretation is more accurate than describing the supplement as completely free of adverse effects and is supported by previous reviews and trials documenting mixed gastrointestinal responses to ginger supplementation (Anh et al., 2020; Estes et al., 2025; Foshati et al., 2023).

From a clinical standpoint, the present findings suggest that ginger supplementation may be considered a complementary dietary strategy for targeting central obesity, particularly abdominal adiposity, which is strongly associated with metabolic and cardiovascular risk. However, the results should be interpreted cautiously because the study used a single-group quasi-experimental design without a control group. Consequently, the observed changes cannot be attributed exclusively to the intervention with the same confidence as in a randomized controlled trial. Nevertheless, the findings remain clinically informative because they provide preliminary local evidence from an understudied population in Jazan and may help guide future intervention research in Saudi Arabia.

This study has several strengths, including its focus on an important public health issue, the use of a clearly defined supplementation protocol, and the assessment of multiple anthropometric and body composition outcomes. It also adds region-specific evidence on ginger supplementation in overweight and obese adults. However, several limitations should be acknowledged. These include the absence of a control group, the relatively short intervention period, the modest sample size, the lack of dietary intake monitoring, and the absence of biochemical markers such as lipid profile, inflammatory markers, glucose homeostasis indices, leptin, or adiponectin. These limitations reduce mechanistic interpretation and limit causal inference. Future studies should therefore adopt randomized controlled designs, longer follow-up periods, tighter dietary monitoring,

and broader metabolic profiling to clarify whether the reduction in waist circumference is sustained and whether it translates into meaningful cardiometabolic benefits.

4. Conclusion

In conclusion, short-term supplementation with 3 g/day ginger was associated with a significant reduction in waist circumference in overweight and obese adults, without significant changes in body weight or other body composition variables. Ginger may therefore be considered a complementary strategy targeting central adiposity, although larger and better-controlled studies are required before firm clinical recommendations can be made.

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Simulation-Based Environmental Risk Prioritization for Industrial Waste Management

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Abstract: Industrial processes produce various types of waste which, when poorly handled, pose public health risks and compromise environmental integrity. There is an increase in environmental regulatory data and tools; however, most waste management practices focus on established regulatory provisions and retrospective management, which limits their ability to anticipate emerging environmental risks and support early intervention. In industrial contexts, this limitation is particularly serious, as delays in risk identification contribute to cumulative environmental degradation in soil and water systems. This study proposes a data-driven intelligent framework for industrial waste management that integrates machine-learning-based classification of regulatory-informed proxy risk levels, waste data, operational standards, and environmental indicators for waste management. A representative synthetic (simulation-based) dataset was generated based on national technical guidelines and regulatory waste classification schemes to enable controlled evaluation of the proposed framework under well-defined regulatory and environmental conditions. An integrated Environmental Risk Index (ERI) was developed by combining hazard intensity, normalized waste quantity, and environmental sensitivity. A Random Forest model, capable of handling uncertainty in regulatory and environmental datasets, was used to classify proxy environmental risk levels (rather than directly modeling real-world contamination processes). The analysis showed 89% classification accuracy and identified high-risk waste streams with high precision, while maintaining consistent differentiation between medium- and low-risk categories. The proposed framework supports structured environmental risk prioritization and encourages evidence-based regulatory decision-making that takes environmental, social, and governance (ESG) factors into consideration, within a simulation-based proof-of-concept setting.

Keywords: industrial waste management; environmental risk assessment; machine learning; decision support systems; AI-based modeling.

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1. Introduction

Industrial activities generate a wide range of waste materials, including sludge, tailings, spent chemicals, and contaminated packaging. What makes the problem worse is that in many cases, reliance on delayed monitoring and incomplete datasets affects handling and disposal decisions, which leads to risks to environmental integrity and public health (Chen, 2025). Across many industrial sectors, waste management still depends on fixed regulatory standards and reactive inspection methods that are not effective for early risk detection. Although regulatory instruments, including Extended Producer Responsibility (EPR), exist, limitations in enforcement capacity, as well as the practice of post-event supervision affect environmental protection outcomes (Tran et al., 2025) and leave early warning signals of environmental risk unnoticed.

Reliable information on the generated waste is central to waste management. Therefore, it is important to design frameworks integrating waste characteristics with operational and environmental conditions in order to support consistent risk identification and management actions (Dawar et al., 2025; Xu & Zheng, 2026). Recent studies emphasize the need for more integrated and adaptive environmental risk assessment frameworks to address increasing system complexity and uncertainty (Geng et al., 2024). Moreover, integrating waste characterization procedures with environmental risk assessment tools (Bisciotti et al., 2025), as well as introducing automated analysis that would not only reduce the burden of analysis and increase efficiency of monitoring (Rao et al., 2025). Such approaches also help align waste management strategies with environmental priorities in light of competing economic and social constraints (Shahab et al., 2026).

Accordingly, this study proposes a data-driven intelligent framework for industrial waste management that integrates waste characterization data, operational parameters, and environmental indicators to: (1) classify industrial waste streams according to proxy environmental risk levels; (2) support the structured prioritization of environmental risk under data-limited conditions; and (3) provide recommendations to support decision-making for treatment, recycling, controlled storage, and final disposal.

1.1 Problem Statement

Although there is an increasing number of industrial waste systems, many of them still rely on reactive, rule-based frameworks which are not efficient in identifying environmental risks early. Moreover, there is no platform that would offer an integrated and data-driven approach that would link waste characteristics with environmental sensitivity indicators.

1.2 Objectives of the Study

To address the identified research gap, this study pursues the following objectives:

- To develop and evaluate a data-driven analytical framework that uses publicly available data to classify regulatory-informed proxy environmental risk levels linked to industrial waste types.
- To implement supervised machine learning methods through a simulation-based case study to support risk-informed decision-making in industrial waste management as a methodological proof-of-concept under data-limited conditions.

1.3 Research Contributions

This study presents three main contributions.

- First, it brings together regulatory logic, environmental indicators, and machine learning into a single, integrated framework for decision support in industrial waste management. Instead of treating these elements separately, the framework shows how they can work together in a more practical and structured way.
- Second, it examines how machine learning models behave when they operate under predefined rules. In such settings, models tend to follow the logic already built into the data rather than discovering entirely new patterns.
- Third, it evaluates how classification performance is affected when the labels are not perfectly reliable. By simulating uncertain and imperfect data conditions, the study shows how model performance responds to noise and highlights some limitations of relying on data-driven approaches in real-world scenarios.

1.4 Research Questions

This study seeks to address the following research questions:

Q1: To what extent can publicly available waste and environmental data be used to classify proxy environmental risk levels linked to types of industrial waste?

Q2: How can data-driven risk classification approaches enhance industrial waste management decision-making in light of limited data?

2. Related works

AI-assisted predictive models are more appropriate than systems that use conventional statistics in certain situations (Abdeljaber et al., 2025; Chau et al., 2025). For example, AI-based sorting systems produce accurate results that can distinguish between material types, aiding

better recycling opportunities (Ahmad et al., 2025). Such schemes are useful for industry since it produces a vast assortment of waste and information (Islam et al., 2025). Other studies require biowaste identification using YOLOv8-SPP architectures (Balasubramanium et al., 2025) and risk assessments for different forms of waste (Bisciotti et al., 2025). These analyses combine modeling with environmental and biochemical testing.

AI-based prediction of waste generation has been identified by Alsabt et al. (2024) and (Alhathlaul et al., 2025). However, issues relating to the rigor of such systems and their validation have raised concerns. Mullane et al. (2025) claimed that inadequate validation practices produce false outcomes, which produce poor decisions. In addition, AI-based real-time optimization has been shown to be possible (Rao et al., 2025; Anitha & Parthiban, 2025).

AI in decision-support systems for smart cities is now available (Nesmachnow et al., 2025). Nevertheless, limitations include poor data quality and the transparency of such models (Zou et al., 2025). Forecasting, classification, decision-making, and risk assessments are usually treated as isolated subjects. Although a combination of some of these topics is present in the Literature, such research usually examines a single stage in the process, which is unsuitable for industrial-scale use (Dao et al., 2025). Recent work has also emphasized the integration of emerging technologies within waste management systems, although such efforts often remain fragmented and limited to specific operational contexts (Martínez-Ramón et al., 2025).

2.1 Research gap

Overall, the literature documents substantial advances in applying AI and machine learning to waste forecasting, classification, and environmental risk estimation. Systematic reviews confirm the growing use and diversity of computational methods and decision-support systems deployed across the waste management lifecycle, particularly within smart city and IoT-enabled contexts (Nesmachnow et al., 2025), but challenges related to the quality of data, transparency of the used models, and analytical integration are commonly found (Zou et al., 2025).

Despite the progress, most studies treat forecasting, classification, decision support and risk assessment as isolated analytical components. Although some multilayer approaches link sensing, sorting, planning, and treatment processes, their focus is usually on specific lifecycle stages and there is still a lack of integrated structures suitable for industrial-scale implementation (Dao et al., 2025). The lack of such analytical frameworks restricts the transferability of research outcomes to regulatory and industrial decision-making, which further demonstrates the need for such an integrated approach that would combine waste characterization, environmental sensitivity assessment, risk modeling, and decision-support.

3. Methodology

This study develops a structured framework to prioritize environmental risks associated with industrial waste. It integrates regulatory logic, environmental indicators, and supervised machine learning within a unified analytical framework, rather than treating them as separate components.

Due to the limited availability of detailed facility-level data and observed contamination outcomes, the study adopts a simulation-based proof-of-concept design. This approach is commonly used to evaluate operational systems under controlled conditions (Dawar et al., 2025). Instead of attempting to directly model real-world contamination processes, the framework operates within a controlled synthetic environment that reflects regulatory principles and realistic industrial scenarios.

The primary objective of this study is methodological rather than predictive: to examine the interaction between rule-based classification, composite risk indices, and machine learning models, and to assess their consistency and robustness under uncertainty. Accordingly, the study focuses on risk prioritization and decision-support design, rather than aiming to predict real-world environmental outcomes

3.1 Data Sources and Variables

The selected variables capture key dimensions of environmental risk in industrial waste management, including hazard severity, scale of waste generation, and environmental exposure. These dimensions are consistent with those commonly used in environmental risk assessment frameworks. The selection of variables is informed by established regulatory approaches, while the ISIC Rev.4 system (United Nations, 2008) is used to classify industrial activities within the dataset. This classification system is also implemented within the Saudi statistical framework (GASTAT, 2019). To balance realism with analytical flexibility, the dataset integrates regulatory-based categorical variables with simulated continuous variables. This hybrid structure preserves the integrity of regulatory classifications while introducing controlled variability in operational and environmental conditions. Specifically, variables such as hazard classification, waste type, and storage conditions follow established regulatory categories, whereas variables including waste quantity and distance to water sources are generated to reflect plausible variation under controlled assumptions.

It is important to clarify the nature of the outcome variable. The target variable, referred to as risk_proxy, does not represent an observed environmental outcome. Instead, it is a regulatory-informed proxy classification introduced strictly for methodological purposes. Accordingly, the framework does not aim to model real-world contamination processes; rather, it seeks to examine how risk categorization can be structured and evaluated within a controlled, regulation-informed setting. Importantly, the proxy labels are derived using rule-based logic based on the same input variables included in the model. Therefore, the model is expected to reproduce the underlying rule-based structure rather than identify independent causal relationships.

Table 1. Variables, roles, and sources within the simulation-based framework

Variable	Description	Type	Role in Framework	Source
waste-type	Type of industrial waste	Categorical	Contextual variable (not used in final model)	NCM (2025)
hazard	Hazard classification	Binary	Core predictor (Hn)	NCM (2025)
quantity	Generated waste quantity (kg)	Continuous	Core predictor (Qn)	Simulated
storage	Storage method	Categorical	Contextual variable	NCM (2025)
industry	Industrial sector	Categorical	Contextual variable	ISIC Rev.4 (GASTAT, 2019)
dist_water	Distance to nearest water source (km)	Continuous	Environmental variable (used to derive S)	GIS / Simulated
ERI	Environmental Risk Index	Continuous	Prioritization index (not used in model)	Computed
risk-proxy	Proxy environmental risk class	Categorical	Target variable (rule-based + noise)	Synthetic

Table 1 summarizes the variables included in the framework, along with their descriptions, types, roles, and sources. It distinguishes between variables used directly in the predictive model and those included for contextual or decision-support purposes.

To further illustrate how these variables are operationalized, the analytical workflow can be conceptualized as a sequence of interconnected steps. The process begins with the core variables hazard, waste quantity, and distance to water sources, which are transformed into derived features (H_n, Q_n, and S). These features form the foundation for both index construction and predictive modeling.

These components are subsequently combined to compute the Environmental Risk Index (ERI), which serves as a composite measure for prioritizing scenarios. Although ERI is not used as an input to the predictive model, it provides a useful benchmark for comparing relative risk levels across cases.

In the subsequent step, proxy risk labels (risk_proxy) are generated using a rule-based approach informed by regulatory logic. To better reflect real-world uncertainty, a controlled level of noise is introduced into these labels, simulating potential inconsistencies in environmental classification.

Finally, supervised machine learning models are trained using the core predictors (H_n, Q_n, and S). The resulting predictions are interpreted alongside the ERI within a conceptual decision-support framework, enabling a comparative perspective between rule-based and data-driven approaches to risk prioritization.

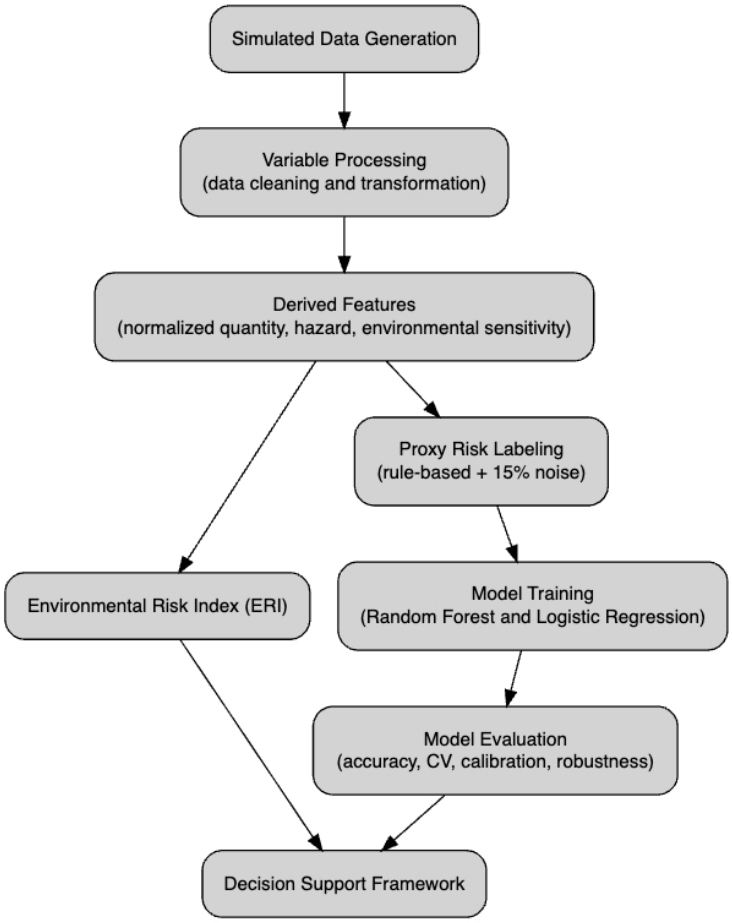


Figure 1. Workflow of the simulation-based environmental risk classification framework

Figure 1 presents the overall workflow of the simulation-based environmental risk classification framework, illustrating how data generation, feature engineering, rule-based labeling, and machine learning components interact within the proposed system.

3.2 Dataset Generation

To support controlled experimentation, a synthetic dataset consisting of 500 observations was constructed. The objective was not to generate arbitrary random data, but to create a structured dataset that reflects plausible industrial waste scenarios under regulatory constraints.

To ensure transparency and reproducibility, the data generation process was defined using explicit distributions and parameter ranges for each variable. The hazard variable was simulated as a binary outcome using a Bernoulli distribution ($p = 0.6$ for non-hazardous waste), reflecting typical industrial patterns.

Waste quantity was generated as a continuous variable within a predefined operational range (e.g., 10–2000 kg), representing realistic variability in industrial production volumes. Distance to water sources was simulated within a realistic spatial range (e.g., 0.2–12 km), serving as a proxy for environmental exposure.

Categorical variables, including waste type, storage method, and industry sector, were sampled from predefined sets aligned with regulatory classifications. These categories were treated as fixed inputs to maintain consistency with existing waste management frameworks.

All simulations were conducted using a fixed random seed to ensure full reproducibility of the dataset. The generation process was intentionally designed to balance realism and simplicity, allowing controlled evaluation of the proposed framework under clearly defined conditions. A simplified description of the data generation procedure is provided to facilitate replication.

3.3 Data Preprocessing and Feature Engineering

Before building the model, the dataset was cleaned up and aligned so that all variables were consistent.

Waste quantity was standardized using z-score normalization to produce (Q_n). Hazard levels were converted into numerical values (H_n) to reflect their relative impact, with higher values assigned to more hazardous waste. Environmental sensitivity (S) was calculated based on how close each case is to water sources, the closer the distance, the higher the sensitivity.

These elements were then combined to form the Environmental Risk Index (ERI), which serves as a simple way to compare different scenarios. It's important to note that ERI is not meant to represent actual environmental risk, but rather to give a relative sense of priority across cases.

In that sense, the index is used for interpretation rather than prediction. This type of index-based approach has also been used in structuring environmental risk assessments, especially in hazardous waste contexts (Zheng et al., 2025).

Since Q_n is standardized, ERI values can sometimes be negative. This doesn't indicate anything problematic, it just reflects where a case sits relative to others in the dataset.

Finally, testing different weighting schemes showed that ERI remains fairly stable. This suggests that the index captures a consistent ranking pattern, rather than depending too heavily on a specific set of weights.

Importantly, ERI was not included as an input to the predictive model. This decision was made to avoid redundancy and prevent information leakage, given that the index is derived from the same underlying variables.

3.4 Risk Labeling and Uncertainty Modeling

The classification labels used in this study are intentionally designed as synthetic constructs. Rather than relying on observed environmental outcomes, the labels are generated through a simplified rule-based structure informed by general regulatory principles in hazardous waste management.

To ensure transparency and reproducibility, the deterministic rules used to assign proxy risk levels are explicitly defined in Table 2.

Table 2. Rule-based structure for proxy risk classification

Hazard Indicator	Quantity Threshold	Rule Description	Assigned Risk Class
1 (Hazardous)	> 1500 kg	Exceeds high-risk threshold	High
1 (Hazardous)	≤ 1500 kg	Within moderate range	Medium
0 (Non-hazardous)	Any	No hazardous properties	Low

The rules presented in Table 2 define the deterministic logic used to generate the target variable (risk_proxy). These rules are intentionally simplified and are based on a predefined threshold (T_n = 1500 kg), which is introduced for simulation purposes rather than derived from a specific regulatory standard. This abstraction allows the study to operate within a controlled, rule-constrained environment while preserving key aspects of regulatory reasoning.

While simplified, this structure is consistent with general regulatory approaches that consider both hazard characteristics and waste generation scale in risk prioritization. It therefore serves as a conceptual approximation of screening-level decision logic, rather than a direct representation of real-world classification systems.

Importantly, the proxy labels are derived from the same underlying variables used as model inputs. As a result, the learning task is inherently constrained, and the model is expected to reproduce the predefined rule structure rather than identify independent relationships. This design is intentional and aligns with the methodological objective of evaluating model behavior within a controlled analytical setting.

To introduce realism and avoid a fully deterministic system, a controlled level of uncertainty is incorporated into the labeling process. Specifically, 15% of the class labels are randomly reassigned. This simulates potential inconsistencies in environmental classification and reflects the imperfect nature of real-world data (Lee & Shin, 2025). It also aligns with noise-aware learning approaches that assess model robustness under uncertain labeling conditions.

3.5 Model Development

Within this framework, machine learning is not intended to uncover new environmental relationships or to predict real-world risk outcomes. Rather, it is explicitly used as a controlled analytical instrument to evaluate how predefined rule-based classifications behave under varying levels of uncertainty. This shifts the role of the model from predictive inference to methodological evaluation, with a focus on consistency, robustness, and behavior under controlled conditions.

To operationalize this evaluation, a Random Forest classifier was selected as the primary modeling approach due to its flexibility and robustness when applied to structured datasets. The dataset was divided into training (80%) and testing (20%) subsets to allow for out-of-sample evaluation. The model was trained using 300 trees, and feature importance measures were extracted to support interpretability.

The model was intentionally restricted to three core predictors: normalized waste quantity (Q_n), encoded

hazard level (H_n), and environmental sensitivity (S). This constraint ensures alignment between the model inputs and the underlying rule-based structure used to generate the proxy labels, while maintaining a transparent and interpretable modeling setup.

In addition to the Random Forest model, a multinomial logistic regression model was implemented as a baseline. This provides a point of comparison between a flexible machine learning approach and a simpler statistical model under the same controlled conditions.

Given that the target variable is derived from the same underlying predictors, the modeling task is inherently constrained. Accordingly, the models are not intended to identify independent relationships, but rather to assess the extent to which the predefined classification structure can be consistently reproduced, particularly under conditions of label uncertainty.

3.6 Model Evaluation

Model performance was evaluated using a set of standard classification metrics, including accuracy, precision, recall, and F1-score. Confusion matrices were used to examine class-level performance and to identify potential imbalances in classification behavior.

However, given the rule-constrained nature of the modeling task, evaluation focused not only on overall predictive performance, but also on model stability and robustness under varying levels of uncertainty.

To assess this, performance was systematically evaluated across different levels of label noise (0%, 15%, and 30%). This allows for a controlled examination of how sensitive the models are to inconsistencies in the target labels, and whether they can maintain stable classification behavior under degraded conditions.

In addition to classification metrics, probabilistic performance was assessed using Brier scores and calibration analysis. These measures provide insight into how well predicted probabilities align with the underlying label distribution, offering a more nuanced view of model reliability beyond discrete predictions.

A hold-out validation approach was combined with five-fold cross-validation to ensure that the results are not dependent on a single data split. This provides a more robust assessment of model consistency across different subsets of the data.

Importantly, given that the target labels are derived from predefined rules, the evaluation is not intended to demonstrate predictive superiority, but rather to assess the consistency, reliability, and robustness of model behavior within a controlled simulation environment. This evaluation design allows for distinguishing between models that merely replicate deterministic rules and those that maintain stable behavior under uncertainty.

3.7 Decision-Support Framework

To bridge analytical outputs with practical application, a conceptual decision-support layer was developed. This component translates model outputs and index-based assessments into structured risk management actions.

Within this framework, risk categories derived from the classification model are linked to differentiated response strategies. High-risk cases are associated with immediate intervention and stricter control measures, while medium-risk cases require targeted monitoring and mitigation. Low-risk cases are managed through routine operational procedures. Rather than prescribing fixed actions, these categories provide a structured basis for prioritization under constrained resources.

Importantly, the Environmental Risk Index (ERI) is evaluated alongside model predictions to offer a complementary perspective on risk prioritization. While the model reflects rule-constrained classification behavior under uncertainty, the ERI provides a continuous measure of relative risk across scenarios. The combined use of these components enables a more nuanced interpretation of risk, particularly in cases where classification boundaries may be sensitive to noise.

This decision-support layer is intentionally presented as a conceptual proof-of-concept. Its purpose is not to define an operational system, but to illustrate how rule-based logic, index-based prioritization, and model outputs can be integrated within a unified analytical framework to support structured decision-making.

3.8 Reproducibility

All analyses were conducted in the R programming environment using open-source tools. Reproducibility was ensured through the use of fixed random seeds and explicitly defined procedures for data generation, preprocessing, and model training.

The full analytical workflow, from synthetic data construction to model evaluation, was designed to be fully transparent and replicable. Each stage of the process follows clearly specified assumptions and parameter settings, allowing independent reproduction of the results under identical conditions.

Given the simulation-based nature of the study, reproducibility is a central component of the methodological design. The controlled structure of the dataset and the deterministic generation of proxy labels provide a consistent baseline for evaluating model behavior across repeated experiments.

4. Results and Discussion

4.1 Dataset Characteristics and Class Distribution

The dataset consists of 500 synthetically generated observations designed to represent a range of industrial waste scenarios under controlled simulation conditions.

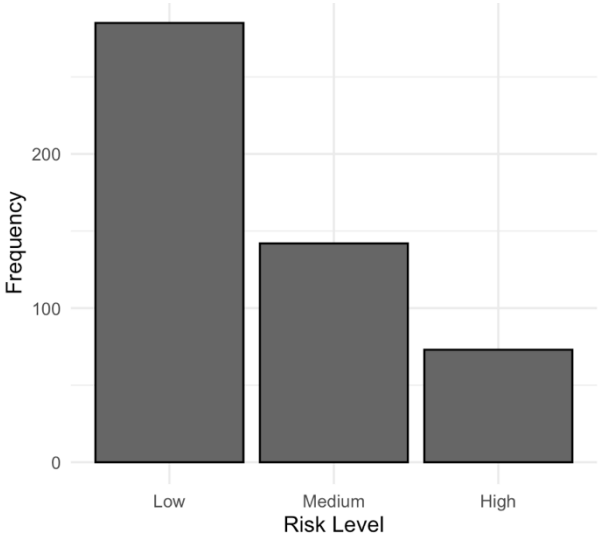


Figure 2. Class Distribution

As shown in Figure 2, the initial class distribution is imbalanced, with Low-risk cases representing the majority (62.6%), followed by Medium (26.4%) and High (11.0%). This imbalance reflects the underlying rule-based structure, where non-hazardous conditions are more frequently represented in the simulated dataset. After introducing 15% label noise, the distribution becomes slightly more dispersed (Low: 57.0%, Medium: 28.4%, High: 14.6%), increasing class overlap and introducing controlled ambiguity into the classification structure. This shift is methodologically significant, as it moves the dataset beyond a purely deterministic structure and introduces a level of uncertainty that more closely resembles classification behavior under imperfect conditions. By introducing controlled noise, the dataset no longer reflects a perfectly rule-driven system, but instead provides a more appropriate testbed for evaluating model robustness and stability under uncertainty.

4.2 Environmental Risk Index (ERI)

The Environmental Risk Index (ERI) is constructed as a composite measure integrating normalized waste quantity (Q_n), hazard level (H_n), and environmental sensitivity (S), providing a continuous representation of relative risk across simulated scenarios.

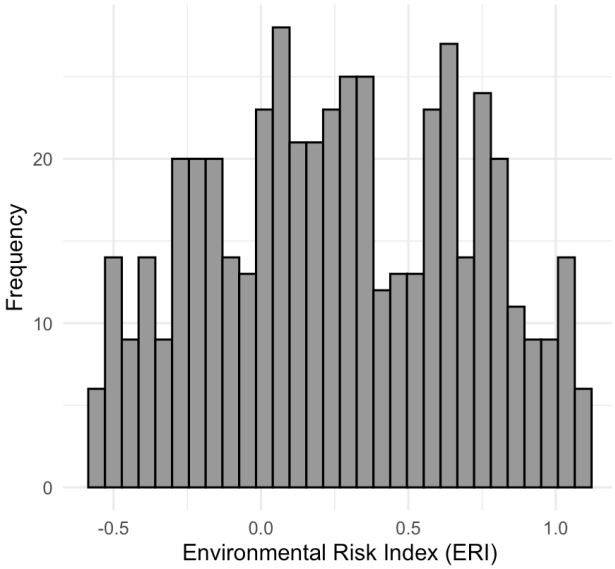


Figure 3. ERI Distribution

As illustrated in Figure 3, ERI values are reasonably well distributed across the dataset, with a mean of 0.264 and a median of 0.255, indicating a relatively balanced spread of risk values rather than concentration within a narrow range. The observed range (−0.558 to 1.093) captures variability in both waste characteristics and environmental exposure, reflecting the combined influence of hazard, quantity, and spatial context.

Negative values arise from the normalization process and do not affect interpretability, as ERI is designed for relative comparison rather than absolute classification thresholds.

Table 3. Sensitivity analysis of ERI weighting schemes

Weights (Q, H, S)	Mean	Min	Max
(0.4, 0.4, 0.2)	0.264	-0.558	1.093
(0.5, 0.3, 0.2)	0.208	-0.761	1.156
(0.3, 0.5, 0.2)	0.320	-0.354	1.033

The sensitivity of the index to weighting choices is summarized in Table 3, where alternative weight configurations produce only minor variations in overall behavior. This indicates that the index is not overly dependent on a specific parameterization, suggesting that its structure is primarily driven by the underlying variables rather than by arbitrary weighting choices.

While the selected weights (0.4, 0.4, 0.2) are not derived from a formal optimization procedure, they represent a balanced and interpretable configuration aligned with screening-level prioritization approaches, where hazard and quantity are typically treated as primary drivers of risk.

Importantly, the stability of ERI supports its role as a complementary analytical tool for relative prioritization, rather than a standalone predictive measure. ERI was therefore excluded from the predictive model to avoid redundancy and potential information leakage, as the index is directly derived from the same underlying variables used as model inputs.

4.3 Model Performance

The Random Forest model achieved an overall accuracy of 0.89, with a Kappa value of 0.806. The associated 95% confidence interval (0.812–0.944) indicates that the observed performance is consistent across the evaluated sample.

While the model outperforms the No Information Rate (0.55), this comparison should be interpreted with caution given the structured nature of the dataset. This apparent improvement primarily reflects the model's alignment with the underlying rule-based structure embedded in the data.

Accordingly, the observed performance should not be interpreted as evidence of predictive capability, but rather as an indication of how effectively the model reproduces the predefined rule-based classification under conditions of uncertainty. In this context, model performance is structurally bounded by the rule-constrained design, and therefore reflects consistency with the label generation process rather than the discovery of independent relationships within the data.

4.4 Classification Behavior

The classification behavior is summarized in Table 4 and further illustrated in Figure 4, providing a detailed view of class-level prediction patterns.

Table 4. Confusion matrix for the test dataset

Predicted \ Actual	Low	Medium	High
Low	55	6	3
Medium	0	18	2
High	0	0	16

As shown in Table 4, the majority of predictions align with the true class labels, indicating consistent reproduction of the underlying classification structure.

Notably, no Low-risk cases are misclassified as High-risk, and no High-risk cases are misclassified as Low-risk. This absence of extreme misclassification is particularly important from a decision-making perspective, as it preserves critical risk boundaries and reduces the likelihood of severe misallocation of management actions.

Misclassifications are primarily concentrated between adjacent categories (Low–Medium and Medium–High), reflecting the transitional nature of the classification boundaries rather than random error. This pattern is consistent with the introduction of label noise and suggests that classification uncertainty is localized near boundary conditions, where small variations in input features can influence class assignment.

This behavior is further reflected in Figure 4, where off-diagonal values remain limited and are largely confined to neighboring classes.

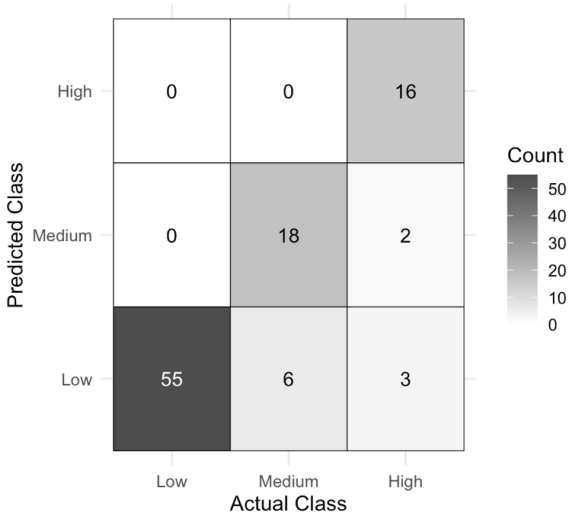


Figure 4. Confusion Matrix

4.5 Class-Level Performance

Table 5. Class-wise performance metrics

Class	Precision	Recall	F1-score
Low	0.859	1.000	0.924
Medium	0.900	0.750	0.818
High	1.000	0.762	0.865

Class-wise performance metrics are summarized in Table 5, providing a more detailed view of model behavior across different risk categories.

The results indicate generally consistent performance across classes, although interpretation should be considered in light of the rule-constrained nature of the labeling process.

Low-risk cases achieve perfect recall, indicating that all such cases are correctly identified. This behavior is consistent with the underlying rule structure, where non-hazardous conditions are more distinctly separated from higher-risk categories.

High-risk cases achieve perfect precision, indicating that all cases classified as high risk correspond to true high-risk instances. From a decision-making perspective, this reduces the likelihood of false alarms in critical scenarios, although it should be interpreted within the constraints of the predefined labeling structure.

The Medium-risk class exhibits lower recall, reflecting its intermediate position between low and high-risk categories. This reduction is consistent with increased overlap at classification boundaries, where small variations in input features and introduced label noise can influence class assignment.

4.6 Model Stability

Model stability was assessed using five-fold cross-validation to evaluate the consistency of performance across different data partitions.

The resulting average accuracy (0.874) and Kappa value (0.772) are consistent with the test results, indicating stable performance across different splits rather than sensitivity to a specific partition.

This consistency further supports the interpretation that model behavior is driven by the underlying rule-constrained structure, with limited variability introduced by data partitioning.

4.7 Feature Importance

Feature importance results are presented in Figure 5, providing insight into how the model weights the relative contribution of input variables.

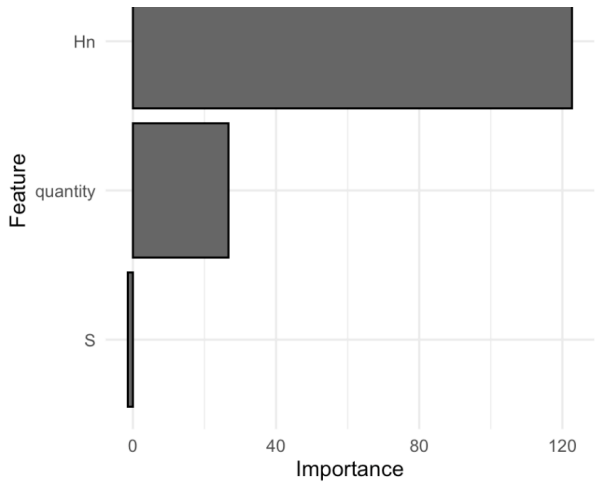


Figure 5. Feature Importance

As shown in Figure 5, hazard level (H_n) appears as the most influential predictor, followed by waste quantity, while environmental sensitivity (S) contributes less prominently.

This hierarchy is structurally expected, as hazard and quantity are the primary drivers embedded in the rule-based labeling process. As such, feature importance should not be interpreted as the discovery of independent relationships, but rather as a reflection of the predefined classification logic.

This alignment reflects consistency with general risk assessment principles, where hazard severity and scale of exposure are central factors, while also reinforcing the rule-constrained nature of the modeling framework.

4.8 Comparison with Rule-Based Classification

The comparison with a rule-based baseline reveals a central methodological result

Table 6. Comparison between rule-based classification and Random Forest

Model	Accuracy	Kappa
Rule-based classification	0.89	0.806
Random Forest	0.89	0.806

As shown in Table 6, both approaches achieve identical performance (accuracy = 0.89, Kappa = 0.806). This equivalence is not coincidental, but a direct consequence of the rule-constrained design, where the learning task is structurally aligned with the label generation process. Because the target labels are derived from predefined rule-based criteria, the machine learning model is inherently constrained to learn and reproduce the same underlying structure, even in the presence of moderate uncertainty introduced through label noise.

Rather than weakening the study, this result provides a clear delineation of the role of machine learning within rule-constrained environments. Under the current setup, machine learning does not provide additional predictive capability beyond the predefined rule structure, but instead demonstrates its ability to reproduce and maintain that structure under uncertainty.

In practical applications, the value of machine learning is expected to increase when data are not strictly governed by predefined rules, and when variability, missing values, and nonlinear relationships become more prominent. In such contexts, data-driven models can extend beyond fixed classification schemes and support more adaptive and scalable decision-making processes.

Taken together, these findings define the boundary conditions under which machine learning is most effective, positioning machine learning as a complementary analytical tool rather than a replacement for established rule-based regulatory frameworks.

4.9 Comparison with Logistic Regression

A comparison between the Random Forest model and multinomial logistic regression is presented in Table 7.

Table 7. Comparison of Random Forest and Multinomial Logistic Regression

Model	Accuracy	CI Lower	CI Upper	Kappa
Random Forest	0.89	0.812	0.944	0.806
Multinomial Logistic Regression	0.86	0.776	0.921	0.752

The Random Forest model shows a modest but consistent improvement in both accuracy and Kappa. The relatively small performance gap is expected, given that both models operate under the same rule-constrained structure.

This improvement likely reflects the flexibility of the Random Forest model in handling boundary conditions and label noise, rather than the identification of fundamentally new relationships.

4.10 Probability Calibration

Probability calibration results are summarized in Table 8 and further illustrated in Figure 6, providing insight into the reliability of predicted probabilities across different risk classes.

Table 8. Brier Scores by Class and Model

Model	Class	Brier Score
Random Forest	Low	0.0887
Random Forest	Medium	0.0913
Random Forest	High	0.0657
Multinomial Logistic Regression	Low	0.0772
Multinomial Logistic Regression	Medium	0.1077
Multinomial Logistic Regression	High	0.0901

As shown in Table 8, the Random Forest model achieves lower Brier scores for the high-risk class compared to logistic regression, indicating improved probabilistic calibration, particularly in scenarios where accurate confidence estimation is critical for decision-making.

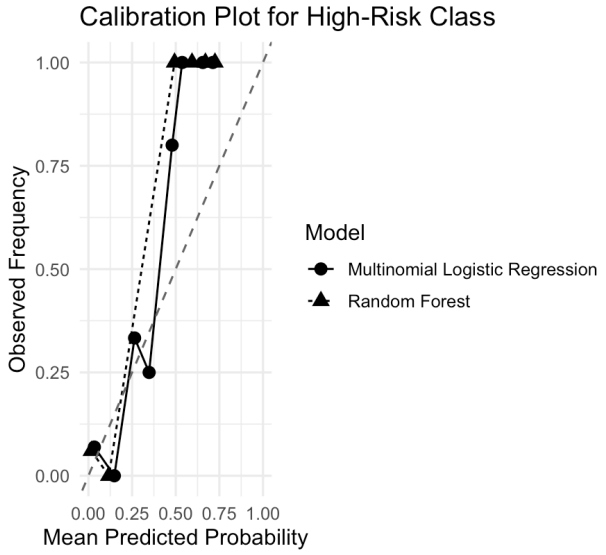


Figure 6. Calibration Plot for High-Risk Class

This is further supported by Figure 6, where predicted probabilities show a generally consistent alignment with observed frequencies, indicating acceptable calibration performance across probability ranges.

Given the rule-constrained nature of the labeling process, calibration results should be interpreted as reflecting the model's ability to maintain probabilistic consistency under uncertainty, rather than capturing true underlying probability distributions.

4.11 Robustness to Uncertainty

The impact of label noise on model performance is evaluated in Table 9 and further illustrated in Figure 7, providing a controlled assessment of robustness under increasing levels of uncertainty.

Table 9. Model performance under different noise levels

Noise Level	Accuracy	95% CI
0%	1.00	(0.964–1.000)
15%	0.89	(0.812–0.944)
30%	0.84	(0.753–0.906)

As shown in Table 9, accuracy declines progressively as noise increases, dropping from near-perfect performance at 0% noise to 0.84 at 30% noise. This trend reflects the model's sensitivity to increasing uncertainty in the target labels.

Performance remains relatively stable, indicating that the model retains a consistent ability to reproduce the underlying classification structure under degraded conditions.

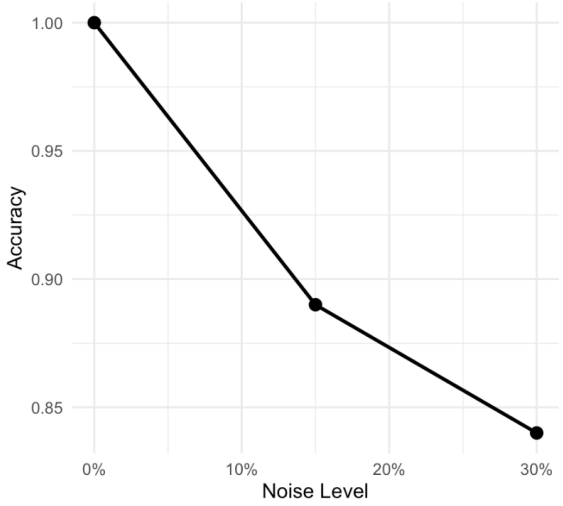


Figure 7. Noise Robustness

Figure 7 illustrates a smooth degradation pattern rather than a sharp drop, suggesting that performance deterioration occurs gradually as uncertainty increases. This behavior indicates that the model is not overly sensitive to moderate levels of label noise, and that classification performance degrades in a controlled and predictable manner.

Given the rule-constrained nature of the problem, this robustness should be interpreted as the model's ability to maintain structural consistency under uncertainty, rather than as resilience in discovering new patterns within noisy data.

4.12 Decision-Support Implications

The decision-support component of the framework establishes a clear linkage between predicted risk levels and corresponding waste management actions.

Table 10. Decision-support rules for waste management actions

Predicted Risk Level	Recommended Management Action
High	Immediate intervention, strict containment, priority inspection, and specialized treatment or disposal
Medium	Controlled handling, regular monitoring, and reinforced storage and compliance checks
Low	Routine waste management procedures and standard regulatory compliance

As illustrated in Table 10, each risk category is associated with a distinct set of recommended interventions. High-risk cases necessitate immediate action and stringent control measures. Medium-risk cases require continuous monitoring and targeted mitigation strategies, whereas low-risk cases can be effectively managed through routine procedures and standard compliance practices.

This mapping serves as a practical bridge between analytical outputs and operational decision-making. Although the framework is presented as a proof of concept, it highlights the potential of translating risk classification results into actionable priorities within real-world waste management systems.

5. Limitations and Future Directions

Although the proposed system demonstrates strong performance within a simulated environment, its results are inherently influenced by the assumptions underlying synthetic data generation and proxy labeling. Consequently, it does not fully capture the complexity of real-world industrial waste systems, where risk is shaped by context-specific interactions among contaminants, environmental conditions, and operational factors (He et al.,2024).

Moreover, the model is trained on proxy labels derived from predefined regulatory rules based on the same input variables. This dependency limits its capacity to provide substantial improvements over traditional rule-based approaches. Additionally, the incorporation of controlled label noise (15%) represents a simplifying assumption and may not adequately reflect the uncertainty present in real-world scenarios.

Furthermore, the absence of real operational data constrains the generalizability of the findings beyond the simulated context.

Future research should therefore investigate hybrid modeling approaches that integrate rule-based logic with data-driven techniques, particularly in data-scarce environments. Combining domain expertise with machine learning has the potential to mitigate the limitations associated with rule-derived proxy labels and enhance model adaptability and robustness in real-world applications.

6. Conclusion

A data-driven system is presented for industrial waste management, which accounts for national guidelines on environmental risks. Combining AI-based modeling with environmental sensitivity indicators, this system provides a structured and rigorous approach for classifying risk levels. An environmental risk index and a random forest classifier were used. The system achieved an overall accuracy of 89% and, most importantly, identified higher-risk waste with precision and consistency. Importantly, this performance should be interpreted within the constraints of the rule-based classification structure, where model outcomes primarily reflect the reproduction of predefined regulatory logic under controlled uncertainty.

An important finding of this study is that, within a rule-constrained setting, the machine learning model reproduces the underlying regulatory logic rather than outperforming it, clarifying its role as a tool for supporting structured decision-making rather than replacing rule-based systems.

Despite successes, a limitation arises relating to its use of simulated data, which affects transferability of the findings to other contexts. Although this enables controlled and reproducible analysis, it does not fully capture the complexity of real-world waste management systems, including variability in operational practices and data quality.Nonetheless, the findings offer a methodological basis for further exploration and subsequent field-based validation.

The suggestion for future studies is to use real-time monitoring data, actual operational records from industry, and geospatial information to improve external validity and increase applicability of the model to diverse settings. In addition, the integration of XAI techniques may increase transparency and support regulatory acceptance. Future work may also examine the framework under less constrained conditions, where variability and complexity extend beyond predefined rule structures. The proposed framework is intended to contribute to the development of more sustainable and data-driven approaches to industrial waste management.

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A Three-Quarter Fold-Over Strategy for Follow-Up Designs in Fractional Factorial Experiments

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Abstract: Follow-up design is a fundamental problem in statistical design of experiments, especially in fractional factorial designs, where aliasing among effects can obscure interpretation and reduce design efficiency. The fold-over technique is commonly used to address this issue by augmenting the initial design with additional runs obtained by switching the levels of one or more factors. In this paper, a new methodology for constructing follow-up designs based on a fold-over approach is proposed and investigated. The performance of the constructed design is evaluated using several statistical design-ranking criteria. The results show that the proposed design achieves higher D-efficiency (up to approximately 98%) and lower average prediction variance than the initial and semi-fold-over designs, indicating more efficient estimation and improved prediction performance..

Keywords: fold-over design, fractional factorial design, D-efficiency, average prediction variance (APV), estimation capacity (EC)

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1. Introduction

One of the main challenges in fractional factorial designs is the aliasing among effects, which can obscure interpretation and reduce the efficiency of the design. A common strategy for addressing this issue is the fold-over technique, which is widely used to construct follow-up experiments. This technique involves reversing the signs of one or more factors in the initial design and augmenting the original runs, thereby improving the resolution and estimation capability of the design. When a full fold-over is applied to a resolution III design by reversing the signs of all factor columns, a resolution IV design is obtained. In such designs, two-factor interactions are confounded with three-factor interactions, which are often assumed to be negligible. Alternatively, a fractional fold-over may be applied by reversing selected factors only, providing greater flexibility in isolating specific effects. For further details, see Montgomery (2017).

Several studies have investigated optimal fold-over strategies for fractional factorial design. Li and Lin (2003) investigated optimal fold-over plans for two-level fractional factorial designs under the minimum aberration (MA) criterion and analyzed their properties using indicator functions (Fries and Hunter, 1980). For nonregular designs, Li et al. (2003) extended this work by proposing optimal fold-over strategies under the generalized minimum aberration (GMA) criterion (Deng and Tang, 2002). These studies highlight the complexity of aliasing structures, particularly in nonregular designs.

The semi-fold-over technique was introduced by Barnett et al. (1997) as a strategy for augmenting the initial design with only half of the runs in the full fold-over design rather than with the complete run size. This approach enables the isolation of important main effects and two-factor interactions while reducing experimental resources (Mee and Peralta, 2000). However, Mee and Peralta (2000) also noted that full fold-over designs with resolution IV are often inefficient in terms of degrees of freedom, as they may provide fewer than $n/2$ additional degrees of freedom for estimating two-factor interactions. To address these limitations, Edwards (2014) proposed an alternative strategy, known as the double semi-fold-over, which is constructed by adding two semi-fold-over fractions to the initial design. This method allows more effects to be estimated than the standard fold-over technique. Furthermore, Liau (2021) presented illustrative examples of semi-fold-over and double semi-fold-over strategies for several experimental designs.

Although fold-over and semi-fold-over design strategies have been used extensively in follow-up experimentation, they still have important limitations. The classical fold-over technique requires augmenting the initial design with an additional design of equal size, resulting in a combined design with twice the number of runs. This increases experimental cost and resource consumption, making the approach inefficient in many practical situations. Although semi-fold-over and double semi-fold-over designs reduce the number of additional runs relative to the full fold-over, they often suffer from residual aliasing, particularly among two-factor interactions, and may exhibit inconsistent performance across design evaluation criteria.

Therefore, more flexible and efficient follow-up design strategies are needed to improve the estimability of interaction effects without substantially increasing the number of experimental runs. To address this gap, this study proposes a three-quarter fold-over design strategy that balances full fold-over and semi-fold-over approaches. The proposed method aims to improve the efficiency of follow-up designs while controlling the number of additional runs. Its effectiveness is evaluated using multiple criteria, including estimation capacity (EC), D-efficiency, and average prediction variance (APV), and is compared with the initial design and existing semi-fold-over techniques.

The remainder of this paper is organized as follows. Section 2 reviews the design evaluation criteria, namely estimation capacity (EC), D-efficiency, and average prediction variance (APV), and explains their relevance for assessing design performance. Section 3 presents the proposed methodology. Section 4 reports the results. Section 5 provides the discussion and concluding remarks.

2. Preliminaries

To evaluate the effectiveness of the proposed design, this study adopts a set of complementary criteria selected to align with the main objective of improving the estimability of interaction effects. Specifically, estimation capacity (EC), D-efficiency, and average prediction variance (APV) are used to assess design performance from different perspectives. Together, these criteria provide a comprehensive evaluation of the estimation capability, statistical efficiency, and prediction performance.

2.1 Estimation Capacity

Estimation capacity (EC) was first introduced by Cheng et al. (1999) and is defined as the total number of estimable models that contain all k main effects and g two-factor interactions. Mee et al. (2017) further described the estimation capacity as a vector (EC_1,…, EC_G), in which each component represents the ratio of estimable models to the total number of possible models with the same structure. Formally, the estimation capacity for g two-factor interactions is defined as:

$$EC_g = \frac{N_g^e}{N_g}, g = 1,2, \ldots . G$$

where N_g^e denotes the number of estimable models containing all k main effects and g two-factor interactions, and N_g denotes the total number of possible models with the same structure. The total number of possible two-factor interactions among k factors is $\binom{k}{2}$; therefore, the total number of candidate models with exactly g interactions is given by:

$$N_g = \binom{\binom{k}{2}}{g}$$

A design is considered effective if all components of the estimation capacity vector reach their maximum value of 1. This criterion is particularly appropriate for evaluating the proposed design because it directly reflects the design's ability to identify and estimate models that include main effects and two-factor interactions. In this sense, estimation capacity provides a meaningful measure of the estimability of the underlying models supported by the design.

2.2 D-efficiency

D-efficiency is derived from the D-optimality criterion introduced by Kiefer and Wolfowitz (1959), which focuses on maximizing the determinant of the information matrix $X'X$ to ensure precise estimation of model parameters (Montgomery, 2013). As a normalized version of this criterion, D-efficiency provides a scale-invariant measure that enables comparisons among designs of different sizes. It is commonly expressed as:

$$D = \left(\frac{det(X'X)}{n^p}\right)^{\frac{1}{p}}$$

where X is the design matrix, n is the number of experimental runs, and p is the number of model parameters. This formulation reflects the amount of information contained in the design relative to its size (Atkinson et al., 2007; Myers et al., 2016).

This criterion is particularly appropriate for evaluating the proposed design because it quantifies the design's ability to provide precise and stable parameter estimates. A higher D-efficiency indicates a more informative design and therefore reflects the overall quality and effectiveness of the design in parameter estimation.

2.3 Average Prediction Variance

Average prediction variance (APV) was first introduced by Box and Draper (1987). It represents the average variance of the predicted responses over the experimental region. A smaller APV value indicates better prediction performance. Simmons (2023) used APV to compare and evaluate different designs before conducting experiments and showed, both theoretically and through simulation studies, that designs with lower APV provide better prediction accuracy.

The APV is based on the variance of the predicted response. According to Montgomery (2013), the variance of the predicted response at a point x is given by:

$$Var(\hat{y}(x)) = \sigma^2 x'(X'X)^{-1}x$$

where X is the design matrix. APV is obtained by averaging this variance over the design region.

This criterion is appropriate for evaluating the proposed design because it reflects the design's ability to provide accurate and stable predictions across the experimental region. In this sense, APV serves as a useful measure of the design's prediction capability.

3. Methodology for Constructing a Three-Quarter Fold-Over Design

This study proposes a structured procedure for constructing a three-quarter fold-over follow-up design. The methodology is formally defined as follows.

Step 1. Let D denote the initial design matrix with n runs and k main effects. Select a factorial effect $\chi \in D$ whose levels will be reversed to introduce a structured modification to the original design.

Step 2. Construct the fold-over design, denoted by D_x, by reversing the signs of the selected factor x. The combined design is then obtained as: $S=D \cup D_x$, which reduces aliasing between main effects and interaction effects.

Step 3. To further refine the design, apply a subsetting procedure to S based on two selected effects (either a main effects and one two-factor interaction, or two two-factor interactions), resulting in four equal-sized subsets, S_i, i=1,2,3,4 such that $S = S_1 \cup S_2 \cup S_3 \cup S_4$. This partitioning facilitates the systematic selection and exclusion of subsets.

Step 4. Select any three subsets and combine them with the original design D to construct the final three-quarter fold-over design: $D^* = D \cup S_a \cup S_b \cup S_c$, where $\{a, b, c\} \subset \{1, 2, 3, 4\}$. This step balances design size and estimation capability by incorporating 75% of the fold-over design, thereby improving estimability without using the full fold-over.

This construction balances full fold-over and semi-fold-over designs while controlling the number of additional experimental runs. The resulting design is evaluated using estimation capacity (EC), D-efficiency, and average prediction variance (APV), as defined in the previous section.

For illustration, consider a 2^{5-1} fractional factorial design defined by the generator E = ABC, resulting in an initial design with 16 runs. A fold-over is performed on factor C. Subsetting is then applied based on the effects E and AB, which partitions the design into four equal-sized subsets. A three-quarter fold-over design is constructed by augmenting the initial 16-run design with three of these subsets, resulting in a total of 28 runs. The proposed construction procedure is illustrated in Figure 1.

	A	B	C	D	E
1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	1
3	-1	1	-1	-1	1
4	1	1	-1	-1	-1
5	-1	-1	1	-1	1
6	1	-1	1	-1	-1
7	-1	1	1	-1	-1
8	1	1	1	-1	1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1
12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1

(a) Initial design

	A	B	C	D	E
1	-1	-1	1	-1	1
2	1	-1	1	-1	-1
3	-1	1	1	-1	-1
4	1	1	1	-1	1
5	-1	-1	-1	-1	-1
6	1	-1	-1	-1	1
7	-1	1	-1	-1	1
8	1	1	-1	-1	-1
9	-1	-1	1	1	1
10	1	-1	1	1	-1
11	-1	1	1	1	-1
12	1	1	1	1	1
13	-1	-1	-1	1	-1
14	1	-1	-1	1	1
15	-1	1	-1	1	1
16	1	1	-1	1	-1

(b) Fold-over on factor C

	A	B	C	D	E
1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	1
3	-1	1	-1	-1	1
4	1	1	-1	-1	-1
5	-1	-1	1	-1	1
6	1	-1	1	-1	-1
7	-1	1	1	-1	-1
8	1	1	1	-1	1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1
12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1

(c) Partitioning based on E and AB

	A	B	C	D	E
1	-1	-1	-1	-1	-1
2	1	-1	-1	-1	1
3	-1	1	-1	-1	1
4	1	1	-1	-1	-1
5	-1	-1	1	-1	1
6	1	-1	1	-1	-1
7	-1	1	1	-1	-1
8	1	1	1	-1	1
9	-1	-1	-1	1	-1
10	1	-1	-1	1	1
11	-1	1	-1	1	1
12	1	1	-1	1	-1
13	-1	-1	1	1	1
14	1	-1	1	1	-1
15	-1	1	1	1	-1
16	1	1	1	1	1

(d) Combined design

Figure 1. Procedure for constructing the three-quarter fold-over design.

3.1 Alias Structure Considerations for Subsetting

To ensure valid subsetting, it is important to account for the design alias structure. In fractional factorial designs, the alias structure defines relationships among effects. For example, in the 2^(4-1) design with generator D=ABC, the alias structure implies relationships such as AB=CD, AD=BC, and BD=AC. Therefore, when selecting two-factor interactions for subsetting, effects should be chosen from different alias groups. Selecting equivalent interactions produce meaningful partitioning, whereas selecting interactions from different groups ensures distinct subsets. Similar aliasing patterns were observed across all considered designs.

This consideration directly affects the quality of the resulting subsets. Selecting interactions from different alias groups enhances the structural diversity of the design and improves its statistical properties, whereas selecting interactions from the same group leads to redundant partitions with limited benefit. Therefore, appropriate selection of subsetting effects is essential for achieving efficient and informative follow-up designs.

4. Results

Factorial designs with different resolutions were considered to evaluate the proposed three-quarter fold-over design. A single-factor fold-over strategy was applied by reversing factor C. The selection of factor C is arbitrary, and the same procedure can be applied to any main effect. Different subsetting schemes were also examined, including combinations of main effects with one two-factor interactions and schemes based solely on two two-factor interactions. The performance of the initial, semi-fold-over, and three-quarter fold-over designs was assessed in terms of D-efficiency, average prediction variance (APV), and estimation capacity (EC), as summarized in Table 1.

Table 1. Evaluation of the proposed three-quarter fold-over design compared with initial and semi-fold-over designs

Design	Generator	Fold-over strategy	Subsetting scheme	Number of runs	D-efficiency	APV	EC_3
$\overline{2^{4-1}_{initial}}$	D=ABC	--	--	8	100	0.291667	0.4
2^{4-1}_{semi}	D=ABC	C	D, AB	12	97.67187	0.20833	0.4
			AD, BC		95.39794	0.20833	0.4
$2^{4-1}_{three-quarter}$	D=ABC	C	D, AB	14	98.21554	0.173611	0.4
			AD, BC		96.86961	0.175595	0.4
$2^{5-2}_{initial}$	D=ABC, E=ABD	--	--	8	100	0.291667	0.4
$\overline{2^{5-2}_{semi}}$	D=ABC, E=ABD	C	A, BC	12	97.67187	0.20833	0.4
			AD, BD		95.39794	0.20833	0.4
$2^{5-2}_{three-quarter}$	D=ABC, E=ABD	C	A, BC	14	98.21554	0.173611	0.4
			AD, BC		96.86961	0.175595	0.4
$2^{5-1}_{initial}$	E=ABC	--	--	16	100	0.166667	0.8
2^{5-1}_{semi}	E=ABC	C	E, AB	24	98.05609	0.118056	0.8
			AB, BE		96.14997	0.118056	0.8
$2^{5-1}_{three-quarter}$	E=ABC	C	E, AB	28	98.51072	0.09871	0.8
			AB, BE		97.38445	0.099702	0.8
$\overline{2^{5-1}_{initial}}$	E=ABCD	--	--	16	100	0.166667	1
2^{5-1}_{semi}	E=ABCD	C	A, CD	24	98.05609	0.118056	1
			AE, CE		98.05609	0.114583	1
$2^{5-1}_{three-quarter}$	E=ABCD	C	A, CD	28	98.97433	0.097222	1
			AE, CE		98.84984	0.097024	1

Note: Table 1 reports estimation capacity up to three two-factor interactions. The values remain identical for cases involving up to seven interactions.

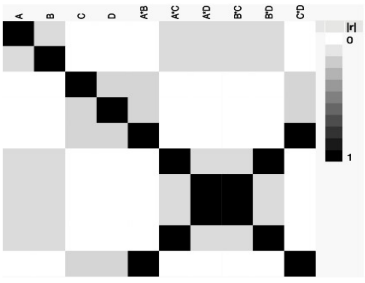
The results indicate that the proposed three-quarter fold-over design consistently improves D-efficiency compared to the semi-fold-over design across all considered cases. In terms of prediction performance, the proposed design yields lower APV values compared to both the initial and semi-fold-over designs. However, no improvement is observed in estimation capacity, as the EC values remain unchanged across all designs.

To further evaluate the robustness of the proposed design, a sensitivity analysis was conducted by considering different fold-over strategies while retaining the same subsetting schemes used in Table 1. The results are summarized in Table 2.

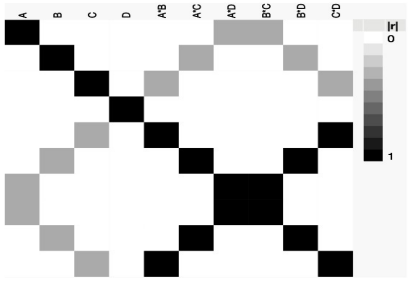
Table 2. Sensitivity analysis under different fold-over strategies

Design	Generator	Fold-over strategy	Subsetting scheme	Number of runs	D-efficiency	APV	EC_3
$\overline{2^{4-1}_{initial}}$	D=ABC	--	--	8	100	0.291667	0.4
2^{4-1}_{semi}	D=ABC	A, B, C, D	D, AB	12	97.67187	0.20833	0.4
			AD, BC		95.39794	0.20833	0.4
$2^{4-1}_{three-quarter}$	D=ABC	A, B, C, D	D, AB	14	98.21554	0.173611	0.4
			AD, BC		96.86961	0.175595	0.4
$2^{5-2}_{initial}$	D=ABC, E=ABD	--	---	8	100	0.291667	0.4
2^{5-2}_{semi}	D=ABC, E=ABD	A, B, C, D, E	A, BC	12	97.67187	0.20833	0.4
			AD, BD		95.39794	0.20833	0.4
$2^{5-2}_{three-quarter}$	D=ABC, E=ABD	A, B, C, D, E	A, BC	14	98.21554	0.173611	0.4
			AD, BC		96.86961	0.175595	0.4
$2^{5-1}_{initial}$	E=ABC	--	--	16	100	0.166667	0.8
2^{5-1}_{semi}	E=ABC	A, B, C, D, E	E, AB	24	98.05609	0.118056	0.8
			AB, BE		98.05609	0.118056	0.8
$2^{5-1}_{three-quarter}$	E=ABC	A, B, C, D, E	E, AB	28	98.51072	0.09871	0.8
			AB, BE		98.51072	0.099702	0.8
$2^{5-1}_{initial}$	E=ABCD	--	--	16	100	0.166667	1
2^{5-1}_{semi}	E=ABCD	A, B, C, D, E	A, CD	24	98.05609	0.118056	1
			AE, CE		98.05609	0.114583	1
$2^{5-1}_{three-quarter}$	E=ABCD	A, B, C, D, E	A, CD	28	98.97433	0.097222	1
			AE, CE		98.84984	0.097024	1

The results indicate that there is no noticeable difference between the full fold-over and single-factor fold-over strategies in terms of D-efficiency and APV. Both approaches yield similar values across the considered designs. However, the choice of subsetting effects has a clear impact on performance. Subsetting schemes that include both main effects and two-factor interactions result in higher D-efficiency, whereas schemes based solely on two-factor interactions lead to lower values. In addition, the aliasing among effects, particularly between main effects and two-factor interactions, was examined, as illustrated in Figure 2.



(a) Correlation map of the three-quarter fold-over



(b) Correlation map of the semi-fold-over

Alias Matrix

Effect	A*B	A*C	A*D	B*C	B*D	C*D
Intercept	-0.2	0	0	0	0	-0.2
A	0	-0.17	-0.17	-0.17	-0.17	0
B	0	-0.17	-0.17	-0.17	-0.17	0
C	-0.2	0	0	0	0	-0.2
D	-0.2	0	0	0	0	-0.2

(c) Aliasing matrix of the three-quarter fold-over

Alias Matrix

Effect	A*B	A*C	A*D	B*C	B*D	C*D
Intercept	0	0	0	0	0	0
A	0	0	-0.33	-0.33	0	0
B	0	-0.33	0	0	-0.33	0
C	-0.33	0	0	0	0	-0.33
D	0	0	0	0	0	0

(d) Aliasing matrix of the semi-fold-over

Figure 2. Correlation maps and aliasing matrices for three-quarter and semi-fold-over designs for 2^{4-1} design.

Figure 2 presents a representative example of the aliasing and correlation structure for the considered designs. Similar patterns were consistently observed across all designs; therefore, only one representative case is shown for clarity. The results indicate that the proposed three-quarter fold-over design reduces correlations among effects compared with the semi-fold-over design, resulting in a more stable design structure.

5. Discussion and Concluding

This study examines the performance of the proposed three-quarter fold-over design in fractional factorial experiments. The results, as reported in Table 1, show that the proposed design achieves higher D-efficiency and lower APV than the initial and semi-fold-over designs. However, no improvement is observed in estimation capacity. In addition, multicollinearity between main effects and two-factor interactions is observed, as illustrated in Figure 2. The results also show no noticeable effect of the fold-over strategy (single-factor versus full fold-over) on the evaluated criteria.

These findings can be understood through the properties of the information matrix $X'X$, where D-efficiency is related to its determinant and APV is linked to its inverse. In the considered cases, designs with larger run sizes show improved D-efficiency and lower APV, indicating more stable estimation and better prediction performance. This observation is consistent with the theory that increasing the run size improves the quality of the information matrix (Montgomery, 2017; Atkinson, 2025).

In contrast, no improvement is observed in estimation capacity across the considered designs. This indicate that estimation capacity depends on the alias structure of the design rather than on the number of runs. Therefore, the proposed design does not improve this criterion, as no additional independent information is introduced and the number of estimable models remains unchanged. This finding is consistent with the fundamental principle in fractional factorial designs that estimability is driven by the defining relation and alias structure rather than simply by increasing the number of experimental runs (Montgomery, 2017).

Moreover, the presence of multicollinearity in the proposed design can be attributed to the structure of the fold-over construction, particularly when partial fold-over strategies, such as semi- and three-quarter fold-over are used. As shown in Figure 2, the alias matrix highlights the correlation between main effects and two-factor interactions, indicating the presence of multicollinearity. When such correlations exist, the estimated coefficients become less stable. In practical terms, small changes in the data may lead to noticeable changes in the coefficient estimates, making it more difficult to interpret the individual effects of the factors. This is consistent with previous findings in the literature. For example, Montgomery (2017) explains that multicollinearity in fractional factorial designs arises from the aliasing structure, which can increase the variance of the estimates and reduce their interpretability. Similarly, regression analysis literature (e.g., Kutner et al., 2005) shows that multicollinearity inflates the variance of coefficient estimates, making them more sensitive to data variation.

At the same time, Figure 2, shows that the proposed three-quarter fold-over design exhibits lower correlation values than the semi-fold-over design. This observation indicates that, in the considered cases, the additional runs and fold-over construction help reduce the correlation between effects. As a result, the columns of the model matrix become less dependent, and the information matrix $X'X$ becomes closer to orthogonality. This is consistent with the role of fold-over designs in breaking alias chains and reducing confounding among effects (Montgomery, 2017).

It is worth noting that some level of multicollinearity is expected in such designs. As highlighted in optimal design theory (Atkinson, 2025), even when parameter estimates are correlated, a design can still achieve good predictive performance. In the present results, despite the observed correlation between effects (Figure 2), the proposed design maintains high D-efficiency and low APV. Therefore, the multicollinearity observed in the proposed design should be viewed as a consequence of the design structure rather than a major limitation.

Building on this observation, a noticeable effect is observed when two-factor interactions are selected for subsetting, particularly with respect to D-efficiency. This behavior can be explained by the structural impact of interaction-based selection on the design matrix. Specifically, two-factor interactions are more sensitive to the underlying alias structure in fractional factorial designs, and selecting them for subsetting tends to reduce orthogonality and introduce higher correlation among the columns of the design matrix. As a result, the information matrix becomes less stable, leading to a reduction in D-efficiency (Montgomery, 2017; Jones and Nachtsheim, 2011; Edwards & Mee, 2023).

In contrast, when subsetting is based on main effects, the impact on the design structure is relatively limited. Main effects are typically well-balanced and less affected by aliasing, which helps preserve design orthogonality. Consequently, subsetting based on main effects generally maintains a higher level of D-efficiency, although it may not capture the interaction structure within the design.

Despite these findings, this study has some limitations. The evaluation is based on a limited number of design examples, and the results may not generalize to all fractional factorial structures. In addition, only specific subsetting schemes were considered, and alternative choices may lead to different performance.

From a practical perspective, the proposed three-quarter fold-over design useful in situations where improved prediction accuracy is required without substantially increasing the number of experimental runs. This is supported by the results, in which the proposed

design achieves higher D-efficiency and lower APV than the initial and semi-fold-over designs. It can also serve as a practical alternative to full fold-over when experimental cost is a concern, particularly in follow-up experiments where partial de-aliasing is sufficient. Within the scope of the considered designs, the proposed design contributes to the literature on follow-up experimental designs by providing a flexible and efficient construction strategy.

Future work may extend the proposed three-quarter fold-over approach to other classes of designs, including nonorthogonal designs, with further attention to both construction and analysis aspects. In addition, exploring alternative subsetting strategies and their relationship with multicollinearity would be of interest. Evaluating the proposed designs using additional criteria, such as minimal dependent sets (MDS), also represents a promising direction for future research.

Overall, the proposed three-quarter fold-over design provides a practical and efficient solution for follow-up experimentation, offering a balance between estimation capability and experimental cost.

6. Declarations

The author declares that there are no competing interests.

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Phytobezoar Predisposing Factors: Re-evaluating the Role of Dietary Fibres - A Systematic Review

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Abstract
Background: Phytobezoar is defined as the compaction of indigestible food material (mainly fibrous plant tissues) localised in the gastrointestinal tract (GIT), leading mainly to GI obstruction (GIO) and many GI health problems. Some researchers claimed that vegetables, fruits, and other DF-containing foods are the main culprits in phytobezoar formation.
Objective: systematic review of the available case reports and case series to identify the actual culprits of phytobezoar formation and to distinguish the role of dietary fibres.
Data Source: We searched PubMed, MEDLINE, Web of Science platform, and Google Scholar with no restriction through April 2026.
Study Selection: available phytobezoar cases (including reports, series and reviews).
Data Extraction: We extracted data on patient demographic information, diagnosis, and emphasizing the predisposing/risk factors.
Data Synthesis: 218 publications met inclusion criteria, reporting on 1382 cases. The cases have been categorized according to the predisposing/ risk factors.
Limitations: no limitation for time, age, and geography, however the study is limited to English publications.
Conclusion: the study unambiguously distinguished the actual predisposing/risk factors for phytobezoar formation including previous GI surgeries, unusual foodstuffs, among others. Although phytobezoars are usually formed of undigested fibrous plant material, however, proper consumption of the recommended amounts of dietary fibre-containing foods is not responsible for phytobezoar formation.

Keywords: Dietary fibres, phytobezoar, bezoar culprits, gastrointestinal surgery.

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1. Introduction

The term "Phytobezoar" has been derived from the Greek word "phyton" (plant) and "bezoar" is thought to refer to the Persian words *pâd* (expelling) and *zahr* (poison).[1,2] The medical term "bezoar" was established in the medical literature since 1854 by Dr. Richard Quain.[3] In medical terminology, bezoars represent an agglomerate of foreign materials, hairs (trichobezoars), indigestible plant material (phytobezoars), or drugs (pharmacobezoars) that ingested, accumulate and solidify inside GIT, creating a solid phase that progressively grows until the point it can prevent the normal digestive process and often obstructs GIT.[3-6]

Although rare cause of primary gastrointestinal obstruction, phytobezoars are the most common cause of bezoar occurrence, accounting for up to 70% of all bezoars.[4,7,8]

Bezoars are responsible for 0.4% - 4% of cases of mechanical gastrointestinal obstruction worldwide. [9,10] Some researchers have claimed that vegetables, fruits, and other fibre-containing foods are the main culprits in the formation of phytobezoars.[3,5,6,11,12] However, they do not differentiate between the recommended amount of dietary fibres and other fibrous plant tissues (unusual food material) that are consumed intentionally or accidentally, leading to phytobezoar formation. Dietary fibres (DF) is a term used to describe indigestible, soluble and insoluble part of usual foodstuffs, especially carbohydrates.[13] These DF are found naturally at a reasonable level in our healthy foods e.g. popular fruits and vegetables, either as soluble fibres (e.g. mucilaginous materials: psyllium seed, chia seeds, Okra, fenugreek, salep tubers, grains …etc.) or insoluble fibres (e.g. grain walls (wheat Bran, oat bran), Beans, shelled nuts, vegetables, fruits ...etc.).[14-17] Here, we have to recognise non-food plant fibres e.g. plant wood fibers, hard or leathery seed skins (sunflower seed coats, watermelon seed coat, Apricot pits, etc.,), these types of plant fibres are not considered as DF. According to common recommendations, DF should be consumed regularly as food habit at a daily dose of 30-38 g for adult men as a part of 2600 kcal food/day, and 28-30 g for adult women as part of 2000 kcal daily food.[13-16] Dieticians and healthcare providers must consider these values in their prescriptions and recommendations to the public. They must also recalculate these quantities based on patient's age and health status. Consumption of the recommended amount of DF has a positive impact and offers great health benefits. DF consumption was linked to increased insulin sensitivity,[18] improved blood sugar levels,[18] management of diabetes,[19]improvement of obesity and body mass index (BMI),[18] prevention of constipation[20], lower blood cholesterol levels,[21] decreased fat and carbohydrate absorption,[22]and lowering of blood pressure.[23,24] Other benefits have also been confirmed, such as improvement of GIT movement ,[22] and increased mineral absorption in the intestinal tract,[25] reduces energy intake,[26] decreases the chance of pathogenic microbial growth, increases the chance of growth and development of beneficial microbial flora,[27] biosynthesis of short-chain fatty acids with valuable health benefits,[28] improvement of the immune system,[29] decreases the absorption of toxic substances and carcinogens for GIT,[30] and prevention of tumour formation (e.g. colorectal cancer) and consequently, enhances the quality of life.[13,31,32]

1.1 Mechanisms of phytobezoar formation:

Phytobezoars are formed in the alimentary canal as a result of specific indigestible plant tissues and biological reactions that interact to form solid or semisolid concretions or conglomerates that are difficult to hydrolyze or fragment and cause partial or complete GIO. Two scenarios have been accepted as mechanisms for phytobezoar formation.

- **Chemical scenario:** Phytobezoar formation (diospyrobezoars) due to consumption of persimmon fruits (*Diospyros kaki*) has been confirmed. Unripe persimmon fruits contain high concentrations of tannins (phlobatannin: shibuol), fibre contents, and indigestible soluble carbohydrates.[33,34] When tannin comes into contact with gastric juice (higher gastric acidity) in the stomach, especially in an empty stomach, it can precipitate and undergo polymerization, forming a coagulum that includes cellulose, hemicellulose, and protein. This coagulum serves as the foundation for the bezoar. As this cluster continues to evolve, it undergoes dehydration and solidification processes. This solidified mass grows, resists fragmentation or hydrolysis and can then be moved to narrow spaces in the GIT, leading to obstruction.[7,8,34]
- **Mechanical scenario:** the formation of phytobezoar may be due to accumulation of indigestible plant materials such as hard leathery or woody plant material (e.g. unshelled watermelon seeds, unshelled pumpkin seeds), or a high amount of hygroscopic material (e.g. dry chia seeds), where these materials accumulate and grow to form a nucleus of phytobezoar under the influence of predisposing factors such as GIT strictures or GI laziness.[35] However, other scenarios have not been confirmed for phytobezoar formation due to easily digestible food materials such as rice, potato-based foods, and meat boluses.[36]

1.2 Phytobezoar - related complications and health problems:

Gastrointestinal obstruction (GIO) is the main complication of phytobezoar formation, where the

phytobezoar can be localised in the stomach and move to close the pyloric canal or continue moving to cause small bowel obstruction in the duodenum, jejunum, or ileum, preventing the normal function of the GIT.[3] However, seed shell-related phytobezoars are commonly formed or agglomerated in the large intestine.[37-39] Gastrointestinal (GI) obstruction of the GIT can lead to serious health issues, such as GI perforation, GI bleeding, intussusception, and strangulation, which may lead to local ischaemia and necrosis.[6,40] Indeed, acute pancreatitis[41], Jejunal Obstruction[42], GI Hemorrhage[43], Restrictive lung pattern[44], small bowel perforation[45], Proximal Ileal Perforation[46], body weight loss, GI ulceration, GI inflammation, fistula formation, and adhesion have also been reported as complications for phytobezoars.[47]

phytobezoar cases have been reported in almost all geographic regions, worldwide due to fibrous and less likely non-fibrous plant materials and non-plant foodstuffs. The exact role of dietary fibres in the formation of phytobezoar is debatable. Consequently, an urgent literature review is needed to clarify the actual causes of phytobezoars. The present study was designed to investigate the published phytobezoar cases from global healthcare centres in order to explain the actual culprits of phytobezoar formation, and distinguishes the role of dietary fibres.

2. Materials and Methods

2.1 The study selection and literature search strategy

The data of the present systematic review were obtained from Life-science databases (PubMed, MEDLINE, Web of Science platform, and Google Scholar).48-51 The search was conducted independently by two reviewers (MA and AA) using specific terms "phytobezoar", "phytobezoar-predisposing factors", "phytobezoar-dietary fibres", and "dietary fibres" to identify studies relevant to phytobezoar cases and the role of dietary fibres. The obtained search results were filtered first by screening titles and abstracts then further filtering has been made to exclude duplicate and irrelevant publications. Then further filtering was performed to exclude irrelevant publications and those lacking important information. Disagreements were resolved by consensus. The search included studies published up to 2026.

2.2 Quality assessment of the eligible publications

The assessment was carried out independently by two investigators (MA & AA) addressing the items available in the case reports. These items include 1) relevance of the title to the reported information, 2) adequacy of demographic information, 3) relevant past history, 4) case diagnosis, 5) type of concretion (phytobezoar mass), and 6) pre-disposing/risk factors if any, 7) discussion of the relevant evidences. Possible item ratings are yes, partially, or no; disagreement was resolved by consensus.

2.3 Inclusion and Exclusion criteria

Inclusion criteria: All studies reported human cases of phytobezoar. There was no limitation for time of publication, and no limitation of countries or geographic regions.

Exclusion criteria: 1) non-plant-related bezoar cases (e.g. trichobezoars, pharmacobezoars); 2) all articles that are free from reported phytobezoar information; 3) non-human phytobezoar cases (e.g. animal bezoar cases); 4) repetitions or case duplicates were also excluded; 5) lacking of important information. 6) articles published in languages other than English.

2.4 Data synthesis and analysis

218 articles have been selected based on the eligibility criteria for inclusion and exclusion, Descriptive statistical analyses were used to data syntheses and categorization process. Microsoft Excel software (Microsoft, USA) has been utilized for Statistical analysis, classification, designing graphs and extracting tables.

3. Results

3.1 Quality appraisal

Based on the items of quality assessment, the overall quality of the included studies was moderate to high. The titles were relevant to the reported information (100%), adequacy of demographic information (age, gender, nationality, residency) (80.4%), relevant past history (93%), case diagnosis (99.0%), type of concretion (phytobezoar mass) (67.9%), pre-disposing/risk factors if any (89.9%), and discussion of the relevant evidences (98.8%).

3.2 Publication characteristics

The eligible publications (218 articles), have been investigated (Figure 1). These eligible publications were found to comprise almost all relevant topics, almost all geographic regions (worldwide), with no limited time period through 2026. The selected articles included case reports, case series, case reports with reviews, review of cases, and other relevant reviews of phytobezoar occurrence. The eligible records were carefully reviewed, and extracted to the Microsoft excel sheets, then categorized into groups as seen in the provided tables (S1 appendix). Total Number of reviewed phytobezoar cases (1382 cases) have been categorised according to patient age with or without previous GI surgery (Figure 2). The phytobezoar cases without previous GI surgery have been classified according to predisposing/risk factors (Figures 3).

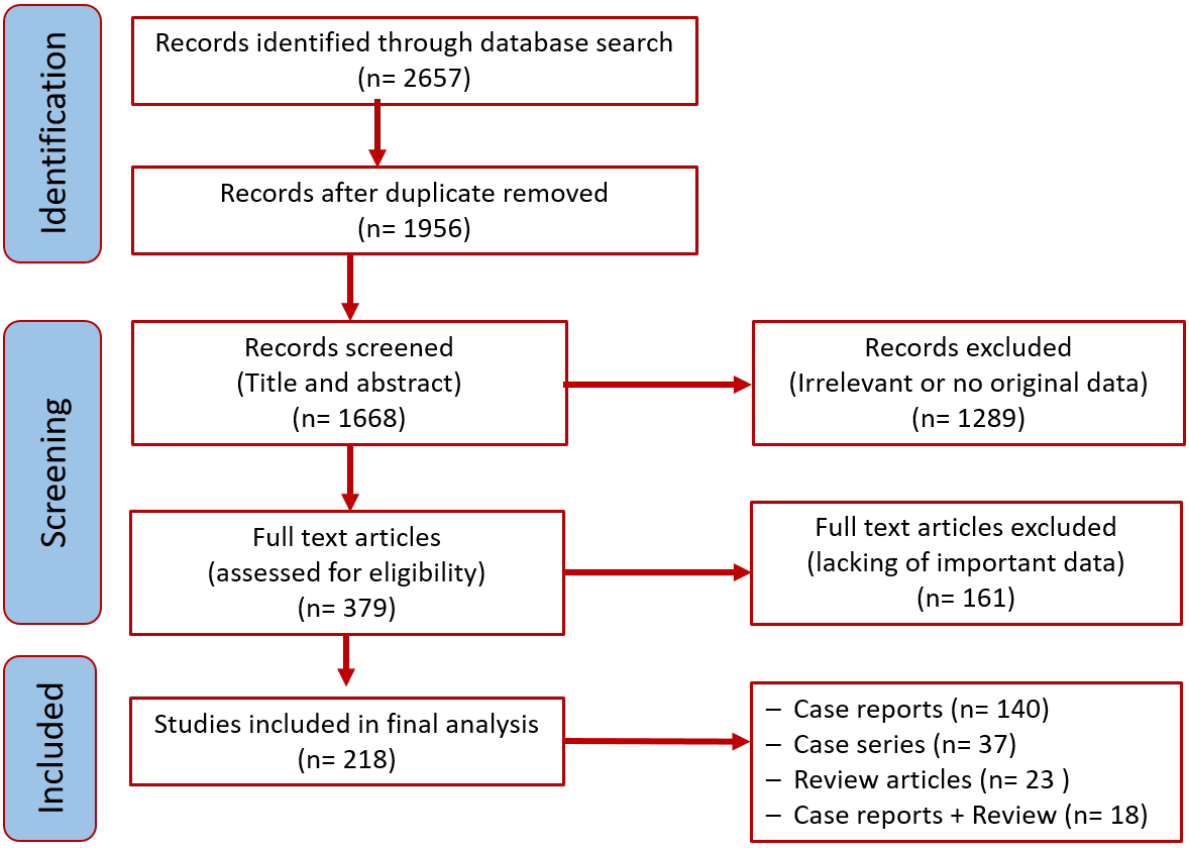


Figure 1. PRISMA 2020 Flow diagram for the selection of records and publications.

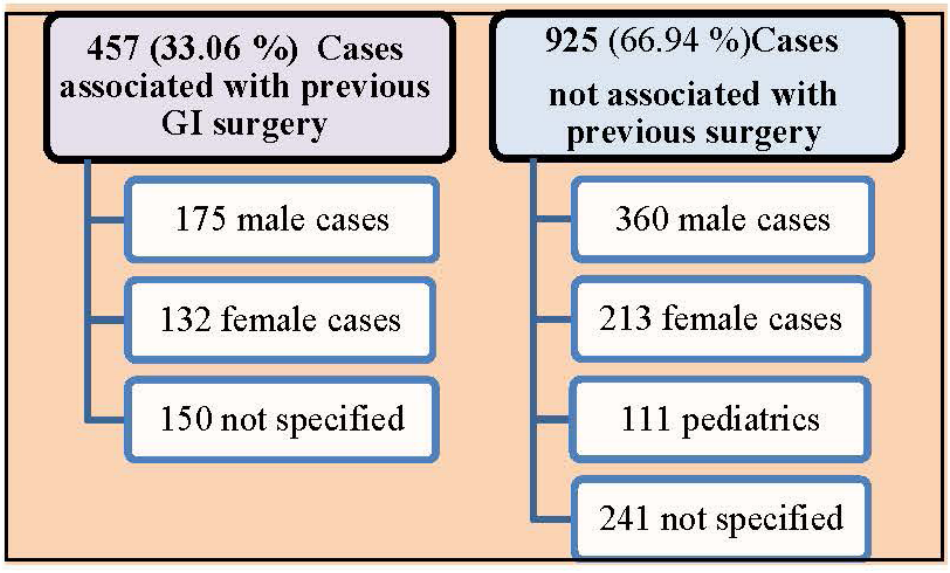


Figure 2. Classification of phytobezoar cases according to age and previous GI surgery.

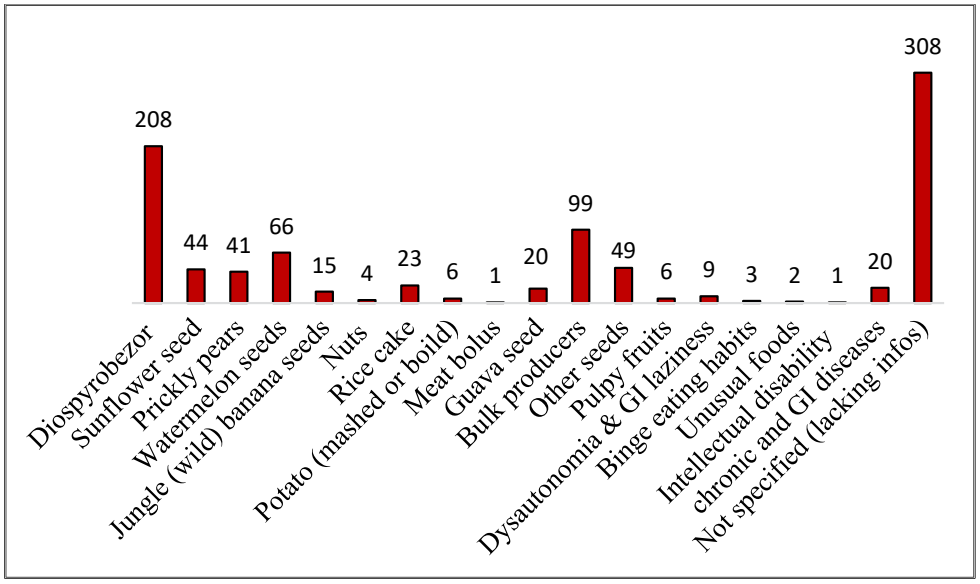


Figure 3. Classification of phytobezoar cases not associated with previous GI surgery.

3.3 Phytobezoar predisposing factors

Several predisposing/risk factors have been recognised (see supporting information tables 1 -6).[34,35] The most common predisposing/risk factors (Figure 4) have been considered the main culprits and discussed in detail in the following sections.

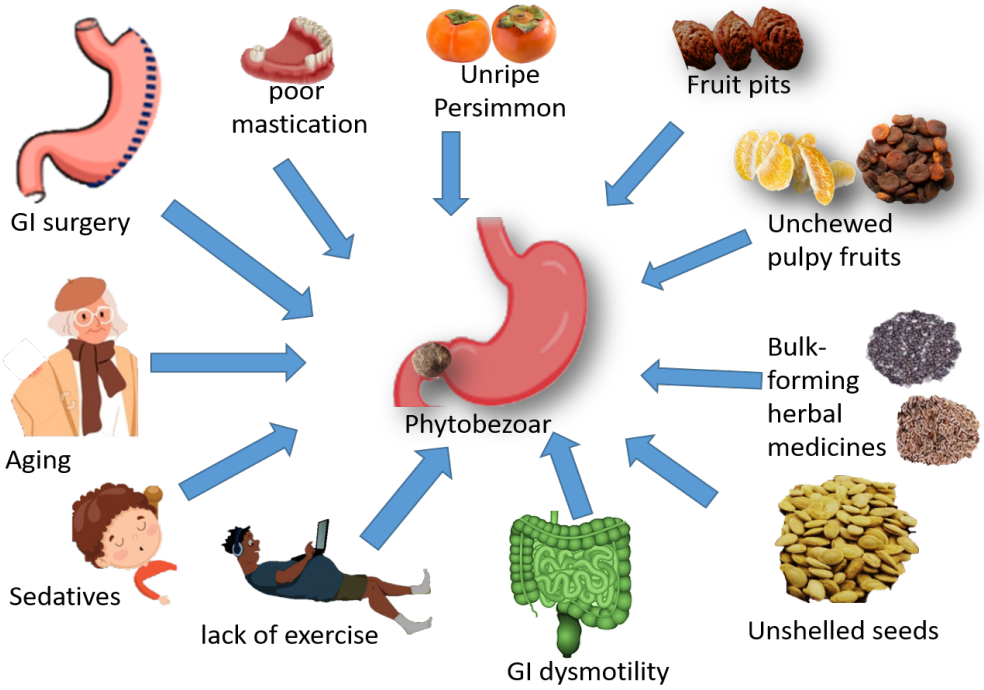


Figure 4: The main culprits for phytobezoar formation

3.4 The Actual culprits in phytobezoar formation

3.4.1 Previous GI surgery

Regardless of the nature of the foodstuff, previous GI surgery represents the major risk factor for phytobezoar formation.[52-59] The present study confirmed the presence of 457 phytobezoar cases (33.06 % of all reviewed cases) of different food materials associated with previous GI surgery (S1 appendix - table 1).

3.4.2 Unripe Persimmon ingestion

In the present study, we have found 296 (diospyrobezoars) cases (21.41 % of total reported cases) due to persimmon ingestion,[8,35,60,61,62] of which 88 cases associated with previous GI surgery while 208 cases not associated with previous surgery, (S1 appendix - table 2). However, Izumi et al. suggested a widely accepted mechanism (chemical scenario, mentioned above) for diospyrobezoar formation based on gastric acidity and the chemical nature of unripe persimmon fruits which contain a large quantity of tannin (shibuol) to form a sticky coagulum easily converted to a semisolid ball representing the basic nucleus of diospyrobezoar.[34] Thus, diospyrobezoar formation depends on two factors: 1) excessive consumption of unripe persimmon fruits, and 2) concentrated gastric acidity. According to Izumi's hypothesis, the fibre content is not responsible for diospyrobezoar formation. Nonetheless, the United States Department of Agriculture (USDA) report[63] states that the total fibre content of persimmon fruit is only 3.6 g/ 100 g fruits, this equal to only 10% of the recommended daily amount of DF.

3.4.3 Unshelled/woody-skin Seeds

44 cases of sunflower seed bezoar, 41 cases of prickly pear bezoar, 66 cases of watermelon seed bezoar, 15 cases of jungle banana seed bezoar, 20 cases of guava seed bezoar, in addition to 49 cases of other seed bezoars including, pumpkin, date, Olive, *Baccaurea macrocarpa*, jaboticaba, sesame, peanuts, lupin, popcorn, pomegranate, tangerine, granadilla, lentil, cherry pits, box myrtle and mango seed bezoars[64-67] have been reported in the present study (S1 appendix - table 3). The unshelled seeds (e.g. sunflower and watermelon seeds) are not usual food; they are ingested with their seed coats (seed skins) which are formed of hard woody or cellulosic shells, and are mainly consumed accidentally or due to psychic disorders.

3.4.4 Fruit kernels (Pits)

Hard pits including date and olive pits[38], apricot pits[68,69], nectarine pit[70], prune pit[71], chestnuts[72,73], all have been reported as causes for phytobezoar formation. (S1 appendix - table 3). These types of phytobezoars are due to high cellulosic woody indigestible plant tissues; however, these plant tissues have never been considered dietary fibres and are accidentally ingested forming bezoar and may develop GIO.

3.4.5 Dietary fibre-containing herbal medicines without professional instructions

FDA, 2007[74] reported a total of 78 cases of phytobezoar or GIO due to ingestion of laxative drugs formed mainly of psyllium seeds or psyllium seed husks in the period from 1980 to-2000 in the USA.[74] Moreover, Hefny et al., Salguero Molpeceres et al., Agha et al., and shin et al.[75-78] have reported cases of gastrointestinal obstruction due to psyllium seeds and psyllium husks. A similar type of GIO has been reported by Rawl and Brawne due to chia seed ingestion.[79] Similar issues have been reported[80-85] due to the ingestion of Karaya gum, linseed, wheat bran, and oat bran (S1 appendix - table 4). These herbal medicines contain a reasonable amount of dietary fibre (soluble and insoluble). Ingestion of such products must follow the orientation and recommendations of the health authorities, considering both the method of ingestion and the quantity to be ingested. These bulk-forming herbal medicines are strong hygroscopic agents due to their soluble fibre content (mucilages). Psyllium and chia seeds can absorb water equal to 28 times their weights. Therefore, the recommended dose of these herbal drugs must be soaked in sufficient quantity of water for at least 2 Hours prior to ingestion and must be swallowed with plenty of water; otherwise, when ingested dry, they will absorb GI fluid and conglomerate to form a sticky and hard compaction, leading to GIO. Similar cases have been reported due to ingestion of dry psyllium seed husk powder[78], bran[82,84].

3.4.6 Poor mastication of Pulpy Fruits and Vegetables

Pulpy fruits and vegetables, such as orange pulp, dry apples, dry apricots, fibrous leaves of rhubarb, and dry grapes[57, 86, 87], have been reported as risk factors for bezoar formation (S1 appendix - table 5). Buchholz and Haisten reported 150 cases of GI obstruction due to different types of phytobezoars (orange pulp, figs, apples, grapefruit, persimmons, coconuts, cabbage, beans, and potatoes) following gastric surgery for duodenal ulcer.[57] They mentioned that 90 % of reported cases were due to orange pulp.[57] They attributed the incidence of phytobezoars to gastric surgery which resulted in loss of normal pyloric function with low gastric acidity, in addition to inadequate chewing of fibrous food, leading to GIO.[57] They published a figure showing approximately intact orange segments as a result of poor mastication. Therefore, inadequate chewing, large amounts of pulpy vegetables and/or fruits, inadequate fluid or water intake and/or previous GI surgery are the main culprits for such bezoar formation.

3.4.7 Easily digested food can also produce GIO in certain condition

Many cases of GIO have been reported due to easily-digested foods like rice cakes, mashed potatoes and meat-bolus[36, 57, 88, 89, 90, 91] (S1 appendix - table 5). These reported cases suggested the predisposing factors as aging, improper cooking, quick feeding, and poor mastication as a result of dental disorders.

3.4.8 Unusual foods

Katsinelos et al. reported a case of phytobezoar resulting from the ingestion of a substantial quantity of honeycomb in young, healthy Greek woman aged 44 years.[92] Similarly, Hsu et al. documented an unusual

case of phytobezoars due to the consumption of large amounts of vegetable-derived fats (S1 appendix - table 5). It is important to note that these health fads are not containing dietary fibres and are not considered typical food materials.[93]

3.4.9 Dysautonomia and GI laziness

Many phytobezoar cases due to dysautonomia, dysmotility and GI laziness have been reported. (S1 appendix - table 6). These predisposing factors present as a results of GI surgery, GI disorders and/or chronic diseases.[5,7,56,59,94-97]

3.4.10 Psychic disorders

Boopathy and Palaniswamy reported a case of giant bezoar due to accidental ingestion of cotton thread along with different objects such as pieces of bone, seeds of various fruits, stapler pins, buttons, and metal wires for a patient with mental disability.[98]

3.4.11 Aging

Geriatric patients and healthy individuals of old age are more susceptible to phytobezoar formation, regardless of the type of food material. They have many predisposing factors, for example: 1- decreased physical fitness; 2- the expected dental issues and related poor mastication; 3- chronic diseases like diabetes, hypertension, psychic depression, malabsorption, impaired metabolism, in addition to drug-related side effects on GIT.[6] several hundreds of phytobezoar cases have been reported for elderly patients. [6,61, 99-102]

However, phytobezoars can develop in patients without common risk or predisposing factors; therefore, they should not be underestimated, especially when GIO is predicted.[56]

3.4.12 The role of dietary fibres in formation ofPhytobezoar

Many studies have implicated dietary fibres as the main reason or risk factor for phytobezoar formation,[6,13,103] while others have reported a strong association between vegetable and fruit ingestion and phytobezoar formation.[103,104] Although phytobezoars are composed mainly of plant fibres (DF and/or non-DF), However, there are many prominent evidences that confirms the non-liability of the recommended amount of dietary fibres to form phytobezoar unless the predisposing factors are present. The most prominent evidence is the positive response of the majority of people worldwide to the recommendations of Global health authorities to eat a reasonable amount of dietary fibres daily without reporting phytobezoar formation, except very rare cases. These rare cases have been reported for patient having one or more predisposing factors (e.g. previous surgery, GI laziness, chronic diseases, poor mastication, …..etc.).

4. Discussion

The present systematic review explained prominently the main culprits that responsible for phytobezoar formation. Although phytobezoar are formed usually of plant fibres (dietary and non-dietary fibres),[5,13,34,56] however, the formation of phytobezoar depends always on the presence of the predisposing factors.[2,4,6,7] Despite of the age, gender, race and geography, phytobezoar formation is expected for any person having the predisposing factors[56]. Prevention of full-beneficial dietary fibres-containing foods is not a proper decision. However, several good practices can be applied to prevent and help manage this health problem. These practices include: a) Health education programs for patients at risk such as those with previous GIT surgery and GIT disorders. Based on various studies, it was established that, maintaining gastrointestinal healthy status through regularisation of meal times and appropriate nutrition, drinking sufficient quantities of water, good mastication, and following health authority recommendations are of great value for preventing bezoar formation. b) parents and relatives of babies and children must be exposed to educational health programs to encourage them to enhance awareness about the predisposing/risk factors. c) herbal medicine practitioners and dieticians must strictly follow and implement the governmental regulations for dispensing herbal medicines and bulk-forming drugs. Indeed, unqualified herbal medicine practitioners must be subjected to an appropriate educational programs. d) the patient and people at risk must be educated about the importance of sport exercise and its positive impact on keeping GI function and prevention of bezoar formation. e) early diagnosis by specialised physicians and effective medical intervention have been considered to avoid or minimise the phytobezoar-related complications.[6, 105, 106,107]

4.1 Limitation of the study

- The present study excluded the publications in languages other than English.
- Some records are lacking some information regarding the exact type of phytobezoar.
- Some case reports didn't report the actual predisposing factors, instead they were more interested in diagnosis and management.

5. Conclusion

Phytobezoars are annoying health problem, responsible for approximately 4.0 % of GIO, in addition to other GI health issues. Based on the present study, the responsibility of the recommended dietary fibres for phytobezoar formation is not established. the recommended amount and types of dietary fibres have great beneficial effects and cannot be excluded from the healthy foods. However, much attention must be paid for people at risk, and those having one or more predisposing factors.

5.1 Data Availability Statement

All data summarized in the text and tables of this review article were obtained from previously published studies with appropriate attributions cited in the text and tables and complete references provided in the reference section.

5.2 Supplementary information

- The summary of the reported cases (S1 Appendix)
- PRISMA 2020 checklist (S2 Appendix)

5.3 Disclosure statement

- The authors declare no conflicts of interest, and no financial supports.

5.4 Author Contributions

- Ashour M: Conceptualisation, research proposal, Data collection, formal analysis, writing-original draft, visualisation; Ashour A: critical discussion, case report review, review-original draft.

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107. S1. Appendix: list of reviewed phytobezoar cases.

Table 1: List for phytobezoar cases associated with previous surgery.

Gender	Age (years)	previous surgery	Other risk factors & medical history	Ref.
Female	51	laparoscopic cholecystectomy	Diabetes mellitus	[1]
Male	65	duodenal ulcer surgery	anamnesis of recurrent ileus	[2]
Male	NA	laparoscopic sleeve gastrectomy (SG)		[3]
Male	NA	laparoscopic sleeve gastrectomy (SG)		[4]
Male	55	Stapled gastroplasty	Nephrolithiasis	[5]
Male	NA	laparoscopic sleeve gastrectomy (SG)		[6]
Male	NA	laparoscopic sleeve gastrectomy (SG)		[7]
Female	33	She had a laparo- scopic Roux-en-Y gastric bypass (LRYGB) for morbid obesity	Obese, Body Mass index: 36.	[8]
150 cases, gender is not specified	NA	All have had previous gastrectomy for duodenal ulcer.	High fiber foods	[9]
Female	63	RYGB		[10]
13 cases (7 males and 6 females)	Range: 44-79	11 patients had previous ulcer surgery, 8 truncal vagotomy with pyloroplasty and 3 partial gastrectomy	Ingestion of persimmon, grapefruits and dried plumes	[11]
Female	68	subtotal gastrectomy due to gastric cancer	dyslipidemia, supraventricular paroxysmal tachycardia anddepression	[12]
Male	75	surgical resction of the sigmoid colon for diverticulitis	he ingested approximately 60 g Oat bran daily	[13]
Male	48	Laparoscopic adjustable gastric banding (LAGB)		[14]
Female,	50	Laparoscopic sleeve astrectomy (in 2014) Roux-en-Y gastric bypass (RYGB) (in 2017)	Poor mastication	[15]
Male	66	Billroth II hemigastrectomy associated with truncal vagotomy to treat a chronic duodenal ulcer	Diabetes	[16]
Female (pregnant)	33	RYGB		[8]
Female	59	laparoscopic adjustable gastric banding (LAGB) for morbid obesity	Obesity and related issues.	[17]
Female	75	a subtotal gastrectomy and Billroth II gastrojejunostomy were performed.	NA	[18]
Female	63	laparoscopic Roux-en-Y gastric bypass surgery	morbid obese	[19]
18 Males/14 Females (1.42/1).	32 cases, (range 17-78) years; Mean age was 53.73±15.56	(19 of them have previous surgery.) 13 have had another predisposing factors.	Peptic ulcera (n = 4, 11.76%), diabetes mellitus (n = 4, 11.76%), cherrylaurel (Prunus Buricerasus) or persimmon (Diospyrus Lotus) intakes (n = 6, 17.64%), mental retardation-trichotillomania (n = 2, 5.88%), high dose intake of H2 receptor antagonists (n = 1, 2.94%) were also found in patients' history.	[20]

Gender	Age (years)	previous surgery	Other risk factors & medical history	Ref.
Male	47	Yes	Raw stinging nettle	[21]
Female	86	appendectomy		[22]
Female	64	Laparoscopic Roux-en-Y gastric bypass		[23]
Female	51	RYGB		[24]
Male	73	Billroth I partial gastrectomy for gastric cancer.		[25]
Female	58	Laparoscopic adjustable gastric banding		[25]
43 cases (23 males and 20 females)	Range: 18-93	8 cases, (18.6%) Gastrectomy	Diabetes, dental problems, Stomach diseases accounted for 25.5%, 43.6%, 69.7% respectively.	[26]
95 cases of 103 (52 Males and 43 Females)	Mean Age : 60.5 ± 11.3) years	gastric surgery (25.2%),	risk factors were history of gastric surgery (25.2%), diabetes mellitus (21.3%), hypothyroidism (15.5%), trichophagia (5.8%), and anxiety disorders (2.9%), respectively	[27]
Female	55	RYGB		[28]
Female	69	open appendicectomy	Mango seed	[29]
Female	66	Appendectomy	Liver cirrhosis	[30]
Male	59	Subtotal gastrectomy		[30]
Male	70	Ivor-Lewis operation	Lung cancer	[30]
Male	55	Primary repair for duodenal ulcer		[30]
Male	81	laparoscopic cholecystectomy, surgical repair of bilateral inguinal hernias with mesh placement	acute myocardial infarction, hypertension, surgery related ileus.	[31]
(78 male and 35 female)	NA	106 patients have had previous surgery for duodenal ulcer.	103 of 113 cases, reported persimmon ingestion prior to GI obstruction.	[32]
Female	19	No	Anorexia nervosa , Binge-purge , Hematemesis	[33]
(20 males, 24 females)	(55.36±15.17)	7 cases out of 44 patients, have had previous surgeries	Relatively older patients (55.36±15.17), Surgery (7 cases), Chronic diseases (13 cases)	[34]
90 Females & 63 M ales including (29 girls + 54 Boys)	Age range (2-80 Y	Only 10 surgery cases	18 cases (1 child, 17 adults) have predisposing factors: gastrointestinal strictures (10/153, 6.5%), diabetes (4/153, 2.6%) and neuropsychiatric disease (4/153, 2.6%).	[35]
Male		laparoscopic sleeve gastrectomy (SG)		[36]
5 Male, 9 Female	52 -82 Y	4 appendictomy (2F+2M), 1 hysterctomy, (1, M) gasterectomy, 1 ileus. +3 cases female cesarean resections	All patients had ingested rice cake by swallowing without chewing.	[37]
Female	93	distal gastrectomy and laparoscopic cholecystectomy	Ingestion of Kaky fruit	[38]
5 Male, 3 Female	62, 63, 68, 76, 85 (M); 56, 65, 83 (F)	abdominal syrgeries, 2 cases (1 m and 1F)	5 have dentures (3M+2F), 1 quick feeder, 1had operation, 1 operation and quick feeder (F)	[39]
Female	34Y	LAGB		[40]
Female	54Y	RYGB		[41]

Gender	Age (years)	previous surgery	Other risk factors & medical history	Ref.
4 Females, 5 Males	52-83 (mean age : 67.3),	5/9 had gastric surgery,	Aging, gastric surgery, Poor mastication, medications DM., hypertention + hyperlipidemia, Abdomino-perineal resection 1/9Unremarkable case (67 Y. old)	[42]
Female	51Y	RYGB		[43]
Hispanic Male	13Y.,	Appendectomy, 6 year ago.	large amount of white fibrous material of unclear etiology	[44]
Female	57 Y	RYGB		[45]
Female	34 Y,	laparoscopic Roux-en-Y gastric bypass (RYGB) due to class III morbid obesity	Morbid obesity	[46]
Male	57 Y.	Gastric laparotomy	Hypertension	[47]
Male	78	Gasterctomy	Diospyrobezoar	[48]
Male	34 Y,	RYGB		[49]
Female	49 Y	RYGB		[50]
Male	57 Y,	RYGB		[51]
Female	46 Y	RYGB		[51]
Male,	57 Y,	Laparoscopic Roux-en-Y gastric bypass	Morbid obesity, BMI of 44, hypertension, obstructive sleep apnea, and ventral hernia due to previous open cholecystectomy underwent laparoscopic gastric bypass	[51]
Female	46 Y	Laparoscopic Roux-en-Y gastric bypass	Morbid obesity, BMI of 44, hypertension, obstructive sleep apnea, and ventral hernia due to previous open cholecystectomy underwent laparoscopic gastric bypass	[51]
Male	70s Y.	open cholecystectomy	Rapid consumption an expiring bag of peanuts, without perfect chewing.	[52]
Female	66	pylorus-preserving gastrectomy	large amount of persimmon fruits	[53]
9Male/ 8Female	(44-80)	Appendicectomy (3 cases), Hysterectomy (4 cases)	Gulping habit (2case), toothless (1case),	[54]
Female	F, 86 Y., solid food bezoar	Cholecystectomy surgery	Ingestion of solid food bezoar	[55]
Japanese male,	56 Y.	pigtail-shaped PEG-J (percutaneous endoscobic transgastric jejunectomy) tube	Levodopa-carbidopa intestinal gel (LCIG) is an established device-aided therapy for patients with advanced Parkinson's disease (PD)	[56]
(7 Males, & 4 Females),	Age ranged between 42-74 Y olds ,	pigtail-shaped PEG-J (percutaneous endoscobic transgastric jejunectomy) tube	levodopa-carbidopa intestinal gel (LCIG) is an established device-aided therapy for patients with advanced Parkinson's disease (PD)	[56]
6 Males, 3 Females	50-65 (males), 36, 56, 69 (females)	All have had previous vagotomy and drainage procedures for duodenal ulcer.	Not mentioned	[57]
Female	47Y	RYGB		[58]
Female	37Y	LAGB		[58]
Female	42Y	LAGB		[59]
51 cases 27 Males : 24 Females	Median Age 62.9 (range: 27-89) years	Previous gastric surgery (n = 16, 31.4%) was the most common predisposing risk factor	Other predisposing factors: diabetes, hypertension, peptic ulcer, persimmon fruit, brown see weeds, and others	[60]

Gender	Age (years)	previous surgery	Other risk factors & medical history	Ref.
Female	21 Y	RYGB		[61]
Male	A 47-years	Yes	underwent a cholecystectomy 10 years ago the patient admitted to consuming a diet high in fibrous vegetables proton pump inhibitors	[62]
Female	59-year	Yes	Roux-en-Y gastric bypass (RYGB)	[63]
Male	67-Year	Yes	Prostatic cancer - radiotherapy	[147]
Female	45-Year	Yes,		[144]
Female	40-Year	Yes,	2 times Cholecystectomy	[137]

Table 2: List for diospyrobezoar (persimmon) cases.

Gender	Age	previous surgery	Risk factors & medical history	Ref.
96 cases (22 females , 74Males)	NA	no	NA	[64]
20 male and 1Female	40-76 Y	no	persimmon fruits	[65]
Male	73	no	persimmon fruits	[66]
(78 male and 35 female)	113 cases	106 patients have had previous surgery for duodenal ulcer.	103 of 113 cases, reported persimmon ingestion prior to GI obstruction.	[32]
Male,	35 Y.,	No	large quantity of unripe persimmons	[67]
49 Males +10 Females	2 -78 Y. (median 56)	Not mentioned	Eating persimmon's fruits	[68]
51 cases 27 Males : 24 Females	Median Age 62.9 (range: 27-89) years	Previous gastric surgery (n = 16, 31.4%) was the most common predisposing risk factor	Other predisposing factors: diabetes, hypertension,peptic ulcer, persimmon fruit (11 cases), brown see weeds (4cases), and others	[60]
Male	27	no	large amount of persimmon fruits	[69]
Girl	5-Years	No	Persimmon	[142]
Female	88-Years	No	Persimmon	[139]
Female	54-Years	No	Persimmon	[145]

Table 3- list for seed bezoar cases

Gender	Age (years)	phytobezoar Type	previous surgery	Other risk factors & medical history	Ref.
Male	78	Giant granadilla's seed bezoar (Passiflora quadrangularis)	no	essential hypertension and prostate benign hyperplasia	[70]
2 Males	6 &10	unshelled sunflower seeds and areca nuts.	No.	unshelled sunflower seeds and areca nuts.	[71]
Male	1.7	Male, 1.7 Y., seed shells	No	Hard fibrous plant material, (seed shells).	[72]

Gender	Age (years)	phytobezoar Type	previous surgery	Other risk factors & medical history	Ref.
16 Male/14 Female	Range: 19 - 79	prickly pear seeds (12 cases), watermelon seeds in (10), sunflower seeds (6), popcorn kernels (1) and pomegranate (1).	not specified	(5 cases) have predisposing factors: neurologic, psychiatric, or anal disorder, as well as previous surgery	[73]
18 Males/14 females (1.29/1).	32 cases, (range 17-78) years; Mean age was 53.73±15.56	32 cases phytobezoar ,	(19 of them have previous surgery.) 13 have had another predisposing factors.	Peptic ulcera (n = 4, 11.76%), diabetes mellitus (n = 4, 11.76%), cherrylaurel (Prunus Buricerasus) or persimmon (Diospyrus Lotus) intakes (n = 6, 17.64%), mental retardation-trichotillomania (n = 2, 5.88%), high dose intake of H2 receptor antagonists (n = 1, 2.94%) were also found in patients' history.	[20]
Female	21	phytobezoar (Food matter)	No	Bulimia nervosa Binge eating episodes	[74]
78 cases	NA	psyllium bezoar	No		[75]
Male	40	Mango seed bezoar	No	The patient was under the influence of alcohol, accidental ingestion of mango seed occurred.,	[76]
Male, Unemployed ,	50 Y	pumpkin seed bezoar.	No	-pumpkin seeds (about 400 gr.) with their shell.	[77]
Male	4y	undisegisted rhubarb	No	undigested rhubarb	[78]
43 cases (23 males and 20 females)	Range: 18-93	43 cases; Suffered from intestinal obstruction due to phytobezoars (40.5% persimmon's bezoars; and 43.6 % gauava's bezoars)	8 cases, (18.6%) Gastrectomy	Diabetes, dental problems, Stomach diseases accounted for 25.5%, 43.6%, 69.7% respectively.	[26]
Male	64	Man, 64 Y, phytobezoar due to unshelled sunflower seeds.	No	No	[79]
2 Males	13 & 6 years	unshelled sunflower seeds	No.	Have had consumed unshelled sunflower seeds	[80]
2 Males	8 &10 Y,	2 boys, 8 &10 Y, phytobezoar due to large amount of unshelled sunflower seeds	No	N.A.	[81]
Male	72	Male, 72 Y., Sunflower-fruits	No	large amount of fried, unshelled sunflower seeds	[82]
Male	12	Rectal bezoar sunflower seeds	No	200 grams of salted sunflower seeds with shells	[83]
16 Males/14 Females	19 - 79	unshelled watermelon seeds (10 cases),	not determined	(5 cases) have predisposing factors: neurologic, psychiatric, or anal disorder, as well as previous surgery	[73]
Male	7	seed bezoar watermelon	No	Unshelled watermelon seeds	[84]
Female	76	prickly pear seeds	No	diabetes, controlled only by diet, 40 prickly pear fruits with their seeds	[85]

Gender	Age (years)	phytobezoar Type	previous surgery	Other risk factors & medical history	Ref.
Male	48	a huge vegetable materials	No	hypertension and kidney failure , high fiber diet	[86]
Male	21	psyllium seed husk bezoar	No	Psyllium husk ingestion without andequate amount of fluid	[87]
95 cases of 103 (52 Males and 43 Females)	Mean Age (60.5±11.3) years	95 cases phytobezoar	gastric surgery (25.2%),	risk factors were history of gastric surgery (25.2%), diabetes mellitus (21.3%), hypothyroidism (15.5%), trichophagia (5.8%), and anxiety disorders (2.9%), respectively	[27]
Female,	43 Y,	43 Y, Female, (olive seeds phytobezoar)	No	• proton pump inhibitors, due to duodenal ulcer • pyloric stenosis	[88]
Male	49	Jujubes	No	Habitual jujubes ingestion	[89]
90 Females & 63 M ales including (29 girls + 54 Boys)	Age range (2-80 Y.). 54Boy+29 girl	153 cases of seed bezoar 55 cases (unshelled watermelon seeds), 30 unshelled sunflower seeds, 28 prickly pears, 11 willed banana seeds.5 unshelled pumpkin seeds, 4 pomegranate seeds. 2 cases have been reported for each of Date, olive pits, tangerine, lupin and popcorn seeds. While 1 case for granadilla, sesame, Baccaurea macrocarpa, jaboticaba, peanuts, lentil, cherry pits, box myrtle, mango seeds and freekeh grains.	No	18 cases (1 child, 17 adults) have adults) have predisposing factors: gastrointestinal strictures (10/153, 6.5%), diabetes (4/153, 2.6%) and neuropsychiatric disease (4/153, 2.6%).	[35]
Male	79	Sesame seed bezoar.	Yes	He underwent a sigmoid colectomy, with histology showing diverticular disease	[90]
Female, (housewife) .	41 Y.,	Phytobezoar formed of undigested vegetable matter (peas), fibrous material and decomposed food residue.	No surgery	No (may be poor physical exercise leads to GI laziness)	[91]
Boy	7 years	Ingestion of a large amount of unshelled broad beans.	No	No	[92]
4 Male cases	(15, 16, 22 &18)	Phytobezoar from jungle banana seeds	No	Ingestion of large quantity of jungle banana with seeds.	[93]
Girl	2 years	Excessive consumption of peas	No	No	[94]
Female	54	Fresh hawthorns 200-250 g every day for a year	No	fresh hawthorns 200-250 g every day for a year	[95]
Female	86	Phytobezoar due to apricot pits	No	she suffered from difficulties in chewing foods due to her denture,	[96]
Female	73	Phytobezoar due to apricot pits	No	She swallowed the pit accidently	[97]
Male	67	Nectarine pit	No	he swallowed the pit accidently	[98]
Male	86	Prune pit bezoar	Yes	He has had previous appendectomy	[22]
Boy	10-years	Seed besoar	No		[138]
Woman	60-years	Seed bezoar	No		[138]

Gender	Age (years)	phytobezoar Type	previous surgery	Other risk factors & medical history	Ref.
Man	25-Years	Guava bezoar	No		[148]
Female	45-Years	Coconut bezoar	yes		[144]

Table 4: list for phytobezoar cases due to bulk producers

Gender	Age (years)	phytobezoar Type	previous surgery	Other risk factors & medical history	Ref.
Male	50	bran	No	(two large Bowls of bran cereal with milk)	[99]
Female	84	Oat bezoar	No	dentureless, poor mustication, High fiber diet	[100]
Male	39	Chia seed	No	asthma and seasonal allergies	[101]
Female	41	psyllium seed bezoar	No	she swallowed dry psyllium seed	[102]
Female	14	Linseed bezoar	No	ingestion of great amount of linseed	[103]
Male	76	psyllium seed bezoar	No	ingestion of psyllium seed husk powder, Parkinson's disease	[104]
Man	66	karaya gum	No	This occurred after ingesting several tablespoons of a granular stool bulking laxative containing 62% karaya gum for chronic constipation, prior to reclining to sleep. He did not drink any liquids after ingesting these granules.	[105]
78 cases		phytobezoars or GIO due to ingestion of laxative drug formed mainly of psyllium seeds or psyllium seed husks.	No		[75]
Male	21	psyllium seed husks	No	He did not drink the required amount of fluids because he wasfasting.	[87]
Female	74	psyllium seed	No		[106]
Female	59	Agiolax® (psyllium seed, psyllium husks, senna pods)	No	body mass index (BMI) of 37.9 kg/m and multiple co-morbidities (hypertension, diabetes, hyperuricemia, hyperlipidemia, depression and osteoarthrosis of low back)	[107]
Male	91	Sterculia gums	No	after mistakenly swallowing a tablespoon of sterculia granules	[108]
Male	75	serutan® (psyllium granules)	No	Insufficient water intake after bulk-producer ingestion	[109]
Male	81	Psyllium-based Bulk laxative "Perdiem"	No	Insufficient water intake after bulk-producer ingestion	[110]
Male	72	Perdiem granules	No	Insufficient water intake after bulk-producer ingestion	[111]
Woman	67	Perdiem granules	No	Insufficient water intake after bulk-producer ingestion	[111]
Woman	41	Perdiem granules	No	Insufficient water intake after bulk-producer ingestion	[111]
Male	66	Plantago ovata seed (psyllium seed)	No	Insufficient water intake after bulk-producer ingestion	[112]
Male	56	Vegan diet, most probably chia seeds bezoar.	No	Strict vegan diet 15 Kg weight loss in 12 months.	[113]
Infant	1.5	Psyllium, beet & lentils		Down syndrome	[146]

Gender	Age (years)	phytobezoar Type	previous surgery	Other risk factors & medical history	Ref.
Man	50	Konjac bezoar			[141]
Man	60	Mushroom			[149]

Table 5: list for unusual food, pulpy and non-fibrous food bezoar cases

Gender	Age	phytobezoar Type	previous surgery	Risk factors & medical history	Ref.
Male	50 Y	Male, Fatty acids and Lecithin	No	No	[114]
Female	44 Y.	large amounts of honeycomb	No	Irritable bowel syndrome Consumption of large quantities of honeycomb for health benefits	[115]
Male	65 Y	Chestnuts phytobezoar	No	Chestnuts consumption	[116]
Male	61 Y.	Chestnuts phytobezoar	No	Consumption of large quantity of Chestnuts	[117]
Male	1.3 Y (16 months)	dried Apricots	No	whole dried apricots , inadequate mastication	[118]
Male	78 Y.	phytobezoar (undigested Apple pieces & whole maize grains)	No	abnormal mastication habits as well as a jejunal diverticulum	[119]
Male	86	pickled plume	No	accidently ingested japanese pickled plum with seeds.	[120]
Male	69	dried Apple	No	coronary arteries bypass, diabetes and hypertension. He had no teeth, and not used dentures for the past 10 years. Only chew various foods with his gums only. but admitted to swallowing food in whole occasionally.	[121]
Not specified	Not specified	150 cases, GI obstruction due to different types of phytobezoars (orange pulp, figs, apples, grapefruit, persimmons, coconuts, cabbage, beans and potatoes)	All have had previous gastrectomy for duodenal ulcer.		[9]
Female	62 Y.	phytobezoar	No	many years she had eating quite a substantial proportion of raw or poorly cooked long stemmed vegetables.	[122]
Male	4 Y.	Undigested rhubarb	no	undigested rhubarb	[78]

Gender	Age	phytobezoar Type	previous surgery	Risk factors & medical history	Ref.
Male	75	Meat bolus bezoar	No	Our patient had not gone under gastric surgery but recalled a right inguinal hernia repair40~ years ago, had a history of diabetes mellitus type II, and he wears a dental prosthesis which increases the possibility of bezoar formation in his GIT.	[123]
Female	59	swollwed whole potatoes	No	medical history of cerebral palsy due to birth hypoxia	[124]
Female	53	swallowed whole potatoes	No	Medical history of learning disability, autism and partial sightedness,	[124]
2 Males, 1 Female	0.25 - 0.3 Y (3-4 months)2 girl, 1 boy	potato bezoar	No	mashed potato	[125]
5 Male, 9 Female	52 -82 Y	Rice cake bezoar , 4 cases no surgery	(7 cases , 3 Male & 4 females) 4 appendictomy (2F+2M), 1 hysterctomy, (1, M) gasterectomy, 1 ileus. +3 cases female cesarian resections	All patients had ingested rice cake by swallowing without chewing.	[37]
5 Male, 3 Female	62, 63, 68, 76, 85 (M); 56, 65, 83 (F)	Rice cake bezoar, 6 cases no surgery	Yes, 2 cases (1 m and 1F*) abdominal syrgeries	5 have dentures (3M+2F), 1 quick feeder, 1had operation, 1 operation and quick feeder (F*)	[39]
Female	68 Y	Rice cake bezoar	No	She had eaten a toasted rice cake without chewing well because of her dentures the day before.	[126]
Female	59 Y	Rice cake bezoar	No	She had eaten a toasted rice cake without chewing well because of her dentures the day before.	[126]
Female	70 Y	Rice cake bezoar	No	She had dentures and had eaten a boiled rice cake 5 hours previously.	[126]
Male	37	Rice cake bezoar	No	He had eaten a boiled rice cake without chewing well the day before.	[126]

Gender	Age	phytobezoar Type	previous surgery	Risk factors & medical history	Ref.
Male	64	Potato, brussels sprouts, and broccoli	No	for obesity and prior cholecystectomy.	[127]
9 Males/ 8 Females	(44-80)	Rice cake bezoar, 10 cases with no surgery	Appendicectomy (3 cases), Hysterectomy (4 cases)	Gulping habit (2 cases), toothless (1case),	[54]

Table 6: list of phytobezoar cases due to chronic diseases or GI disorders

Gender	Age	phytobezoar Type	previous surgery	Risk factors & medical history	Ref.
1 Boy, 5 Girls	(12-18 Y)	Phytobezoar		Dysautonomia (6 patients)	[128]
Male	60	food bezoar	No	GI laziness and constipation due to khat consumption	[129]
Female	24	Giant phytobezoar	No	No expected risk factors., but most likely dyspepsia and hypoacidity (she mentioned consumption of antacids for three months before admission). These factors may causes delayed gastric emptying.	[130]
Housewife	41	phytobezoar formed of undigested vegetable matter (peas), fibrous material and decomposed food residue.	No	No (may be poor physical exercise leads to GI laziness)	[91]
Male	11	Boy, 11 Y., phytobezoar	No	Intellectual disability and seizure disorder	[131]
Female	21	phytobezoar (Food matter)		Bulimia nervosa Binge eating episodes	[74]
Male	48	a huge vegetable materials	No	hypertension and kidney failure , high fiber diet	[86]
Female	19	(Vegetable matter)	No	Anorexia nervosa , Binge-purge , Hematemesis	[40]
Girl	11	giant phytobezoar due to ileal duplication.	No	Ileal duplication.	[132]
Woman	59	phytobezoar	No	type 2 diabetes and hypertension	[133]
(20 males, 24 females)	(55.36±15.17)		7 cases out of 44 patients, have had previous surgeries	Chronic diseases (13 cases) out of 44 patients	[34]
90 Females & 63 M ales including (29 girls + 54 Boys)	Age range (2-80 Y.).		Only 10 surgery cases	gastrointestinal strictures (10 cases/153, 6.5%), diabetes (4 cases/153, 2.6%) and neuropsychiatric disease (4 cases/153, 2.6%).	[35]

Gender	Age	phytobezoar Type	previous surgery	Risk factors & medical history	Ref.
Man	57-years	phytobezoar	No	type 2 diabetes with autonomic neuropathy have impaired gastrointestinal emptying functions, increasing the retention time of food and causing phytobezoar	[134]
Man	84-years	phytobezoar	No	Ischemic HD, Coronary artery by-pass graft, heart failure, Dementia, diabetes, benign prostatic hypertrophy, bipolar disorder.	[140]
Girl	17-Years	phytobezoar	No	Chronic eating disorder	[136]
Male	67-Year	Phytobezoar	Yes	Surgery due to Prostatic cancer - radiotherapy	[147]
Boy	12-Years	phytobezoar	No	Meckel's diverticulum	[150]

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S2. Appendix

151. **PRISMA 2020 Checklist**

Section and Topic	Item #	Checklist item	Reported on page
TITLE			
Title	1	Identify Systematic Review	1
ABSTRACT			
Abstract	2	A structured summary	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	4,5
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	5,6
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	5
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	5
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	6
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	6
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	5
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	5
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	NA
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	NA

Section and Topic	Item #	Checklist item	Reported on page
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	5,6
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	5,6
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	5,6
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	5,6
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	NA
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	NA
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	NA
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	6
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	7
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	7
Study characteristics	17	Cite each included study and present its characteristics.	S1 appendix
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	NA
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/ credible interval), ideally using structured tables or plots.	S1 appendix
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics	S1 appendix
	20b	Present results of all statistical syntheses conducted.	7-9
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	NA
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	NA
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	NA
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	6
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	12-13
	23b	Discuss any limitations of the evidence included in the review.	13
	23c	Discuss any limitations of the review processes used.	13
	23d	Discuss implications of the results for practice, policy, and future research.	12-13

Section and Topic	Item #	Checklist item	Reported on page
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	-
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	NA
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	NA
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	13
Competing interests	26	Declare any competing interests of review authors.	13
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	S1 appendix

***NA: Not applicable**

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Comprehensive Assessment of Biological Nutrient Removal Performance in Carrousel-Type Activated Sludge Systems adopted by wastewater treatment plant in Jazan, KSA

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Abstract
This study presents a comprehensive process design analysis of the Jazan Sewage Treatment Plant (STP) on the Red Sea coast of Saudi Arabia, employing a Carrousel-type oxidation ditch with Oxidation–Reduction Potential (ORP)-controlled intermittent aeration for biological nutrient removal. The analysis covers all unit operations from preliminary treatment through effluent disinfection across two design phases (20,004 and 37,003 m³/day for Phase 1 and the combined Phase 1 + Phase 2 capacity, respectively, derived from projected population equivalents of 100,000 and 185,000 inhabitants at a per-capita generation rate of 200 L/capita/day), and validates the design calculations against 29 months of effluent monitoring data (January 2023 – July 2025, representing all monitoring records available at the time of analysis). The extended aeration configuration (Solids Retention Time, SRT = 16.9 days, Hydraulic Retention Time, HRT = 30.05 hours) provides a denitrification safety factor of 1.53. Operational monitoring confirms that actual performance substantially exceeds design targets, achieving removal efficiencies of 98.5% for five-day biochemical oxygen demand (BOD5) (mean effluent 4.19 mg/L vs. ≤25 design), 99.0% for total suspended solids (TSS) (2.77 mg/L), 91.4% for total nitrogen (TN) (5.19 mg/L vs. 83.3% design), and 88.7% for total phosphorus (TP) (2.04 mg/L vs. 55.6% design). The marked phosphorus removal suggests effective enhanced biological phosphorus removal under ORP-controlled intermittent aeration. Comparative analysis with Carrousel installations at Wangtang, China (HRT = 5.3 h) and Al-Qateef, Saudi Arabia (HRT = 14.9 h) confirms that the Jazan design adopts a deliberately conservative approach with significantly longer hydraulic retention time, prioritizing operational stability under arid coastal climatic conditions. This study provides a documented and operationally validated design methodology applicable to similar arid coastal municipalities.

Keywords: ORP-controlled aeration; Oxidation ditch; Wastewater treatment; Extended aeration; Denitrification

Abbreviations: ASM – Activated Sludge Model; BOD5 – Five-day Biochemical Oxygen Demand; COD – Chemical Oxygen Demand; DO – Dissolved Oxygen; DWF – Dry Weather Flow; EBPR – Enhanced Biological Phosphorus Removal; F/M – Food-to-Microorganism ratio; HRT – Hydraulic Retention Time; MCRT – Mean Cell Residence Time; MLSS – Mixed Liquor Suspended Solids; MWE – Ministry of Water and Electricity (Saudi Arabia); NH3-N – Ammonia Nitrogen; NO3-N – Nitrate Nitrogen; NO2-N – Nitrite Nitrogen; ORP – Oxidation–Reduction Potential; PAO – Phosphorus-Accumulating Organism; PO4-P – Orthophosphate; SND – Simultaneous Nitrification–Denitrification; SRT – Solids Retention Time; SS – Suspended Solids; STP – Sewage Treatment Plant; TDS – Total Dissolved Solids; TN – Total Nitrogen; TP – Total Phosphorus; TSS – Total Suspended Solids; WWTP – Wastewater Treatment Plant.

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1. Introduction

The city of Jazan is the capital of the Jazan Region in southwestern Saudi Arabia, situated along the Red Sea coast at approximately 16.9°N latitude. The region experiences an arid tropical climate with high ambient temperatures, which significantly influences wastewater characteristics and treatment process kinetics. As urbanization has accelerated across Saudi Arabian cities, the need for advanced wastewater treatment facilities that can meet stringent effluent standards while operating efficiently under local climatic conditions has become increasingly critical (Drewes et al., 2012; Haider et al., 2021).

Saudi Arabia faces significant water scarcity challenges exacerbated by its arid climate and limited freshwater resources. Wastewater treatment and reuse have emerged as critical strategies for sustainable water management in the Kingdom (Aleisa & Al-Zubari, 2017; Dawoud, 2011). Currently, approximately 70 sewage treatment plants operate throughout the country, with conventional activated sludge systems being the most common secondary treatment technology (Alhajri et al., 2025). The Ministry of Water and Electricity has established design guidelines specifically tailored for wastewater treatment plants operating under Saudi Arabian conditions (MWE, 2006). Within this national framework, the Jazan Region presents unique challenges due to its coastal location along the Red Sea, high ambient temperatures exceeding 35°C for much of the year, and the ecological sensitivity of the receiving marine environment.

The Jazan Sewage Treatment Plant was designed in 1999. The plant employs a Carrousel-type oxidation ditch system, which represents a modified form of the extended aeration activated sludge process. The Carrousel system was originally developed in the Netherlands in the 1970s and has gained worldwide recognition for its ability to achieve simultaneous nitrification-denitrification through the creation of alternating aerobic and anoxic zones within the same reactor volume (Xu et al., 2017).

Oxidation ditch technology has been widely adopted globally for municipal wastewater treatment, particularly in small-to-medium scale facilities, due to its advantages of simple construction, flexible operation, low sludge production, and inherent capability for simultaneous nitrification and denitrification (Zhou et al., 2015; Ammary & Radaideh, 2005). Liu et al. (2010) demonstrated that simultaneous nitrification and denitrification (SND) in Carrousel oxidation ditches can achieve 60-70 total nitrogen removal efficiency with hydraulic retention times of 4-6 hours. Then, Xie et al. (2011) showed that integration of the Activated Sludge Model 2d (ASM2d) with optimization algorithms can further enhance Carrousel system performance. Yang et al. (2011) utilized computational fluid dynamics (CFD) to optimize energy consumption and effluent quality in full-scale oxidation ditch systems.

The integration of ORP (Oxidation-Reduction Potential)-controlled intermittent aeration into the Carrousel design represents a significant advancement over conventional continuous aeration systems. Li and Bishop (2002) demonstrated through year-long field testing at three full-scale wastewater treatment plants that ORP values correlate well with nutrient removal efficiency, with nitrification occurring at ORP values above 380 mV and organic substrate oxidation at approximately 250 mV. Charpentier et al. (1989) established that ORP-based aeration control can optimize energy consumption while improving both carbonaceous and nitrogenous pollutant removal. Chang and Hao (1996) showed that ORP-controlled intermittent aeration in extended aeration systems can achieve total nitrogen removal exceeding 93% with residual effluent TN of only 2.94 mg/L. Lu et al. (2000) further confirmed that for simultaneous carbon and nitrogen removal, optimal ORP set-points should range between −50 mV and +175 mV.

Recent investigations have continued to refine the understanding of Carrousel and oxidation ditch performance. Alhajri et al. (2025) provided an updated national review of wastewater treatment in Saudi Arabia and projected the 2035 reuse demand, concluding that conventional activated sludge variants-including oxidation ditches-will remain the dominant secondary treatment route, yet identifying nutrient removal under hot-arid conditions as the principal performance bottleneck. In a comparable Saudi context, Alramthi et al. (2022) analyzed seven years of influent, effluent and operational data from the Bishah Governorate oxidation ditch in Saudi Arabia and demonstrated consistent compliance with national and international reuse standards, illustrating both the long-term durability of the technology under arid conditions and the diagnostic value of multi-year operational records. Liu et al. (2025) compared Carrousel oxidation ditches against high-efficiency multi-cycle A2/O processes for urban wastewater treatment and reported that the oxidation ditch configuration retains a robust performance envelope, particularly where stable effluent quality is prioritized over compactness. With specific reference to aeration control, the recent review by Owaes et al. (2024) on operational strategies for partial and conventional nitrification documented that real-time control schemes coupling redox potential and pH outperform dissolved-oxygen-only strategies for nitrification-denitrification, while highlighting the relative scarcity of long-term full-scale validation datasets. In parallel, Navada and Vadstein (2022) synthesized the evidence that brackish-water salinities of approximately 9-12‰ constitute a critical inhibition threshold for nitrifier

communities, with substantial drops in nitrification capacity above 8-15‰, implying that direct transfer of temperate-climate criteria to Saudi coastal plants-where groundwater infiltration may drive influent salinity into this range-is not advisable. Critical re-examination of these contributions reveals three persistent gaps: (i) the absence of operationally validated, end-to-end process design audits for Carrousel systems located on hot-arid coastlines; (ii) limited reporting of paired design-versus-actual performance datasets covering sustained operational periods; and (iii) insufficient discussion of how conservative hydraulic retention times interact with EBPR and SND under simultaneously high temperature, elevated salinity and ORP-controlled aeration. The present study directly addresses these three gaps by combining a full design verification of the Jazan STP against established criteria with a 29-month operational performance validation under representative arid-coastal conditions.

Despite the growing number of wastewater treatment facilities in Saudi Arabia, detailed process design documentation for plants operating under arid coastal conditions remains limited in the published literature. This paper addresses that gap by presenting a comprehensive analysis of the complete process design calculations for the Jazan Sewage Treatment Plant, covering all major unit operations from preliminary treatment through effluent disinfection and sludge handling. Beyond documenting the design methodology, the analysis evaluates the adequacy of the adopted design parameters against established engineering criteria and published data from comparable Carrousel oxidation ditch installations in China and Saudi Arabia. This comparative framework serves not merely as a benchmarking exercise, but rather as a diagnostic tool to identify design margins, potential operational limitations, and optimization opportunities specific to high-temperature, high-salinity influent conditions characteristic of arid coastal environments. By systematically linking design inputs to treatment performance outcomes, this study aims to provide a replicable technical reference that supports evidence-based decision-making for the design and upgrading of similar facilities in climatically analogous regions.

2. Methodology

The analytical approach adopted in this study is based on a systematic review of the original process design documentation prepared for the Jazan STP. Design calculations for each unit operation were independently verified against established engineering criteria, primarily from Metcalf & Eddy (1991), WEF/ASCE (1998), and the Saudi MWE (2006) design guidelines. Each design parameter was evaluated by comparing the adopted value against the recommended criteria range for the corresponding treatment technology. The nitrogen and phosphorus removal capacities were recalculated using the Kayser (1991) denitrification correlation and mass balance principles. A comparative benchmarking analysis was conducted against published operational data from two Carrousel oxidation ditch installations: the Wangtang WWTP in China (Xie et al., 2011) and the Al-Qateef WWTP in Saudi Arabia (Elsergany, 2014). Additionally, effluent monitoring data collected over a 29-month dataset (2023-2025), covering 16 physicochemical parameters were compiled from the plant laboratory records to validate the design calculations against actual operational performance (Section 11).

3. Site Description and Design Basis

3.1 Overview

The Jazan Sewage Treatment Plant (STP) is a municipal wastewater facility located in Jazan city on the Red Sea coast of southwestern Saudi Arabia (Fig. 1). The plant employs a Carrousel oxidation ditch system with ORP-controlled intermittent aeration for biological nutrient removal, and operates in two phases with design capacities of 20,004 m^3/day (Phase 1) and 37,003 m^3/day (Phase 2), corresponding to design population equivalents of approximately 100,000 and 185,000 inhabitants, respectively, based on an estimated per capita wastewater generation rate of 200 L/capita/day. The plant serves the sewered population of Jazan city, which had a total population of approximately 200,000 according to the 2022 Saudi Census (GAS, 2022); however, not all residents are connected to the centralized sewer network, with some areas still relying on septic tank systems.



Figure 1: Site location map and satellite image of the Jazan Sewage Treatment Plant, Jazan Region, Saudi Arabia.

3.2 Design Loadings

The plant was designed in two phases to accommodate projected population growth. The hydraulic design of the Jazan STP was structured in two developmental

phases to accommodate projected population growth and increasing wastewater generation. Under Phase 1, the plant was designed to treat an average daily flow of 20,004 m³/day, with a peak hourly capacity of 1,667.0 m³/hr, applying a peak factor of 2:1. The full-scale configuration (Phase 1 + Phase 2) was designed to nearly double the treatment capacity, accommodating an average daily flow of 37,003 m³/day, a peak hourly flow of 3,083.6 m³/hr, and a corresponding peak flow rate of 860 L/sec. The design flows of 20,004 and 37,003 m³/day are not arbitrary round numbers; they are derived from population-equivalent calculations carried out for Jazan city by the original design consultant (Phase 1 horizon: 100,020 inhabitants × 200 L/capita/day = 20,004 m³/day; ultimate horizon: 185,015 inhabitants × 200 L/capita/day = 37,003 m³/day). The slightly "non-round" values therefore preserve the traceability of the design to its underlying demographic assumptions and have been retained throughout this paper rather than rounded for presentation purposes.

3.3 Influent Wastewater Characteristics

The influent wastewater characteristics were based on average loads typical to Saudi Arabia. The influent BOD_5 concentration of 275 mg/L falls within the reported range of 150-450 mg/L for Saudi Arabian domestic wastewater, consistent with the medium-strength classification in Metcalf & Eddy (1991, Table 3-16). The COD:BOD ratio of 2:1 confirms the predominantly domestic nature of the wastewater. Fig. 2 presents a comparative visualization of the influent concentrations and mass loadings for Phase 1 and the combined Phase 1 + Phase 2 capacity, highlighting the proportional increase in organic and nutrient loads associated with the plant expansion.

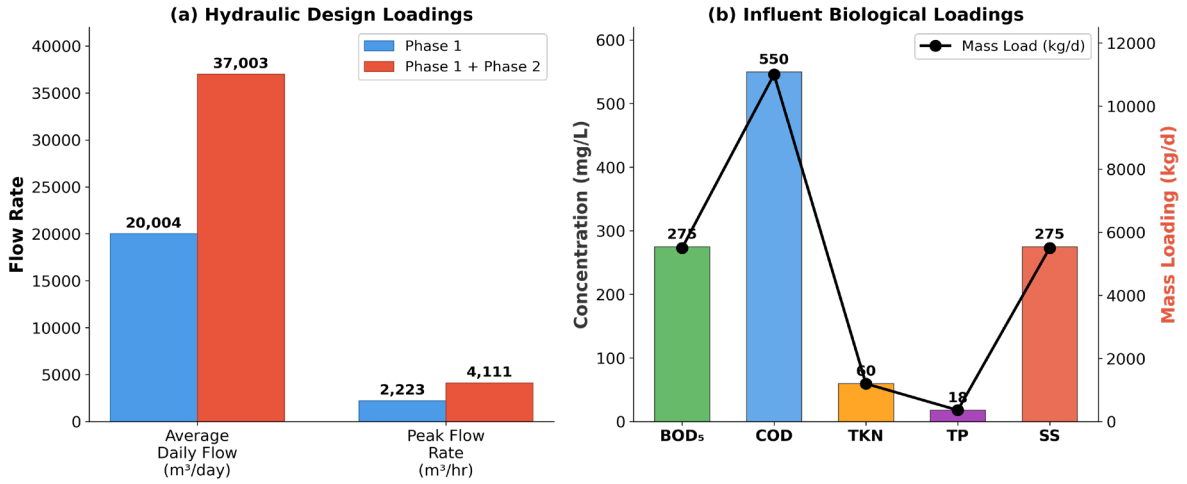


Figure 2: Design Loadings - Hydraulic and Biological Parameters

3.4 Effluent Quality Standards

The guaranteed final effluent standards are presented in Table 1. These targets are consistent with the general secondary treatment standards applicable at the time of design (1999). While BOD_5 and SS are subject to contractual guaranteed limits of ≤ 25 mg/L, corresponding to a minimum removal efficiency of 90.9%, no contractual guarantees were specified for nutrient removal. Nevertheless, the Carrousel oxidation ditch system, operating with ORP-controlled intermittent aeration, is anticipated to achieve total nitrogen and total phosphorus concentrations of ≤ 10 mg/L and ≤ 8 mg/L, respectively, through biological nitrification-denitrification and enhanced biological phosphorus removal (EBPR) mechanisms. It is worth noting that the 1999 design predates the more stringent Saudi MWE (2006) discharge standards for unrestricted reuse applications (Al-Jasser, 2011), which mandate $BOD_5 \leq 10$ mg/L, SS ≤ 10 mg/L, TN ≤ 10 mg/L, and TP ≤ 1 mg/L for unrestricted reuse applications. Consequently, while the plant's organic removal targets remain broadly adequate, the anticipated phosphorus removal of 55.6% falls considerably short of current regulatory requirements, suggesting that supplementary chemical phosphorus removal or process optimization may be required to meet present-day compliance thresholds.

Table 1: Final Effluent Quality Standards and Anticipated Performance

Parameter	Guaranteed	Anticipated	Removal %
BOD_5 (mg/L)	≤ 25	≤ 25	90.9%
SS (mg/L)	≤ 25	≤ 25	90.9%
Total N (mg/L)	-	≤ 10	83.3%
Total P (mg/L)	-	≤ 8	55.6%

4. Process Description

The Jazan STP process train consists of the following major unit operations: (1) inlet works screening, (2) grit removal, (3) Carrousel aeration system, (4) secondary settlement tanks, (5) sludge recycle and wasting, (6) sludge thickening, (7) sludge drying beds, and (8) chlorine contact disinfection. The overall process flow diagram is presented in Fig. 3.

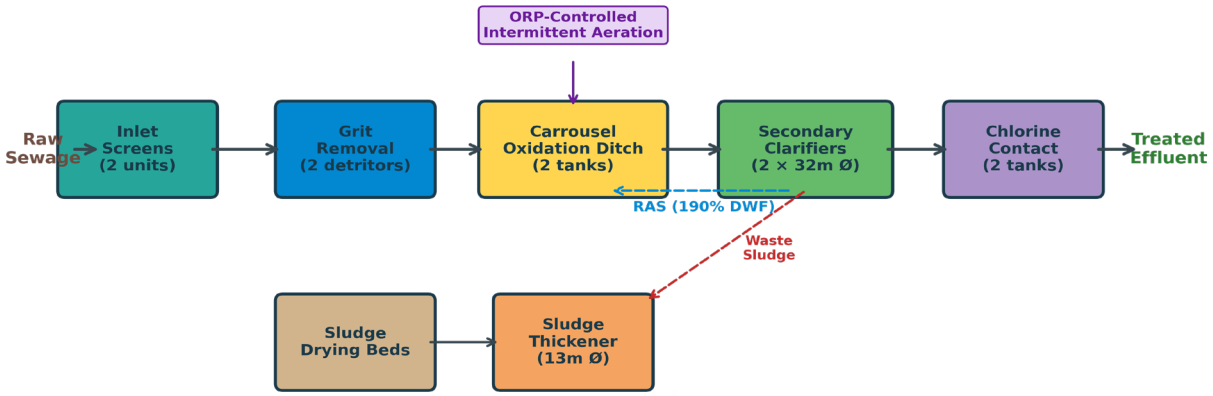


Figure 3: Jazan STP Process Flow Diagram - Carrousel Oxidation Ditch System

5. Preliminary Treatment

5.1 Inlet Works Screens

The inlet works screening equipment is designed for Phase 2 flows (37,003 m³/day average, 860 L/sec peak). The design parameters conform to the criteria established in Metcalf & Eddy (1991, Table 9-2) for mechanically cleaned bar racks. Screen channel width of 1.25 m provides maximum velocity of 0.82 m/sec at peak flow, within the design criterion of 0.9 m/sec. Table 2 summarizes the design verification.

Table 2: Inlet Works Screen Design Parameters

Parameter	Design Value	Criteria Range
Number of screens	2	-
Peak flow rate per screen (L/sec)	430	-
Channel width (m)	1.25	-
Clear opening between bars (mm)	19	15-75
Min. velocity at avg flow (m/s)	0.600	0.6-0.9
Max. velocity at peak flow (m/s)	0.82	≤ 0.9

5.2 Grit Removal

Two detritor-type grit removal units achieve 95% removal efficiency for particles down to 0.21 mm (65-mesh), consistent with design guidelines in Metcalf & Eddy (1991, Table 9-3). The average detention time of 42 seconds is slightly below the lower bound of the typical design range of 45-90 seconds, while the horizontal velocity of 0.27 m/sec falls within the recommended range of 0.25-0.40 m/sec (Table 3). The marginally shorter detention time is considered acceptable given the conservative horizontal velocity and adequate removal efficiency.

Table 3: Grit Removal Design Parameters

Parameter	Design Value	Criteria
Number of detritors	2	-
Removal efficiency	95% (≥ 0.21mm)	65-mesh
Surface area per detritor (m²)	36	-
Average detention time (sec)	42.0	45-90
Horizontal velocity (m/sec)	0.27	0.25-0.40

6. Biological Treatment - Carrousel Aeration System

6.1 Design Concept

The heart of the Jazan STP is a Carrousel-type oxidation ditch equipped with vertical shaft aerators. Nitrogen removal occurs through alternating oxygen-rich and oxygen-poor zones within the channels. In zones where dissolved oxygen exceeds 0.5 mg/L, ammonium is oxidized to nitrate (nitrification), while in low-oxygen

zones, nitrate is reduced to nitrogen gas (denitrification). This mechanism is consistent with the SND observations reported by Liu et al. (2010) and Zhou et al. (2015) in full-scale Carrousel systems.

The proposed design incorporates ORP-controlled intermittent aeration. The redox potential indicates the ratio of oxidizable to reducible materials in the water. High ORP values signal high nitrate concentrations, requiring reduced aeration for denitrification; low ORP values indicate high ammonium, requiring increased aeration for nitrification. This control strategy is supported by the findings of Li and Bishop (2002), who demonstrated that ORP provides reliable real-time indication of the metabolic state within activated sludge systems, and by Charpentier et al. (1989), who showed that ORP-based regulation is both more cost-effective and easier to implement than dissolved oxygen-based control. As illustrated in Fig. 4, the cyclic ORP profile between the high and low setpoints produces inverse temporal patterns of NH_4-N and NO_3-N, confirming the simultaneous occurrence of nitrification and denitrification within each aeration cycle, while the concurrent PO_4-P fluctuations indicate enhanced biological phosphorus uptake during the aerobic phase.

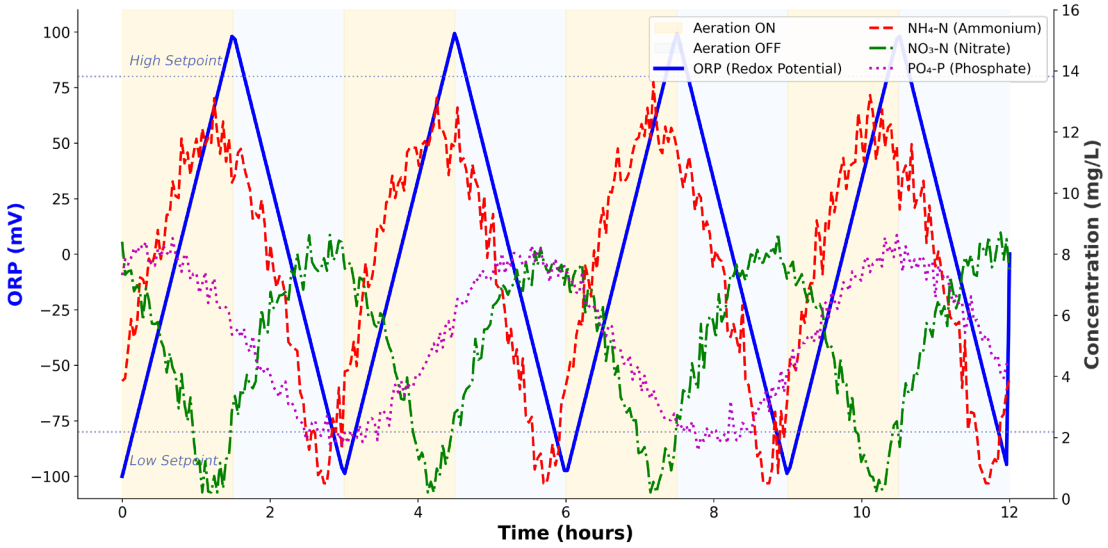


Figure 4: ORP-Controlled Intermittent Aeration - Redox Signal and Nutrient Dynamics

6.2 Aeration Tank Design

The system consists of two aeration tanks, each a 4-channel system with 8.0 m channel width, equipped with two aerators and two propellers per tank. The complete design parameters (Table 4) fall within the extended aeration process criteria documented in Metcalf & Eddy (1991, Table 10-5), which specifies F/M ratios of 0.05-0.15, SRT of 20-30 days, and MLSS of 3,000-6,000 mg/L for conventional extended aeration. However, oxidation ditch variants commonly operate within broader ranges of F/M = 0.05-0.30 and SRT = 10-30 days (WEF/ASCE, 1998). The adopted SRT of 16.9 days positions the Jazan design in a transitional zone between conventional activated sludge and extended aeration, while the F/M of 0.063 remains firmly within the extended aeration range. The non-rounded values of SRT = 16.9 days and HRT = 30.05 hours reflect direct calculation outcomes rather than nominal design choices. The SRT is obtained as the ratio of total mixed-liquor solids inventory to daily waste activated sludge production (25,050 m³ × 3,500 mg/L ÷ 4,676 kg/d ≈ 16.9 d), while the HRT is obtained directly from the aeration volume divided by the Phase 1 design flow (25,050 m³ ÷ 20,004 m³/d × 24 ≈ 30.05 h). The decimal precision is preserved to support reproducibility of the design audit and to highlight that both parameters sit comfortably within the criteria range without margin manipulation.

Table 4: Carrousel Aeration Tank Design Parameters

Parameter	Design Value	Criteria Range
Number of tanks	2	-
Total aeration volume (m³)	25,050	-
F/M ratio (kgBOD/ kgDS·d)	0.063	0.05-0.30
MLSS concentration (mg/L)	3,500	3,000-6,000
HRT (hours)	30.05	18-36
SRT / MCRT (days)	16.9	10-30
Sludge production (kg/d)	4,676	-

6.3 Nutrient Removal Design

The simultaneous nitrogen removal calculations (Table 5) demonstrate adequate denitrification capacity. The influent TKN load of 1,200 kg/d is partitioned into three pathways: 280 kg/d (23.3%) is incorporated into excess sludge biomass, 720 kg/d (60.0%) is biologically nitrified to nitrate, and the remaining total nitrogen in the effluent is maintained at 200 kg/d (16.7%), corresponding to the target effluent TN of ≤ 10 mg/L. In a well-operated nitrification system, this effluent nitrogen would typically comprise residual TKN (NH_4-N + organic N) of approximately 2-4 mg/L and nitrate-nitrogen (NO_3-N) of approximately 6-8 mg/L. The denitrification capacity available (1,100 kg N/d), calculated using the Kayser (1991) correlation (NO_3-Nd/BOD = 0.20), exceeds the requirement (720 kg N/d) by a safety factor of 1.53. This margin is important given the operational variability inherent in ORP-controlled systems (Wareham et al., 1993).

Table 5: Simultaneous Nutrient Removal Design

Parameter	Value	Unit
TKN in excess sludge	280	kg/d
Total N in effluent	200	kg/d
TKN to be nitrified	720	kg/d
Denitrification capacity required	720	kg/d
Denitrification capacity available	1,100	kg/d
TP in effluent	160 (8 mg/L)	kg/d

Fig. 5 illustrates the nitrogen distribution, with 60.0% nitrified, 23.3% removed in excess sludge, and 16.7% remaining as total nitrogen in the effluent, alongside the denitrification balance showing a safety factor of 1.53. The bar charts confirm that all nutrient removal parameters fall within the acceptable design criteria.

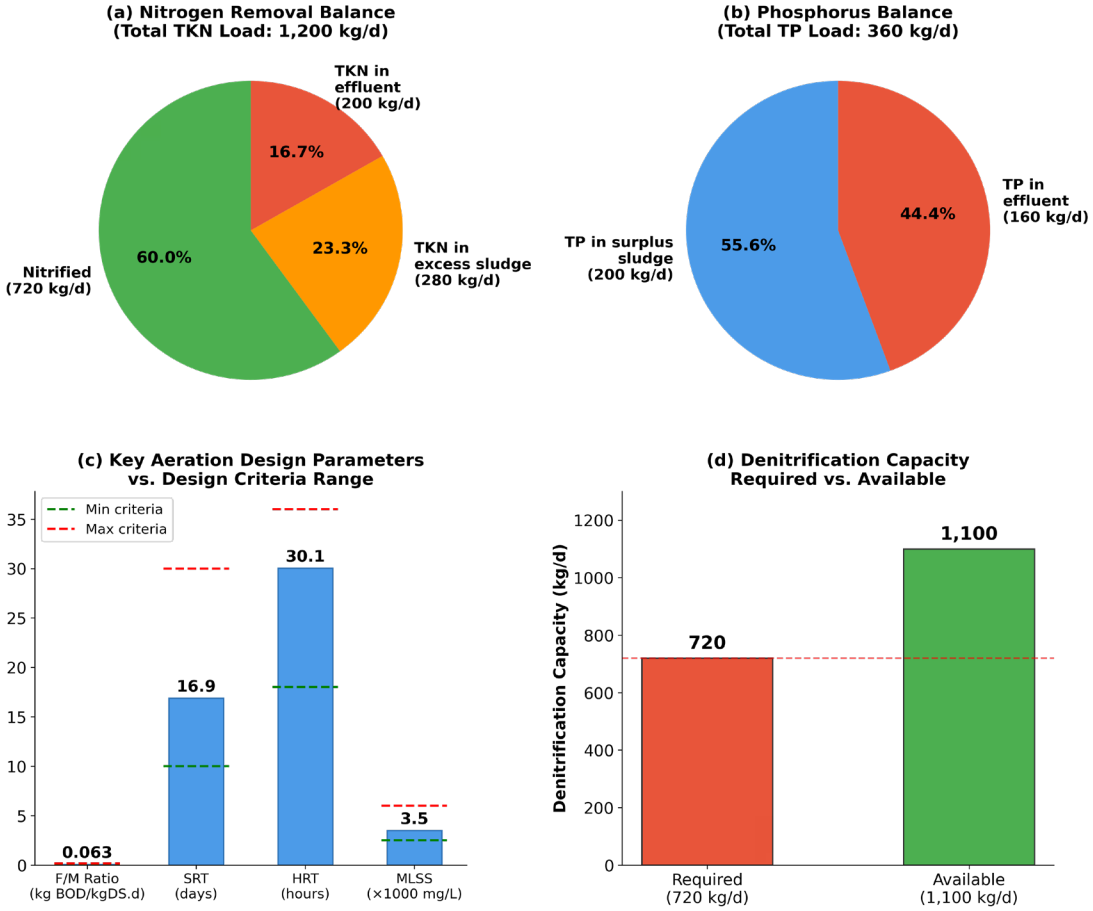


Figure 5: Carrousel Aeration System - Design Analysis

7. Secondary Clarification

Two circular clarifiers (32 m diameter) are provided. Design verification (Table 6) confirms compliance with criteria from Metcalf & Eddy (1991, Table 10-12) and WEF/ASCE (1998).

Fig. 6 confirms that both average (12.44 $m^3/m^2/d$) and peak (24.90 $m^3/m^2/d$) overflow rates fall within the acceptable range defined by the minimum and maximum criteria, while the grouped bar chart demonstrates that all design values for overflow rates, solids loading, and retention time remain below their respective maximum thresholds, verifying the adequacy of the two 32 m-diameter secondary clarifiers.

Table 6: Secondary Clarifier Design Parameters

Parameter	Design	Min	Max
Tank diameter (m)	32	-	-
Overflow rate avg ($m^3/m^2/d$)	12.44	8.14	16.28
Overflow rate peak ($m^3/m^2/d$)	24.9	24.42	32.56
Solids loading avg ($kg/m^2/hr$)	2.6	0.97	4.88
Retention time avg (hours)	3.18	2	4

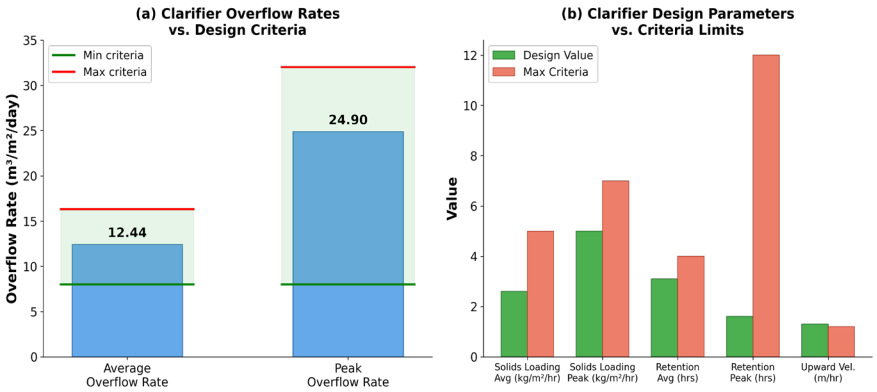


Figure 6: Secondary Clarifier Design Verification

8. Sludge Management

Sludge recycle employs two pumps (2 × 300 L/sec) providing 190% DWF recycle rate. The gravity thickener (13 m diameter) achieves solids loading of 35.23 $kg/m^2/day$, slightly exceeding the upper limit of the recommended range of 24.4-34.2 $kg/m^2/day$ for activated sludge thickening per Metcalf & Eddy (1991, Table 12-14), which may necessitate operational monitoring to ensure adequate thickening performance. Retention time of 15.6 hours, while below the 24-hour specification, is sufficient for process requirements.

9. Effluent Disinfection

Two chlorine contact tanks (576 m^3 total) provide contact times of 31.1 minutes at average flow and 15.55 minutes at peak flow. Chlorine dosage of 12 mg/L is consistent with the range recommended by the U.S. EPA (1993) for secondary effluent disinfection. Stage I daily chlorine usage is 240.05 kg/day with 30-day storage of 7,201 kg.

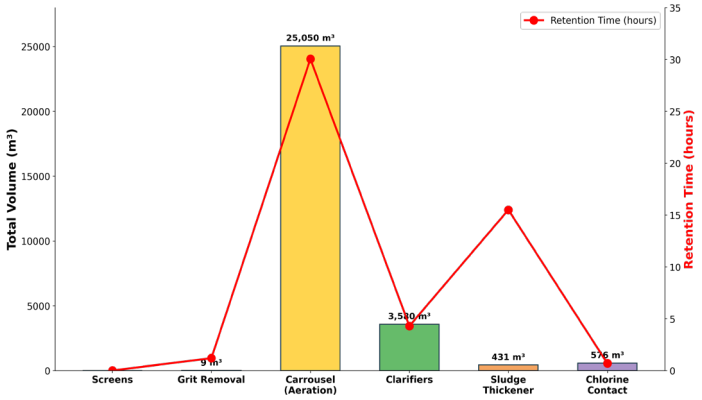


Figure 7: Summary of Unit Process Volumes and Retention Times

Fig. 7 shows the chlorine contact tank volume relative to other treatment units, with the overlaid retention time curve (red line) confirming adequate contact times of 31.1 and 15.55 minutes at average and peak flows, respectively. Fig. 8 compares the daily chemical usage and 30-day storage requirements, highlighting that chlorine dominates consumption at 240.05 kg/d with a corresponding 30-day storage of approximately 7.2 tonnes, consistent with U.S. EPA (1993) recommendations for secondary effluent disinfection.

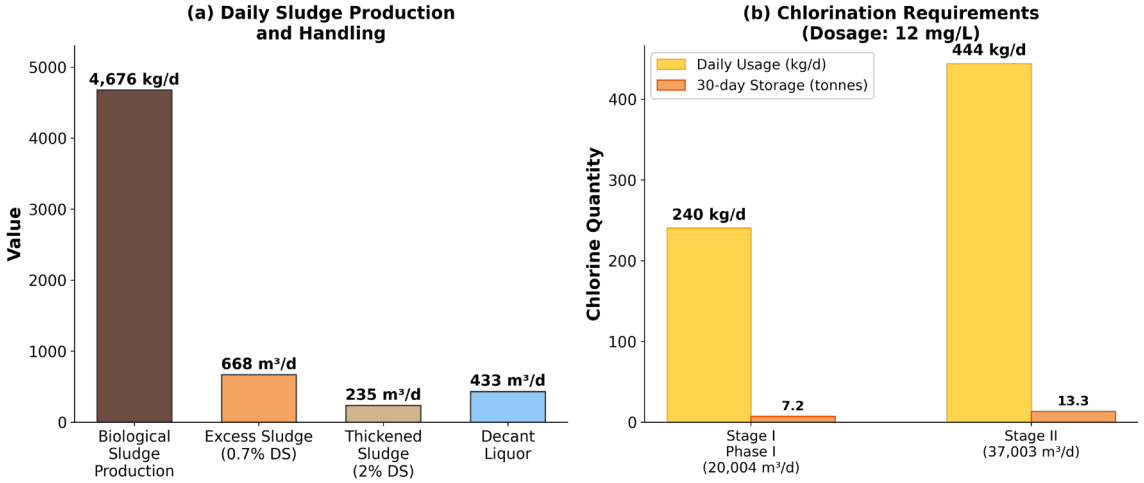


Figure 8: Sludge and Chemical Management

10. Comparison with Previous Studies

10.1 Comparison with Other Carrousel Plants

Table 7 presents a comparative analysis of the Jazan STP design parameters with published data from other Carrousel oxidation ditch installations. The comparison reveals several notable observations regarding the design philosophy adopted for the Jazan facility.

Table 7: Comparative Analysis with Other Carrousel Installations

Parameter	Jazan STP	Wangtang, China	Al-Qateef, KSA	Criteria Range
Flow (m^3/d)	20,004	100,000	45,000	-
Volume (m^3)	25,050	22,000	28,000	-
F/M	0.063	0.05-0.15	0.08-0.12	0.05-0.30
SRT (days)	16.9	12-20	15-25	10-30
HRT (hours)	30.05	5.3	14.9	18-36
MLSS (mg/L)	3,500	3,000-4,000	3,500-4,500	3,000-6,000
TN removal %	83.3	70-85	75-80	60-90

The Jazan STP design is characterized by a notably higher HRT (30.05 hours) compared to the Wangtang WWTP in China (5.3 hours; Xie et al., 2011) and the Al-Qateef plant in Saudi Arabia (14.9 hours; Elsergany, 2014). This conservative approach reflects the extended aeration operating mode that prioritizes sludge stabilization and operational simplicity-an important consideration for smaller municipalities in remote areas of Saudi Arabia where skilled operator availability may be limited.

10.2 Performance Under Arid Climate Conditions

The design of the Jazan STP must be evaluated within the context of arid climate effects. Bachi et al. (2022) demonstrated that activated sludge processes under arid conditions in Algeria achieved biological pollution removal exceeding 90%, with seasonal variation due to temperature effects. Haider et al. (2021) reported similar challenges for wastewater facilities in the Qassim region of Saudi Arabia related to high evaporation rates and elevated influent temperatures.

For the Jazan STP, elevated ambient temperatures (annual average exceeding 30°C) accelerate biological reaction rates but reduce oxygen saturation capacity. Li and Bishop (2002) observed that ORP values at higher water temperatures (20-26°C) were systematically lower than at lower temperatures (14-19°C), due to reduced oxygen saturation and increased microbial oxygen consumption. This finding has direct implications for ORP set-point calibration at Jazan, where water temperatures routinely exceed 25°C. Metcalf and Eddy (2014) note that a 10°C decrease reduces biological reaction rates by approximately half, suggesting the warm Jazan climate provides a kinetic advantage for nitrification and denitrification.

Three coastal-arid factors compound the temperature effect discussed above and deserve explicit attention in the Jazan context. First, proximity to the Red Sea makes the sewer network vulnerable to brackish groundwater infiltration; the observed rise in effluent conductivity from approximately 2,800 µS/cm in 2023 to approximately 5,800 µS/cm in 2024-2025 is consistent with this mechanism and remains below the chloride threshold

(10,000 mg/L) reported by Metcalf & Eddy (2014) for measurable nitrifier inhibition, which is corroborated by the sustained low effluent NH3-N (mean 0.51 mg/L). Second, the very high evaporation rate characteristic of the southern Red Sea coast tends to concentrate dissolved species in open process units, which interacts with the long HRT adopted at Jazan to amplify the apparent salinity gradient between influent and effluent; this provides an a posteriori justification for the conservative HRT, which buffers the biological system against transient salinity excursions. Third, the combination of high air temperature and high relative humidity that prevails on the Jazan coast for much of the year favours volatilisation of free chlorine in open chlorine-contact tanks; the design dose of 12 mg/L (Section 9) therefore represents the upper end of the U.S. EPA (1993) range and is appropriate for the local climatic envelope. Taken together, these coastal-arid considerations confirm that the conservative configuration of the Jazan STP is not merely the legacy of a 1999-era design philosophy, but is well aligned with the specific environmental pressures of its site.

10.3 Nutrient Removal Efficiency Analysis

The anticipated nitrogen removal (83.3%), now confirmed by actual monitoring data showing 91.4% TN removal, compares favorably with Liu et al. (2010), who reported 60-70% TN removal in Carrousel ditches at HRTs of 4-6 hours. The higher removal at Jazan is attributable to: (1) the significantly longer HRT (30.05 hours); (2) ORP-controlled intermittent aeration optimizing nitrification-denitrification balance; and (3) favorable temperature regime enhancing both nitrifier and denitrifier activity.

While the design anticipated only 55.6% phosphorus removal (effluent TP of 8 mg/L) through biological uptake alone, actual monitoring reveals 88.7% removal (mean effluent TP of 2.04 mg/L), indicating effective EBPR under ORP-controlled conditions. Elsergany (2014) demonstrated that the Al-Qateef Carrousel plant required supplemental chemical treatment with alum (50 mg/L) to achieve effluent TP below 1 mg/L, suggesting similar polishing may be necessary at Jazan should future regulations become more stringent.

10.4 Design Methodology Evaluation

The empirical, criteria-based design approach was standard practice in 1999 but has since been supplemented by dynamic process modeling using frameworks such as the IWA Activated Sludge Model (ASM) series. Xie et al. (2011) demonstrated that ASM2d integration with optimization algorithms can significantly improve Carrousel performance. Future upgrades at Jazan would benefit from calibrated process modeling to optimize ORP control set-points and intermittent aeration cycling patterns.

11. Operational Performance Validation

To validate the design calculations against actual plant performance, effluent monitoring data were compiled from the Jazan STP laboratory records over a 29-month span from January 2023 to July 2025. The 29-month window was not selected as a target duration; it represents the entire set of consecutive monthly monitoring records that were available, validated, and released by the plant's laboratory at the cut-off date for this analysis (July 2025). A round 30-month or 2.5-year window was not used because it would have required either including August 2025 data, which had not yet been validated by the plant's quality-control protocol at the time of submission, or excluding July 2025 to retain a 28-month round window, which would have unnecessarily discarded one validated reporting cycle. Retaining all 29 validated months therefore preserves the maximum statistical information from the operational record while remaining fully traceable to the plant's certified data. Monthly composite samples were analyzed for 16 physicochemical parameters including pH, temperature, BOD5, COD, TSS, dissolved oxygen, MLSS, ammonia-nitrogen, nitrate-nitrogen, nitrite-nitrogen, total phosphorus, turbidity, conductivity, TDS, free chlorine, and oil and grease. Table 8 presents the summary statistics of the key effluent quality parameters, while Table 9 compares the actual performance against the original design targets.

Table 8: Effluent Monitoring Data Summary

Parameter	Unit	Mean	Min	Max
pH	-	7.38	7.05	7.65
Temperature	°C	29.95	26.18	33.32
BOD_5	mg/L	4.19	2.04	10.52
COD	mg/L	14.35	6.83	39.06
TSS	mg/L	2.77	1.00	10.74
DO	mg/L	5.54	3.84	6.64
MLSS	mg/L	3,528	3,159	3,811
NH_3-N	mg/L	0.51	0.07	3.84
NO_3-N	mg/L	4.53	1.11	7.08
NO_2-N	mg/L	0.15	0.01	0.26
Total Phosphorus	mg/L	2.04	0.03	6.86
Turbidity	NTU	1.42	0.59	3.34
Conductivity	µS/cm	4,541	2,349	6,017
TDS	mg/L	3,094	1,355	4,653

Table 9: Design Targets versus Actual Operational Performance

Parameter	Design Influent (mg/L)	Design Effluent (mg/L)	Actual Effluent (mg/L)	Design Removal %	Actual Removal %
BOD_5	275	≤ 25	4.19	90.9	98.5
COD	550	-	14.35	-	97.4
TSS	275	≤ 25	2.77	90.9	99.0
Total N	60	≤ 10	5.19	83.3	91.4
Total P	18	≤ 8	2.04	55.6	88.7

The operational data reveal that the Jazan STP consistently exceeds its design performance targets across all parameters. Most notably, the actual total phosphorus removal of 88.7% substantially surpasses the design-anticipated 55.6%, suggesting that the ORP-controlled intermittent aeration regime effectively promotes enhanced biological phosphorus removal (EBPR) by creating alternating anaerobic-aerobic conditions favorable for phosphorus-accumulating organisms (PAOs). However, the TP effluent (mean 2.04 mg/L) still exceeds the current MWE (2006) standard of ≤ 1 mg/L for unrestricted reuse, confirming that supplementary chemical polishing remains necessary for full regulatory compliance. The mean effluent total nitrogen of 5.19 mg/L, well below the 10 mg/L design target, demonstrates effective simultaneous nitrification-denitrification, with effluent nitrogen dominated by NO_3-N (mean 4.53 mg/L) and minimal residual ammonia (mean 0.51 mg/L), indicating robust nitrification performance. The MLSS concentration averaged 3,528 mg/L, closely matching the design value of 3,500 mg/L, confirming appropriate biomass management. A distinct performance shift is observed between 2023 and 2024-2025, with BOD_5 decreasing from a 2023 mean of approximately 8.3 mg/L to approximately 2.5 mg/L in 2024-2025, potentially reflecting operational optimization or improved influent quality over time.

12. Discussion

The selection of the Carrousel system with ORP-controlled intermittent aeration represents an appropriate technology choice for Jazan. The extended aeration mode (F/M = 0.063, SRT = 16.9 days) provides excellent BOD removal and sludge stabilization, while ORP control enables efficient biological nutrient removal without separate anoxic zones. The calculated denitrification safety factor of 1.53 provides adequate operational margin.

Critically benchmarked against regulatory standards and published full-scale data, the validated performance of the Jazan STP can be interpreted along three axes. (i) Against the MWE (2006) unrestricted-reuse standard (BOD5 ≤ 10, TSS ≤ 10, TN ≤ 10, TP ≤ 1 mg/L), the plant comfortably satisfies all parameters except TP (mean 2.04 mg/L); even so, the actual TP performance halves the design-anticipated 8 mg/L, demonstrating that ORP-controlled intermittent aeration delivers measurable EBPR benefit even where no separate anaerobic selector was provided. (ii) Against published Carrousel installations, the Jazan TN removal of 91.4 % exceeds the 70-85 % range reported at Wangtang, China (Xie et al., 2011) and the 75-80 % range at Al-Qateef, Saudi Arabia (Elsergany, 2014), as well as the 60-70 % range reported by Liu et al. (2010) for low-HRT Carrousel SND. The differential is consistent with the substantially longer HRT (30.05 h vs. 5.3 and 14.9 h, respectively), confirming that the conservative hydraulic configuration translates directly into a measurable nutrient-removal advantage. (iii) Against the dynamic-modelling benchmarks of Yang et al. (2011) and Xie et al. (2011), the empirical, criteria-based design adopted at Jazan in 1999 has nonetheless converged on operating set-points that recent ASM2d optimisation studies retrospectively endorse for warm-climate Carrousel systems. This convergence indicates that the inclusion of operational ORP feedback in the original design provided robustness comparable to that obtained, in more recent studies, through dynamic model calibration.

The ORP-controlled intermittent aeration strategy offers significant energy optimization potential compared to conventional continuous aeration. Charpentier et al. (1989) showed that ORP-based control reduces energy consumption while maintaining treatment performance. Chang and Hao (1996) reported that pH/ORP dual control achieved energy savings with average aeration ratios of 0.23 versus 0.33-0.50 for fixed-time systems. The use of propellers for flow velocity maintenance during aerator-off periods is offset by elimination of internal recirculation pumps required in conventional pre-denitrification configurations.

The design effluent targets (BOD ≤ 25 mg/L, SS ≤ 25 mg/L) were consistent with 1999 standards. However, the 2006 MWE guidelines require BOD5 and TSS not to exceed 10 mg/L for unrestricted agricultural irrigation (Al-Jasser, 2011). Meeting these would require tertiary treatment upgrades at the Jazan STP, as demonstrated at the Al-Qateef plant where sand filters were added (Elsergany, 2014).

The secondary clarifiers demonstrate conservative design with all parameters within established criteria.

The sludge thickener retention time of 15.6 hours, while below the 24-hour specification, is a practical compromise reflecting the available tank diameter and follows the solids loading guidelines from Metcalf & Eddy (1991, Table 12-14) for air-activated sludge thickening.

12.1 Sensitivity Considerations

The design calculations presented herein are based on average influent loading conditions and steady-state assumptions. In practice, several factors may affect actual performance. During peak flow conditions (2:1 peaking factor), the HRT decreases to approximately 15 hours and the clarifier overflow rate doubles to 24.9 $m^3/m^2/d$, which may temporarily reduce effluent quality. The elevated ambient temperatures in Jazan (annual average exceeding 30°C) accelerate biological kinetics but simultaneously reduce oxygen saturation capacity from approximately 8.4 mg/L at 25°C to 7.6 mg/L at 35°C, affecting ORP response characteristics and potentially requiring seasonal adjustment of aeration set-points. Furthermore, coastal groundwater infiltration into the sewer network may introduce elevated salinity into the influent, which can inhibit nitrifying bacteria at chloride concentrations exceeding 10,000 mg/L (Metcalf & Eddy, 2014). The operational monitoring data support this concern, showing a marked increase in effluent conductivity from a 2023 mean of approximately 2,800 µS/cm to approximately 5,800 µS/cm in 2024-2025, with TDS rising correspondingly from approximately 2,000 to 4,000 mg/L, warranting investigation into potential groundwater infiltration sources. These operational variables underscore the importance of adaptive ORP control and regular process monitoring. Compared with the sensitivity ranges reported in the recent literature for similar systems, the observed Jazan responses fall within expected envelopes: Bachi et al. (2022) documented temperature-driven seasonal removal swings of 5-10 % in activated sludge plants operated under arid Algerian conditions; Navada and Vadstein (2022) showed that nitrification capacity declines sharply only above the brackish-water salinity range, a level above the equivalent salinity inferred from the conductivity record at Jazan; and Owaes et al. (2024) reported that real-time control schemes coupling redox potential and pH tolerate seasonal variation without significant set-point recalibration, provided the SRT remains sufficient to sustain a stable nitrifier population. The Jazan SRT of 16.9 d therefore lies comfortably within this operational envelope, which is consistent with the observation that the 29-month effluent record shows no statistically meaningful nitrification breakthrough despite the documented salinity rise.

12.2 Limitations

Several limitations of this study should be acknowledged. First, while 29 months of effluent monitoring data have been incorporated to validate the design analysis, the available dataset does not include concurrent influent quality measurements; therefore, the removal efficiencies presented assume that actual influent concentrations are consistent with the design values. Systematic influent-effluent paired sampling would enable more precise efficiency calculations. Second, the comparative analysis is limited to two Carrousel installations (Wangtang and Al-Qateef), which constrains the generalizability of the benchmarking conclusions. A broader comparison with additional plants in arid coastal settings would strengthen the findings. Third, the analysis employs steady-state, empirical design methods rather than dynamic process simulation using calibrated ASM models, which would provide more accurate predictions of performance variability under transient loading conditions. These limitations are not unique to the present work: Alhajri et al. (2025) reported that fewer than 15 % of operational performance reports for Saudi WWTPs include paired influent-effluent records, and Owaes et al. (2024) noted that long-term validation windows for ORP-controlled aeration studies remain comparatively rare in the peer-reviewed literature. The 29-month dataset compiled here therefore already provides one of the longer published validation windows for a Carrousel system in a hot-arid coastal setting; nevertheless, extending the analysis to a full five-year cycle with paired influent-effluent sampling, ideally coupled with calibrated ASM2d modelling along the lines of Xie et al. (2011), would constitute the most informative next step.

13. Conclusions

This paper has presented a comprehensive process design analysis of the Jazan STP. The following conclusions are drawn:

1. The Carrousel system with total aeration volume of 25,050 m^3, operating at F/M of 0.063 and SRT of 16.9 days, achieves effluent BOD and SS of 25 mg/L or below, consistent with the design criteria documented in Metcalf & Eddy (1991) and WEF/ASCE (1998).
2. ORP-controlled intermittent aeration enables simultaneous nitrification-denitrification, with available denitrification capacity (1,100 kg N/d) exceeding requirements (720 kg N/d) by 53%. The anticipated effluent TN of ≤ 10 mg/L compares favorably with published results from similar facilities (Liu et al., 2010; Xie et al., 2011).
3. The Jazan STP design, when compared with the Wangtang WWTP (China) and Al-Qateef WWTP (Saudi Arabia), demonstrates a more conservative approach characterized by longer HRT, which prioritizes operational stability and sludge mineralization.

4. Under the arid climate of the Jazan Region, elevated temperatures provide kinetic advantages for biological treatment but require careful calibration of ORP set-points due to temperature-dependent effects on redox measurements (Li & Bishop, 2002).
5. Operational monitoring over 29 months validates the design, with actual BOD_5 removal of 98.5%, TSS 99.0%, TN 91.4%, and TP 88.7%, indicating effective enhanced biological phosphorus removal under ORP-controlled aeration.
6. The design methodology, validated by operational data, provides a technical reference for similar projects in arid coastal regions, though future expansions would benefit from ASM-based dynamic modeling.

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Examining Burnout Using the MBI-ES and Its Contributing Factors Among Academic Staff in Saudi Universities During the Educational Reform Period

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Abstract:
Purpose: This study is aimed to investigate the prevalence of burnout among academic staff in higher education institutions in Saudi Arabia and exploring its influencing factors.

Methods: A cross-sectional correlational study was performed involving 208 faculty members from several governmental universities around Saudi Arabia. Data were gathered by a self-administered questionnaire that included demographic variables and the Maslach Burnout Inventory-Educators Survey. Data analysis utilized descriptive statistics, correlation analyses, independent t-tests, ANOVA tests, and the Kolmogorov-Smirnov test.

Results: Overall, 59.7% of participants reported low burnout levels, 29.4% moderate burnout, and 10.7% high burnout. Emotional exhaustion was positively correlated with depersonalization and negatively correlated with personal accomplishment. Significant associations were found between burnout dimensions and workload, job satisfaction, perceived threats, managerial relationships, income, and intention to leave employment.

Conclusion: Although 59.7% of participants reported low burnout levels, 40.1% experienced moderate-to-high burnout, indicating that a substantial proportion of academic staff remain at risk. Institutional strategies targeting workload management, organizational support, and fair compensation are essential to enhance faculty well-being and sustain academic productivity.

Keywords: Keywords: burnout; academic staff; Saudi Arabia; higher education.

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1. Introduction

In recent decades, universities have experienced substantial transformations influenced by technical progress, market growth, and globalization (McCaffery, 2024). These changes have significantly influenced the academic workplace, augmenting and expanding the responsibilities of academic personnel. The demands encompass on-campus and online instructions, student performance assessments, mentoring, academic advising, administrative responsibilities, professional development, publication pressure, institutional accreditation tasks, and adaptation to organizational changes (Salvagioni et al., 2017; Kinman & Wray, 2018). This extensive range of tasks leads to professional burnout among academic personnel.

Burnout prevalence in different professions varies between 5% and 45%, contingent upon the specific field (Li, Li, & Castaño, 2019). Higher education institutions experience significantly elevated burnout rates, with estimates exceeding 40% (Stelmokienė, Genevičiūtė-Janonė, & Gustainienė, 2019). Consequently, universities bear a significant obligation to enhance their workforce's capacity to manage burnout and meet institutional demands (Cadena-Povea et al., 2025). The cumulative performance pressure on academic staff can significantly impact their quality of life and the overall quality of education (Kinman & Wray, 2018; Watts & Robertson, 2011), leading to increased burnout rates and a decline in student outcomes. Long-term exposure to a stressful environment can lead to burnout (Kurczoba et al., 2025).

Burnout is a multifaceted condition defined by emotional exhaustion, depersonalization, and a reduced sense of personal achievement (Maslach & Jackson, 1981). It presents itself as emotional fatigue, resulting from persistent excessive work demands, a tendency to distance oneself from others as a coping mechanism (depersonalization), and an awareness of the disparity between their initial optimistic outlook and their current perspective, leading to feelings of inadequacy in social interactions and job performance (diminished personal accomplishment).

Research has classified the origins of burnout into environmental and individual components. Environmental factors encompass elevated teaching responsibilities, substantial research obligations, administrative tasks, insufficient administrative support, job security concerns, a detrimental work atmosphere, restricted access to training and development opportunities, and inflexible schedules and expectations that promote prolonged working hours, all of which hinder staff from achieving a healthy work-life balance (Salami, 2011). Individual sources contributing to burnout include leadership challenges, insufficient trust and collaboration within the team, an inability to pursue professional development, and a deficiency in recognition and rewards (Akram et al., 2022). Additionally, individual sources of burnout encompass social factors, including lifestyle choices, social isolation, and insufficient interpersonal trust (Protasenko, 2025; Hunderfund et al., 2022), alongside work-related factors such as perceptions of supervision and attitudes towards work and workload (Teven, 2007; Olivos-Jara et al., 2014).

Burnout has significant consequences for both individuals and institutions. At the individual level, it is associated with psychological issues such as exhaustion, reduced professional efficacy, cynicism, and mental health problems (Putri & Dudija, 2024), as well as physical health risks, including insomnia affecting approximately 25% of nurses, which is linked to sleep apnea, cancer, hypertension, chronic pain, gastrointestinal, autoimmune, and endocrine disorders (Nagy et al., 2021). At the organizational level, burnout negatively influences turnover intentions, commitment, work engagement, job satisfaction, and work quality (Pranata et al., 2025; Malik, 2025) and may also impact students' development (Pu et al., 2016). Collectively, these effects compromise both individual well-being and the quality of education and research productivity (Deep et al., 2025).

While burnout in primary and secondary education has been thoroughly examined, the COVID-19 pandemic has led researchers to concentrate more on burnout syndrome within higher education institutions (Jihan Turkistani et al., 2022; Marinoni, Van't Land, & Jensen, 2020; O'Brien et al., 2023; Rahman et al., 2024). Despite the increasing interest in this field, limited research has examined the frequency of burnout syndrome among academic personnel (Naidoo-Chetty & Plessis, 2021). The higher education system in Saudi Arabia has experienced substantial adjustments recently, propelled by the nation's ambitious Vision 2030 initiative (Organization for Economic Cooperation and Development [OECD], 2020). The reforms intend to modernize the education sector, improve learning results, and augment the worldwide competitiveness of Saudi universities (OECD, 2020). Nonetheless, the execution of these reforms has encountered its own difficulties. A primary issue is the welfare and job satisfaction of university personnel. Moreover, the expectations imposed on university personnel in Saudi Arabia, including heightened workloads, administrative duties, and pressure to achieve performance benchmarks, may lead to increased stress and burnout.

Burnout syndrome is an increasing issue among healthcare professionals in Saudi Arabia, particularly nurses (Alenezi et al., 2022). Healthcare and social professionals in the country have documented a significant incidence of adverse work-related responses (Jaber et al., 2025). The literature has predominantly concentrated on

healthcare workers; nonetheless, it is essential to examine the prevalence and contributing factors of burnout among university faculty in Saudi Arabia, especially in light of current educational changes. Furthermore, the cultural and social context in Saudi Arabia, where peer influence and social pressures play a significant role in shaping individuals' well-being (Alshehri, 2021), may exacerbate the risk of burnout among university staff, particularly as these factors can lead to increased stress and decreased job satisfaction in an already challenging educational environment.

The United Nations' Sustainable Development Goals (SDGs), including SDG 3: Good Health and Well-being, which emphasizes the promotion of mental health, and SDG 4: Quality Education, which focuses on empowering educators to deliver inclusive and equitable education, are relevant to the Saudi Arabian context. Addressing burnout among academic staff aligns with Saudi Vision 2030, which emphasizes building a globally competitive education system and prioritizing the well-being of educators as a foundation for national growth and innovation. By effectively managing burnout, Saudi universities can strengthen the resilience of their educational institutions, create a supportive and productive academic environment, and ensure that faculty members are well-equipped—both mentally and physically-to deliver high-quality education to support the Kingdom's long-term sustainable development goals.

The proposed research study aims to measure the prevalence of burnout and analyze the contributing factors among university staff in Saudi Arabia. This study contributes to a deeper understanding of the challenges that faculty members face and provides a foundation for developing evidence-based strategies to promote their well-being and maintain high educational standards. This study is aimed to examine the prevalence of burnout and its contributing factors among the faculty in government universities in Saudi Arabia during the current period of educational reforms. The objectives of the study were:

1. To identify sociodemographic factors associated with burnout among academic staff.
2. To determine the correlations among emotional exhaustion, personal accomplishment, and depersonalization.

2. Methodology

This research utilized a cross-sectional correlational design to examine the prevalence and factors contributing to burnout syndrome among teaching members at Saudi universities. A convenience sample of two hundred eight (N = 208) faculty members from several governmental colleges in Saudi Arabia, including Jazan University, Taibah University, Umm Al-Qura University, Imam Abdulrahman Bin Faisal University, Taif University, Islamic University of Madinah, and King Saud University. The sample size was calculated using the formula:

$$n = \frac{Z^2 \times SD^2}{e^2}$$

Where Z = 1.96 (95% confidence Interval). SD = Standard Deviation (approximate value), based on the Range of Emotional Exhaustion = (54/4) =13.5, e = Margin of Error (selected as 2 for larger sample size and higher precision). The sample size calculated was 175. Total of 208 samples were included to ensure adequateness and sufficiency. Data were collected using self-administered questionnaires. Data analysis was conducted using IBM SPSS Statistics Version 27. Descriptive statistics, such as means, medians, modes, and percentages, were computed to summarize the sample characteristics and the incidence of burnout syndrome. Correlation and Spearman rank correlation studies were used to investigate the associations between burnout and other demographic and occupational variables. Independent t-tests were employed to compare burnout level domains with the overall burnout score. The Kolmogorov-Smirnov test was conducted to evaluate the normality of the data distribution.

2.1 Operational Definition

2.1.1 Educational Reform:

Educational reform is operationally defined as the ongoing structural and organizational changes in Saudi higher education aligned with Saudi Vision 2030, including increased performance expectations, accreditation requirements, digital transformation, and expanded academic roles. In this study, it is operationalized as the current work environment experienced by academic staff during the period 2020–2025.

2.2 Measures

This study employed an online self-administered questionnaire divided into two sections. The initial segment gathered sociodemographic, personal, and professional information. The personal data encompassed age, gender, marital status, number of children, monthly income, and nationality. The professional data encompassed years of experience, contentment with schedules and workloads, and relationships with management. Workload was assessed using a self-reported item measuring average weekly working hours, categorized as less than 35 hours, 35–40 hours, and more than 40 hours per week, in addition to items evaluating satisfaction with workload and working conditions.

The second section of the questionnaire employed the validated Maslach Burnout Inventory-Educators Survey (MBI-ES; Maslach, Jackson & Leiter, 2017), delivered in both English and Arabic languages. The MBI-ES assesses burnout in three areas: emotional

exhaustion, depersonalization, and personal accomplishment. Emotional exhaustion, evaluated using nine items, measures feelings of depletion resulting from work obligations. Depersonalization, assessed by five measures, examines negative and cynical attitudes towards service recipients. The personal accomplishment scale, consisting of eight items, assesses sentiments of competence and achievement in the workplace. The MBI-ES utilizes a 7-point Likert scale from 0 (never) to 6 (every day) to evaluate the frequency of the feeling 'lack of satisfaction and unproductiveness', through its 22 components. Elevated scores on the emotional exhaustion and depersonalization subscales are associated with an increased level of burnout. Conversely, diminished scores on the personal accomplishment subscale, signify elevated degrees of burnout. Burnout, in this sense, is defined as a continuous variable ranging from low to high levels of the feeling of being ineffective or unproductive.

2.3 Ethical Approval

Before initiation, ethical approval for this study was obtained from the Institutional Review Board of Deanship of Graduate Studies and Scientific research, Jazan University, Saudi Arabia (reference no. REC-43/08/172). An informed consent form asking participants to volunteer to be human research participants was obtained. The identities of the participants were not disclosed for privacy, and confidentiality was strictly maintained on all the collected questionnaires.

3. Results

3.1 Sociodemographic Characteristics of the Faculty Members

For this research, a total of 208 faculty members from various Saudi universities were recruited. The findings revealed that the median age of the people who participated in the study was forty years old or older. In terms of gender and marital status, the majority of the faculty members were married and female (81.3% and 80%, respectively). This was the case according to the data collected. Sixty-seven percent of the faculty members had between one and three children, and 57.2% of the participants claimed that their monthly wages were greater than thirty thousand Saudi Riyals (SRs), as shown in Table 1. The high number of contributions in answering the questionnaire was shared by non-Saudi faculty members, with a total of 61% of participants, in contrast to the 39% of participants who were Saudi.

Table 1. Sociodemographic characteristics of the study subjects

Characteristics	No	%
Age		
< 25	4	1.9
25 – 29	64	30.8
30-39	12	5.8
≥ 40	128	61.5
Mean ± SD	3.52±0.7	
Gender		
Male	42	20
Female	166	80
Number of children		
No children	43	20.7
1-3 children	118	56.7
More than 3 children	47	22.6
Mean ± SD	1± 0.7	
Monthly income		
Less than 10000 SR	8	3.8
10000-19000 SR	41	19.7
20000-30000 SR	40	19.2
More than 30000 SR	119	57.2

In terms of the participants' occupations, the largest percentage of those who took part in the research were professors (46.6%). The percentage of lecturers who were represented was the lowest, at 0.4 percent. Considering the classification of job titles according to nationality, the largest percentages of non-Saudi and Saudi individuals were found to be professors (29.9% and 16.8%, respectively). The lectures, on the other hand, had the lowest percentages of both non-Saudi and Saudi speakers, with less than 2.8 percent in each group. (Table 2).

Table 2. Distribution of study subjects according to job title and nationality

Job title	Nationality				Total	
	Non-Saudi		Saudi			
	No.	%	No.	%	No.	%
Demonstrator	46	22.1	9	4.3	55	26.44
Lecturer	4	1.9	2	0.8	6	2.88
Assistant professor	5	2.4	26	12.5	31	14.90
Associate professor	10	4.8	9	4.3	19	9.13
Professor	62	29.9	35	16.8	97	46.63
Total	127	61.1	81	38.9	208	100

3.2 Burnout Level Among Faculty Members

A percentage distribution of the study participants is presented in Table 3, which is organized according to the levels of burnout domains. An examination of the table revealed statistically significant differences between the participants in the study in terms of the mean scores of the three different domains of burnout ($p<0.001$). Furthermore, the greatest percentage of faculty members exhibited low levels of emotional exhaustion, a lack of personal accomplishment, and depersonalization (38.4%, 62.0%, and 78.8%, respectively), during the course of their careers. In terms of the mean total burnout score, there was no statistically significant difference between the participants in terms of the mean burnout score ($p = 0.813$). A total of 59.7% of the people who participated in the survey reported a low level of burnout, which was the highest number reported. On the other hand, 29.4% of the participants reported moderate burnout, whereas 10.7% of the individuals reported significant emotional exhaustion.

Table 3. Distribution of the percentages of study participants according to the levels of burnout

Burnout domains	No.	%	t- test	p - value
Emotional exhaustion High Moderate Low	 51 77 80	 24% 37.0% 38.4%		
Mean ± SD	24.41± 14.42		24.4**	<0.001
Personal accomplishment High Moderate Low	 8 71 129	 3.8% 34.1% 62.0%		
Mean ± SD	34.73 ±9.26		54.04**	<0.001
Depersonalization High Moderate Low	 8 36 164	 3.8% 17.3% 78.8%		
Mean ± SD	5.4 ±6		5.97**	<0.001
Total burnout score High Moderate Low	 67 184 373	 10.7% 29.4% 59.7%		

Higher levels of emotional exhaustion (45%) and depersonalization (21%) were observed among participants aged <25 years. In contrast, lower levels of personal accomplishment were more prevalent among participants aged 30–39 years and ≥40 years (43.17% and 43.48%, respectively). Emotional exhaustion (38.7%) and depersonalization (12.2%) were more prevalent among Saudi staff, whereas reduced personal accomplishment was more common among non-Saudi staff (43.63%). The mean of each domain was compared with that of the overall burnout mean. Therefore, we used t-test to compare, to gain insights, if the means were statistically significantly different. Repeated ANOVA analysis is conducted and shown in Table 7.

Table 4. Correlations between selected sociodemographic characteristics and burnout domains

Socio-Demographic Characteristics	Emotional exhaustion		Personal accomplishment		Depersonalization	
	ρ	p-value	ρ	p-value	ρ	p-value
Age	-0.109	0.05	0.115	0.040	-0.098	0.089
Nationality	0.230**	0.00	-0.138*	0.017	0.222**	0.000
Marital status	-0.033	0.60	-0.071	0.200	0.004	0.900
Number of children	-0.082	0.13	-0.024	0.700	-0.129*	0.024
Do you have domestic support at home?	-0.005	0.927	-0.095	0.099	0.057	0.339
Is your spouse currently employed?	-0.117*	0.034	0.0220	0.685	-0.122*	0.032
Level of education	0.003	0.961	0.0860	0.127	-0.039	0.503
Job title	-0.021	0.698	0.0090	0.872	-.039	0.484

Socio-Demographic Characteristics	Emotional exhaustion		Personal accomplishment		Depersonalization	
	ρ	p-value	ρ	p-value	ρ	p-value
Monthly income	0.131*	0.016	-0.027	0.600	0.124*	0.028
Years of experience in current university	-0.017	0.75	0.0550	0.307	0.099	.0750
Position	0.062	0.274	-0.030	0.598	0.166**	.0040
Work hours per week	0.189**	0.000	0.0790	0.078	0.129*	0.022

**** Correlation is significant at the 0.01 level (2-tailed).**
*** Correlation is significant at the 0.05 level (2-tailed).**

Table 4 shows the correlations between selected sociodemographic characteristics and the burnout domains (emotional exhaustion, personal accomplishment and depersonalization). The correlations between age and the selected domains are weak positive for PA and weak negative for EE and DP. Similarly, a statistically significant negative correlation was found between nationality and personal accomplishment. Furthermore, there was a statistically significant negative correlation between the number of children and depersonalization (faculty members with more than 3 children experienced lower depersonalization levels than faculty members with 1 to 2 children and who had no children). The work of the husband or wife has a statistically significant negative correlation with emotional exhaustion and depersonalization. Monthly income shows slightly greater correlations than the other sociodemographic do. As the level of education increases, income increases; hence, the workload increases. Therefore, we observe a significant but weak positive correlation between monthly income and emotional exhaustion and depersonalization. Although the work per hour gives the participants a sense of personal accomplishment, it increases the EE and DP.

Table 5 displays the relationships among specific components of burnout, including emotional exhaustion, personal accomplishment, and depersonalization. Statistically significant positive associations were found between the emotional exhaustion domain, perceived threat, administrative work, and the intention to leave employment. Nevertheless, it has a statistically significant inverse link with work satisfaction, relationships with management, perceptions of health status, satisfaction with schedules, satisfaction with workload, and remuneration. In the realm of personal accomplishment, there are statistically significant positive relationships with work satisfaction, the relationship with one's manager, satisfaction with one's schedule, and satisfaction with one's workload. In the realm of depersonalization, statistically significant positive relationships were observed between depersonalization, feelings of threat, and the intention to leave one's job. Nevertheless, it has a statistically significant inverse link with work satisfaction, relationships with management, perceptions of health conditions, satisfaction with work schedules, and work.

Table 5. Correlations between selected items related to burnout domains

Items related to burnout	Emotional exhaustion		Personal accomplishment		Depersonalization	
	ρ	p-value	ρ	p-value	ρ	p-value
Have been exploited or perceived threat inside the academia	.360**	.000	-0.055	.338	.177**	.003
Administrative work is one of my responsibilities	.184**	.001	.022	.700	.088	.139
Satisfaction with work	-.445**	0.000	.164**	0.002	-.348**	0.000
Relationship with manager	-.279**	0.000	.132*	.019	-.226**	0.000
Perception of health status	-.339**	0.000	.171**	.002	-.77**	0.000
Intention to leave job	.465**	0.000	-0.064	.246	.310**	0.000
Satisfaction with current schedule	-.430**	0.000	.109*	.050	-.285**	0.000
Satisfaction with workload	-.483**	.000	.112*	.041	-.338**	.000
Is salary commensurate with effort?	-.299**	0.000	-.027	.619	-.198**	0.000

**** Correlation is significant at the 0.01 level (2-tailed).**
*** Correlation is significant at the 0.05 level (2-tailed).**

Table 6 shows the correlations between emotional exhaustion, personal accomplishment, and depersonalization. According to the table, there were statistically significant positive correlations between emotional exhaustion and depersonalization (r = .595, p = 0.000). However, statistically significant negative correlations were found between emotional exhaustion and personal accomplishment (r = -0.162, p = 0.019). Moreover, statistically significant negative correlations were found between personal accomplishment and depersonalization (r = -.391, p = 0.000).

Table 6. Correlations between emotional exhaustion, personal accomplishment and depersonalization

Domains	Personal exhaustion		Personal accomplishment		Depersonalization	
	ρ	p-value	ρ	p-value	ρ	p-value
Emotional exhaustion	1	<0.001	-.162*	0.019	.595**	<0.001
Personal accomplishment	-.162*	0.019	1	0.000	-.391**	<0.001
Depersonalization	.595**	<0.001	-.391**	0.000	1	<0.001

**** Correlation is significant at the 0.01 level**
*** Correlation is significant at the 0.05 level**

Table 7. Repeated ANOVA comparing the domains emotional exhaustion, personal accomplishment, and depersonalization

Source	Sum of Squares	df	Mean Square	F-Value	p-value	Effect size
Burnout	92066.39	2	46033.19	438.81	<0.001	0.679

The repeated ANOVA indicates that there is statistically significant difference between the burnout domains. The effect size is large (0.679) emphasizing the statistical significance. The p-value of linear trend and quadratic trend were <0.001, indicated that both the linear and quadratic patterns are significant. Therefore, we can conclude that the burnout dimensions do not uniformly change, rather their variation is non-linear.

4. Discussion

4.1 Overall burnout levels

This study investigated the prevalence of burnout among faculty members and explored its relationship with various sociodemographic and professional factors. The findings contribute to a deeper understanding of workplace well-being in academic settings and offer insights for potential interventions. The study revealed that a majority of participants (59.2%) exhibited a low level of burnout, suggesting a generally positive view of their overall well-being. These results are consistent with those of previous studies conducted in different countries showing that many faculty members can maintain a healthy level of emotional and professional engagement through supportive job resources and individualized approaches (Duke et al., 2019; Mudrak et al., 2017).

However, the study also revealed that a significant portion of the faculty (29.4%) experienced a moderate level of burnout, and an additional 10.7% reported a high level of burnout. This suggests that a number of faculty members are at risk of experiencing the detrimental effects of burnout, which can include decreased job satisfaction, poor mental and physical health, and reduced productivity (Asfahani, 2023). In the broader MENAT region, Alhassan et al. (2025) reported high emotional exhaustion among 40% of healthcare and educational workers, depersonalization among 31%, and reduced personal accomplishment among 38%. These regional findings suggest that although low burnout was most common in the present study, the proportion of faculty reporting moderate-to-high burnout remains important and should not be overlooked.

4.2 Associations between faculty demographic and professional characteristics and their level of burnout

As with the second aim of this study, the findings shed light on the complex interplay of various factors that contribute to the burnout experienced by faculty members at participating Saudi governmental universities. The study revealed a weak correlation between the age of faculty members and the emotional exhaustion and personal accomplishment subscales. This finding is consistent with Zabrodska and others (2018), who reported that there is a small negative correlation between worker age and emotional exhaustion. However, these findings contrast with the findings of other studies, which revealed that younger faculty members were more susceptible to high levels of emotional exhaustion due to factors such as limited coping mechanisms, work–life balance challenges, and pressure to establish themselves in their careers (Rožman, Grinkevich & Tominc, 2019; Sestili et al., 2018; Watts & Robertson, 2011), whereas their older counterparts reported higher levels of lack of personal accomplishment, as individuals approach retirement, their time horizon for achieving long-term work goals naturally shrinks (Obliopas et al., 2019; Watts & Robertson, 2011).

Older faculty members often experience less emotional exhaustion and depersonalization while reporting higher levels of personal satisfaction. This pattern likely reflects a set of interconnected influences, including accumulated professional experience, the gradual development of adaptive coping strategies, whereby individuals unable to cope effectively may have already withdrawn from the profession (Giuseppe et al., 2021). Even if there is a weak correlation, it does not mean that age directly affects these outcomes.

The study results also revealed that working spouses were negatively related to the level of emotional exhaustion and depersonalization. Similarly, the results of a study carried out by Yang and others (2023) indicated that primary health workers who have work-family support can protect against burnout syndrome. Partners can provide emotional support, practical assistance, and a shared understanding of work-related challenges, which can prevent burnout (Demerouti & Schaufeli, 2005; Claponea, & Iorga, 2023). The impact of a working spouse likely depends on individual coping mechanisms, relationship quality, and the specific nature of both partners' work (Krannitz, Grandey, Liu, S., & Almeida, 2015). Supportive relationships with healthy communication and shared responsibilities might protect against emotional exhaustion and depersonalization.

The present results highlight that perceived threats and the intention to leave the job can contribute to emotional exhaustion and depersonalization. The perceived threats by faculty members could include job insecurity, a lack of resources, unfair treatment, or being the victim of work incivility (Cadena-Povea et al., 2025; Erdemir, 2023). Threats to one's job or career can disrupt feelings of control and predictability, leading to increased anxiety and a diminished sense of personal agency and control. Depersonalization might manifest as a way to cope with this loss of control by emotionally distancing oneself from the situation or work (Edú-Valsania, Laguía & Moriano, 2022). Previous research has indicated that feelings of depersonalization, rather than emotional exhaustion, are a direct factor in decisions to leave a job (Maniscalco, Enea, de Vries et al., 2024).

On the one hand, a lack of satisfaction with work, schedules, and workloads; poor relationships with managers; and poor health contribute to emotional exhaustion, depersonalization, and personal accomplishment among faculty members. Heavy workloads, conflicting demands, and poor workplace relationships can lead to feelings of being overwhelmed, depleted, and disconnected from one's work and colleagues (Sabagh et al., 2018). This interpretation is further supported by Gulf-based literature indicating that burnout among academic staff is shaped by institutional and occupational demands. In Saudi and Gulf universities, rapid higher education expansion, role conflict, workload, research productivity expectations, administrative duties, and limited institutional support have been identified as important contributors to faculty burnout (Asfahani, 2023; Polo & Abid, 2025). This can negatively impact faculty members' well-being, job satisfaction, and ability to effectively fulfil their teaching, research, and service responsibilities. Additionally, many faculty members can cope with these challenges successfully (Sabagh et al., 2018). Through effective time management and access to wellness resources, they may be able to navigate the demands of their roles without experiencing burnout (Salimzadeh et al., 2021). Moreover, factors such as intrinsic motivation, a sense of purpose, and strong collegial relationships can serve as protective factors against burnout, allowing faculty to thrive even in the face of significant workloads and stressors (Sabagh et al., 2018). In contrast, the study by Quesada-Puga et al. (2024) suggested that a sense of overall satisfaction is beneficial; this alone may not be sufficient to prevent emotional exhaustion and depersonalization.

The study findings revealed that inadequate remuneration (in this study, only direct financial compensation, which is in the form of salaries), can contribute to emotional exhaustion and depersonalization among faculty members. When pay and benefits are perceived as insufficient or unfair, they can lead to feelings of being undervalued and undercompensated for the significant workloads and emotional labor required in their roles (Essien et al., 2025). This can exacerbate feelings of burnout and detachment. A study of pharmacists who experienced long-term job stress indicated that remuneration was an important factor that affects burnout, which ultimately affects turnover intention (Matloob, Bhatti, Halim & Sikander, 2018). Furthermore, transparent and merit-based pay structures can foster perceptions of organizational justice, which may reduce feelings of emotional exhaustion and depersonalization (Claponea & Iorga, 2023).

Finally, this study revealed that emotional exhaustion among faculty members is positively correlated with depersonalization and negatively correlated with personal accomplishment. This finding is consistent with the literature, as high levels of emotional exhaustion can potentially lead to a lack of energy to focus on relationships, which further contributes to emotionally drained individuals being less likely to focus on their job, resulting in a subsequent lack of personal accomplishment (Anastasiou & Belios, 2020; Parayitam et al., 2021).

4.3 Strengths and limitations

4.3.1 Strengths

This study has made a number of key contributions to the understanding of burnout among university academic personnel in Saudi Arabia. First, it uses a strong cross-

sectional correlational design with a sample of 208 faculty members from several governmental universities in Saudi Arabia, thus giving the findings more breadth than single-institution studies. Burnout is measured with conceptual fidelity and cultural sensitivity by using a validated and internationally recognized instrument, the Maslach Burnout Inventory-Educators Survey (MBI-ES), administered in both English and Arabic, to minimize the risk of language-related measurement error in a bilingual academic workforce.

Secondly and more importantly, our work fills a real and well documented vacuum in the area literature. A review of the primary academic literature discovered only two studies that addressed burnout among university professors in Saudi Arabia (Alhassan, 2023; Alhassan, 2025). Research on burnout in Saudi Arabia and the wider Gulf Cooperation Council (GCC) region has focused largely on healthcare personnel, especially nurses and doctors, with very little attention paid to the academic workforce. The virtual absence of research on faculty burnout in this location is not a limitation of the present study but instead represents a gap that the study is designed to address. Thus, this study is one of the few empirical studies on teacher burnout in Saudi higher education and the first, to our knowledge, to explore it in the context of the educational reform phase of Vision 2030.

Third, the study explored a wide range of predictors such as sociodemographic variables, professional qualities, organizational factors, and individual views, allowing for a complex analysis of the burnout landscape among Saudi academic professionals. The substantial connections between aspects of burnout and satisfaction with workload, relationships with management, perceived threats, appropriateness of compensation and intention to leave employment give an empirically supported basis for institutional intervention. These findings are particularly important considering Saudi Arabia's continued investment in higher education transformation under Vision 2030, making faculty well-being both a strategic and a human resource concern.

Finally, this study is consistent with and directly contributes to the United Nations' Sustainable Development Goals, particularly, SDG 3 (Good Health and Well-being) and SDG 4 (Quality Education), by providing evidence that can help inform the protection of educator well-being as a basis for inclusive, equitable, and quality education provision in the Kingdom.

4.4 Limitations

Despite these contributions, some limitations should be acknowledged while interpreting the findings. First, the cross-sectional design of the present study does not allow to establish causal links between the sociodemographic and professional variables analyzed and the burnout aspects. Thus, the interactions described should be considered as associations rather than causal effects and longitudinal studies will be needed to explore the direction and stability of these relationships over time. Second, the study adopted a convenience sample technique that limits generalizability of the findings to the wider population of Saudi university teachers. Participants were selected from several governmental universities in Saudi Arabia. However, the sampling method does not allow us to claim that the sample is fully representative of the country.

Third, the sample was weighted towards female participants (80%) and non-Saudi faculty members (61%). These distributions may partly reflect the demographic composition of the universities surveyed, particularly when recruiting from female dominated academic schools, but they restrict the extent to which findings may be generalised to male faculty and to Saudi national academic staff. Saudi and expatriate academics may have different burnout profiles due to different employment security, contract kinds, cultural expectations, and institutional positions. Future research should fill this gap, with emphasis on gender-balanced and nationality-stratified sampling. Finally, we did not measure individual-level coping methods and institutional support systems, both known moderators of burnout, and these may have influenced the observed relationships. Future studies combining these variables will offer a more holistic view of factors protecting professors from or making them more vulnerable to burnout in the Saudi higher education setting.

4.5 Research, Practical and Policy Implications

4.5.1 Future Research Recommendations

This work presents a number of fruitful options for further research. These findings should be taken with the noted lack of research on professor burnout in the Saudi and larger Gulf region. The literature search revealed only two studies investigating burnout among university academic personnel in Saudi Arabia (Alhassan, 2023; Alhassan, 2025), while the rest of the burnout literature in the region has been conducted on healthcare workers. The very lack of evidence provides a powerful incentive to additional research. The present study can be seen as a first contribution to an area yet severely underexplored. Future research should address the methodological constraints of this research by using longitudinal designs that allow for the tracking of burnout trajectories over time, especially throughout different periods of the Vision 2030 reform cycle. Longitudinal data would allow causal conclusions that cannot be drawn from cross-sectional designs and would allow researchers to determine if organizational changes associated with reform increase or decrease risk of burnout over time. Future study

should also focus on gender-balanced sample and include stratified analyses by nationality (Saudi vs. expatriate) and by academic level. The strong connections between nationality and burnout dimensions found in the present study with Saudi faculty expressing higher emotional tiredness and depersonalization, and non-Saudi faculty reporting lesser personal accomplishment need focused investigation. Such patterns are likely due to different structural pressures and job characteristics that should be analyzed in disaggregated fashion rather than estimated in pooled fashion. Qualitative and mixed methods techniques would also contribute greatly to the evidence base. In-depth interviews or focus groups with faculty members may shed light on the lived experience of burnout in the Saudi academic context, the meaning faculty members attribute to reform-related pressures, and the informal coping techniques they use. Preliminary qualitative work would be beneficial to understand why male faculty members appear to be underrepresented in burnout research participation, a pattern that is seen in this study and more broadly in the occupational health literature, so that future studies can design more inclusive recruitment strategies. Finally, future research should expand the measurement of compensation and institutional support to include non-salary benefits, availability of mentorship, research infrastructure and formal wellness programs, all of which may provide meaningful buffers against burnout and whose effects have not been adequately assessed in the Saudi academic context yet.

4.6 Practical Advice for University Administrators

Prioritize faculty wellbeing during reform by monitoring workload and redistributing tasks where possible. Offer accessible mental health resources and confidential counseling. Establish peer-support and mentoring programs. Provide clear communication and participatory decision-making to reduce uncertainty. Invest in professional development and time for research/teaching balance. Implement regular wellbeing assessments to identify at risk groups. Consider targeted interventions (e.g., reduced administrative load, teaching relief, or flexible scheduling) for those showing signs of burnout.

4.7 National-Level Stakeholder Policy Recommendations

National policymakers should prioritise faculty wellbeing in reform by providing targeted funding for mental health services and developing institutional capacity, issuing clear national guidelines on workload limits and fair evaluation practices and requiring regular confidential wellbeing monitoring across all universities. Support should encompass funds for professional development, incentives for institutions that incorporate evidence-based burnout prevention (peer support, counseling and flexible scheduling) and mandates for transparent reporting and evaluation of faculty working conditions. And fund longitudinal research to track the effects of changes, promote the exchange of best practices among institutions, and use performance indicators connected to staff welfare to hold universities accountable so that reforms do not undermine the health or productivity of academic staff.

5. Conclusion

The issue of burnout among university faculty members is a significant concern that warrants further investigation and action. According to this study, faculty burnout in Saudi universities generally involves a low level. However, a considerable proportion of faculty members remain at risk. Burnout was found to be associated with several key factors, including workload, working hours, job satisfaction, satisfaction with work schedules, perceived threat or exploitation, managerial relationships, income, perceived health status, and intention to leave employment. Universities can develop targeted strategies addressing these factors to support the well-being and productivity of their academic staff, ultimately benefiting the entire academic community.

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Utilization and Predictors of Evidence-Based Practice Among Nurses and Midwives: A Cross-Sectional Study from Al-Jouf, Saudi Arabia

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Abstract
Background: Evidence-Based Practice (EBP) enhances the quality and safety of nursing and midwifery care by integrating research evidence into clinical decision-making. This study aims to assess the current level of EBP use and identify its individual and organizational predictors among nurses and midwives at the Maternity and Children's Hospital in Al-Jouf, Saudi Arabia.

Methods: This cross-sectional study involved 183 nurses and midwives. A validated online questionnaire was used to assess EBP knowledge, utilization, barriers, and facilitators. Data were analyzed using SPSS version 29 with descriptive statistics and Fisher's exact test to determine significant associations.

Results: Most participants demonstrated good knowledge of evidence-based practice (EBP) (88.0%), yet the majority reported poor EBP utilization (83.1%). Knowledge was significantly associated with EBP utilization ($p = 0.029$). Significant associations were also found with work unit ($p < 0.001$) and educational level ($p < 0.001$), with higher utilization among ICU nurses and those holding a master's degree. Key barriers included limited research skills, insufficient time, and a lack of authority to change practice.

Conclusion: The findings emphasize the need for better organizational support, leadership empowerment, and training programs aligned with Saudi Vision 2030 to strengthen EBP implementation and improve healthcare quality.

Keywords: Evidence-Based Practice, Nurses, Midwives, Women's Health, Al-Jouf, Saudi Arabia.

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1. Introduction:

Evidence-Based Practice (EBP) integrates the best available scientific evidence to guide clinical decision-making and enhance the quality of patient care.(Reynolds et al., 2026; Schmidt & Brown, 2024). To provide optimal care, healthcare professionals must continuously update their knowledge and skills. Sackett's EBP model offers a structured framework that supports practitioners in applying evidence systematically to improve clinical outcomes and overall care quality. By utilizing this model, caregivers can ensure that their practice is grounded in the most current and effective evidence. Sackett's model outlines six essential steps: (1) formulating a clear clinical question, (2) searching for the best available evidence, (3) critically appraising the quality and relevance of the evidence, (4) integrating the evidence with clinical expertise and patient preferences, (5) evaluating the outcomes of the applied evidence, and (6) disseminating or sharing the findings with others. Although the implementation of EBP requires time, resources, and effort, the resulting improvements in patient outcomes and quality of care justify the investment (Atalla et al., 2025) .

Nursing forms the foundation of healthcare systems worldwide, and ensuring high-quality patient care depends on evidence-based nursing practice. Both nurses and midwives play a vital role in advancing healthcare by providing superior services throughout women's lifecycles. The implementation of EBP is essential not only for improving patient outcomes but also for fostering professional growth, accountability, and staff competencies. Over time, EBP has gained increasing importance within the nursing profession and has become an integral part of routine clinical practice (Katowa-Mukwato et al., 2021).

Nonetheless, unsafe care is a significant global health concern that poses challenges for all nations; therefore, decisions must continue to assess the quality and safety of medical care (8). The growing number of medical errors and subpar care presents challenges to healthcare organizations from time to time (Dang et al., 2021; Rahmayanti et al., 2020). In addition to differences in results, health disparities and insufficient medical treatment continue to be problems for nurses and midwives worldwide. Low implementation of EBP leads to inadequately informed decision-making, resulting in substandard service delivery. This failure creates variations in practice that reduce effectiveness, efficiency, and equity of care. (Crawford et al., 2023).

The regular implementation of EBP in clinical settings has been an ongoing challenge for all organizations for decades. (Alatawi et al., 2020). In a study on primary care nurses, researchers found that organizational concerns about costs, shifts in workload, time constraints, patient compliance, and a lack of incentive to adopt EBP were the top obstacles to EBP. (Leiviska et al., 2025). A study conducted in Cyprus by (Pitsillidou et al., 2021). reported that, according to nurses, the primary barrier to implementing Evidence-Based Practice was their limited authority or inability to modify care procedures. The second major obstacle identified was the perception that research findings did not apply to their clinical settings.

While concentrating solely on nurses' individual decisions to apply EBP oversimplifies the problem, this does not diminish the staff nurse's role. Instead, research suggests that supportive work environments and strong nursing leadership are crucial because they are what truly enable staff nurses to engage in EBP(Ominyi et al., 2025). Supportive organizational culture is a key element in promoting the adoption of EBP within healthcare settings. Institutions that emphasize professional development, leadership support, and shared decision-making tend to create environments conducive to EBP implementation. Nevertheless, organizational initiatives alone may not be sufficient to enhance EBP utilization. It has been suggested that integrating strong institutional support with nurses' competencies, motivation, and confidence in applying evidence can foster a more effective and sustainable EBP culture(Atalla et al., 2025).

In Saudi Arabia (SA), increasing attention has been directed toward improving the quality of healthcare services. Over recent years, nursing practice has undergone a gradual transformation, as most nurses were previously diploma holders rather than bachelor's degree graduates. Compared with diploma nurses, those holding a bachelor's degree receive more extensive training in research and EBP. (Alsufyani et al., 2020). Despite these advancements, nursing education and clinical practice in the Kingdom are still developing and require further enhancement.(Alruwaili et al., 2025). Studies from Saudi Arabia and neighboring countries such as Jordan, Oman, and Iran have shown that nurses face significant challenges in implementing EBP, and limited research has explored this issue in depth. (Atalla et al., 2025; Hamad et al., 2025; Mohebi et al., 2025). Moreover, the Saudi nursing workforce is unique, as a substantial proportion of nurses are expatriates with limited proficiency in the Arabic language and limited familiarity with the local culture. These factors may hinder effective communication and culturally sensitive care, thereby influencing the overall quality of nursing practice. (Alruwaili et al., 2025; Atalla et al., 2025).

Midwives play a critical role in implementing evidence-based practices to improve maternity health. Their unique position allows them to bridge clinical knowledge with the specific needs of mothers and their families. Enhancing maternal health during pregnancy and delivery is one of the World Health

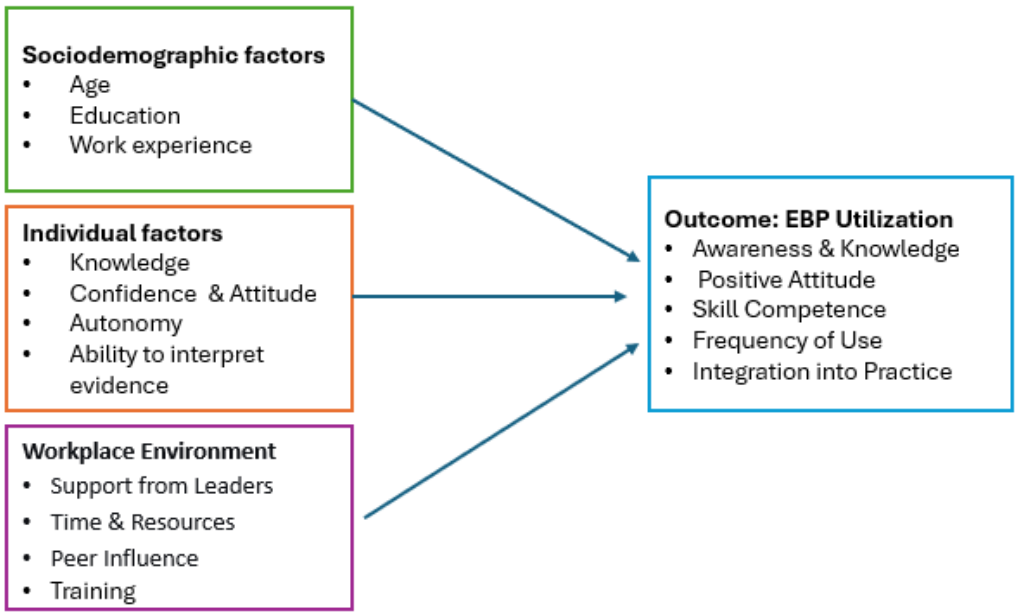
Organization's primary developmental goals for the fifth millennium. Global public health has been concerned about the maternal death rate as a measure of standard maternal health care (Rahman et al., 2020). In 2023, Saudi Arabia reported a maternal mortality rate of 7.0 deaths per 100,000 live births, underscoring the need to further enhance the safety and quality of maternal healthcare(Ahmed et al., 2026). The implementation of EBP and continuous quality improvement is an essential competency for all healthcare professionals, particularly nurses and midwives who serve as frontline caregivers. Therefore, evaluating the extent of EBP utilization and identifying its influencing factors among nurses and midwives are critical steps toward improving patient outcomes, strengthening professional competence, and advancing the overall quality of healthcare services in the Kingdom(Alarifi et al., 2025).

Despite the growing global emphasis on integrating Evidence-Based Practice (EBP) into clinical care, there remains a notable scarcity of research in Saudi Arabia examining its implementation among nurses and midwives, particularly within the Al Jouf region. Given the essential role of these professionals in ensuring high-quality maternal and child healthcare, it is crucial to understand their engagement with EBP. Therefore, the present study aimed to assess the level of EBP implementation and identify the factors influencing its application among nurses and midwives working at the Maternity and Children's Hospital in Al Jouf, Saudi Arabia.

1.1 Conceptual Framework

To strengthen the conceptual rationale for examining these factors, this study is guided by the Diffusion of Innovation framework, which explains how individuals and organizations adopt new practices(Moraes et al., 2025). The conceptual framework presented in Figure 1 illustrates the relationships between sociodemographic factors, individual factors, workplace environmental factors, and EBP utilization. The theory offers a robust framework for understanding how new practices, including evidence-based interventions, are communicated, adopted, and sustained within social systems. The theory posits that adoption rates are shaped by potential users' perceptions of an innovation's relative advantage, compatibility with existing values and practices, complexity, trialability, and observability. Within nursing and midwifery practice, this framework is particularly useful for explaining the often slow and uneven uptake of clinical guidelines and research evidence, as it shifts attention from simple evidence dissemination toward the psychosocial, organizational, and contextual factors that influence implementation(Iqbal & Zahidie, 2022). By applying this theoretical lens, researchers can move beyond assessments of individual knowledge or skills to examine how innovative characteristics, adopter attributes, and environmental conditions interact to predict the utilization of evidence-based practice (EBP). In this regard, the present study, which examines the utilization and predictors of evidence-based practice among nurses and midwives in Al-Jouf, Saudi Arabia, is informed by theory and seeks to identify both the level of EBP utilization and the key individual and organizational predictors shaping its adoption within a regional healthcare context.

Figure 1: Conceptual Framework Based on Diffusion of Innovation Theory



2. Methods

2.1 Study Design:

An institution-based cross-sectional study was conducted at the Maternity and Children's Hospital, a 150-bed tertiary referral facility situated in the Al Jouf region of northern Saudi Arabia. Data collection was conducted over five months, from January to May 2025.

2.2 Sample/Participants:

The study population comprised all nurses and midwives employed at the Maternity and Children's Hospital in the Al Jouf region of Saudi Arabia. The hospital employed a total of 320 registered nurses and 26 midwives, resulting in a total population of 346 healthcare professionals. The required sample size was calculated to be 183 participants using the online Calculator.net tool based on a 95% confidence level and a 5% margin of error. The calculator applies standard statistical formulas commonly used for sample size estimation. A nonprobability sampling technique was used in this study. All eligible participants were invited to participate in the survey, and 183 completed the questionnaire, yielding a response rate of 52.9%.

2.3 Inclusion criteria:

Registered nurses and midwives, both Saudi and non-Saudi, employed at the Maternity and Children's Hospital in Al Jouf, Saudi Arabia, with at least one year of clinical experience, both full-time and part-time staff actively working during the data collection period, were invited to participate in this study, including nurses in clinical and managerial positions.

2.4 Exclusion criteria:

Nurses and midwives with less than one year of clinical experience, interns, and healthcare personnel not employed in nursing or midwifery roles were excluded from the study, as were staff members on extended leave during the data collection period, including annual, maternity, or sick leave. Participation was voluntary, and individuals who declined to participate were also excluded.

2.5 Instruments:

Data were collected using a self-administered, structured online questionnaire. To ensure data quality, the online questionnaire was designed to allow only one response per participant and included mandatory fields to minimize missing data. The questionnaire was pilot tested before data collection to assess clarity, readability, and understanding of the items. Participants were also provided with clear instructions before completing the survey. Permission to use the instrument was obtained via email from the original developers. The scale's validity and reliability were previously assessed by Aynalem et al., with prior studies reporting good internal consistency (Cronbach's alpha 0.85–0.93) across subscales, supporting the instrument's reliability and methodological rigor. (Aynalem et al., 2021).

The questionnaire comprised 56 items divided into six sections. The first section included eight items assessing sociodemographic characteristics, such as age, gender, marital status, nationality, and work experience. The second section consisted of six items evaluating nurses' knowledge of Evidence-Based Practice (EBP), including understanding of EBP principles, research appraisal, and the integration of evidence into clinical practice. The third section included nine items assessing sources of information supporting EBP, such as classroom learning, hospital protocols, and national guidelines. The fourth section consisted of six items evaluating the implementation of EBP and the frequency of applying research evidence in patient care decisions. The fifth section included 14 items addressing barriers to EBP utilization, such as lack of autonomy to change practice, insufficient research skills, and limited organizational support. The final section comprised five items examining facilitators of EBP use, including training opportunities, managerial support, and improving research knowledge. There were yes/no questions in Part 2, and Levels in Parts 3, 4, and 6 varied from never (1) to always (5). A 5-point Likert scale, ranging from strongly disagree (1) to strongly agree (5), was used to produce part five. This 5-point Likert scale was combined for analytical purposes in accordance with the results of a prior study, which made it simpler to compare the findings of this survey with those of the other study. Consequently, the terms disagree and strongly disagree were combined to become disagree and agree and strongly agree to form agree. (Megersa et al., 2023).

2.6 Data Collection Procedure:

Regarding the data collection Procedure, the nursing director in the hospital received the survey link via email from the researcher, and they helped distribute it to the nurses who worked under their supervision. The email invitation provided comprehensive information about the study's objectives and the consent required from participants. To proceed with the survey, participants were required to click a confirmation indicating their consent, and completion of the survey was taken as agreement to participate. To encourage wider participation, a web-link invitation was distributed to staff nurses via email and several social media platforms, including WhatsApp, Instagram, and Messenger. Participants were assured of anonymity and informed that they could withdraw from the study at any time before submission without any consequences.

2.7 Data Analyses:

All statistical analyses were conducted using IBM SPSS Statistics version 29.0. Descriptive statistics summarized the characteristics of the 183 participants,

including demographics, knowledge, perceptions, engagement, and barriers/facilitators related to evidence-based practice (EBP), with categorical data presented as frequencies and percentages. Knowledge of EBP was assessed using six questions. Each correct response was assigned one point, resulting in a total knowledge score ranging from 0 to 6. Knowledge levels were categorized as good or poor using a cutoff point of ≥60%, with scores ≥4 classified as good knowledge and scores <4 classified as poor knowledge. The 60% cutoff was selected based on commonly used criteria in similar EBP questionnaire-based studies and to facilitate interpretation of the findings. In addition to categorical classification, descriptive statistics, including frequencies, percentages, and mean scores, were also reported to provide a more comprehensive presentation of participants' knowledge levels. EBP utilization was measured using 18 items on a four-point Likert scale (0 = never, 1 = sometimes, 2 = usually, 3 = often). A mean utilization score was calculated for each participant. Utilization levels were then categorized as good or poor based on the mean score, with a mean score ≥2 indicating good utilization and a mean score <2 indicating poor utilization. Fisher's Exact Test was applied. Effect sizes were measured using Cramér's V. A p-value of <0.05 was considered statistically significant for all analyses.

2.8 Ethical consideration:

Ethical approval for the study was obtained from the Bioethics Institutional Review Board at Jouf University (Approval No. 6897, dated 25/12/2024) as well as from the Al Jouf Health Cluster.The study adhered to the ethical principles outlined in the Declaration of Helsinki. Participant confidentiality and anonymity were strictly maintained by assigning each participant a unique identification code and reporting all findings in aggregate form. Data were stored securely in a password-protected electronic database accessible only to the researcher. Informed consent was obtained electronically from all participants before they completed the online survey through Google Forms.

3. Results:

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Table 1: Demographic Characteristics of Participants (N = 183)

Variables		Frequency	Percent
Age	20 – 24	46	25.1
	25-30	29	15.8
	31- 35	58	31.7
	36- 40	37	20.2
	More than 40	13	7.1
Gender	Male	8	4.4
	Female	175	95.6
Work unit in which you are working	ER	37	20.2
	ICU	9	4.9
	Labor room	12	6.6
	Maternity word	5	2.7
	OPD	8	4.4
	Others	112	61.2
Marital status	Single	71	38.8
	Married	107	58.5
	Divorced	5	2.7
Nationality	Saudi	154	84.2
	Non-Saudi	29	15.8
Work experience	1–4 years	75	41.0
	5–8 years	13	7.1
	9–12 years	21	11.5
	More than 12	74	40.4
Educational level	BSc	92	50.3
	Diploma	56	30.6
	MSc	30	16.4
	PhD	5	2.7
Current role at the hospital	Midwife	12	6.6
	Staff nurse	114	62.3
	Nurses at managerial position	57	31.1

Table 1 shows that the study included 183 participants. The largest proportion were aged 31–35 years (31.7%, n = 58), and most were female (95.6%, n = 175). The majority worked in other departments (61.2%, n = 112), were married (58.5%, n = 107), and were Saudi nationals (84.2%, n = 154). Most participants had 1–4 years (41.0%, n = 75) or more than 12 years (40.4%, n = 74) of work experience. In terms of education and role, most held a bachelor's degree (50.3%, n = 92) and were employed as staff nurses (62.3%, n = 114).

Table 2: Knowledge and Perceptions of Evidence-Based Practice Among Nurses

	No		Yes	
	N	%	N	%
Have you received training courses on evidence-based practices?	104	56.8%	79	43.2%
Are you aware of the concept of EBP in nursing?	26	14.2%	157	85.8%
Evidence-based practice is a problem-solving approach.	18	9.8%	165	90.2%
It enhances the delivery of the highest quality of care	23	12.6%	160	87.4%
EBP combines knowledge and theory	22	12.0%	161	88.0%
EBP is for nurse educators and for those in the clinical area	59	32.2%	124	67.8%

As shown in Table 2, most participants demonstrated good awareness and positive perceptions of evidence-based practice (EBP). Most respondents reported being aware of the concept of EBP in nursing (85.8%, n = 157) and recognized it as a problem-solving approach (90.2%, n = 165). Additionally, a high proportion agreed that EBP enhances delivery of the highest quality of care (87.4%, n = 160) and that it combines knowledge and theory (88.0%, n = 161). Furthermore, 67.8% (n = 124) acknowledged that EBP applies to both nurse educators and clinical practitioners. However, only 43.2% (n = 79) reported having received training courses on EBP, while the majority (56.8%, n = 104) had not.

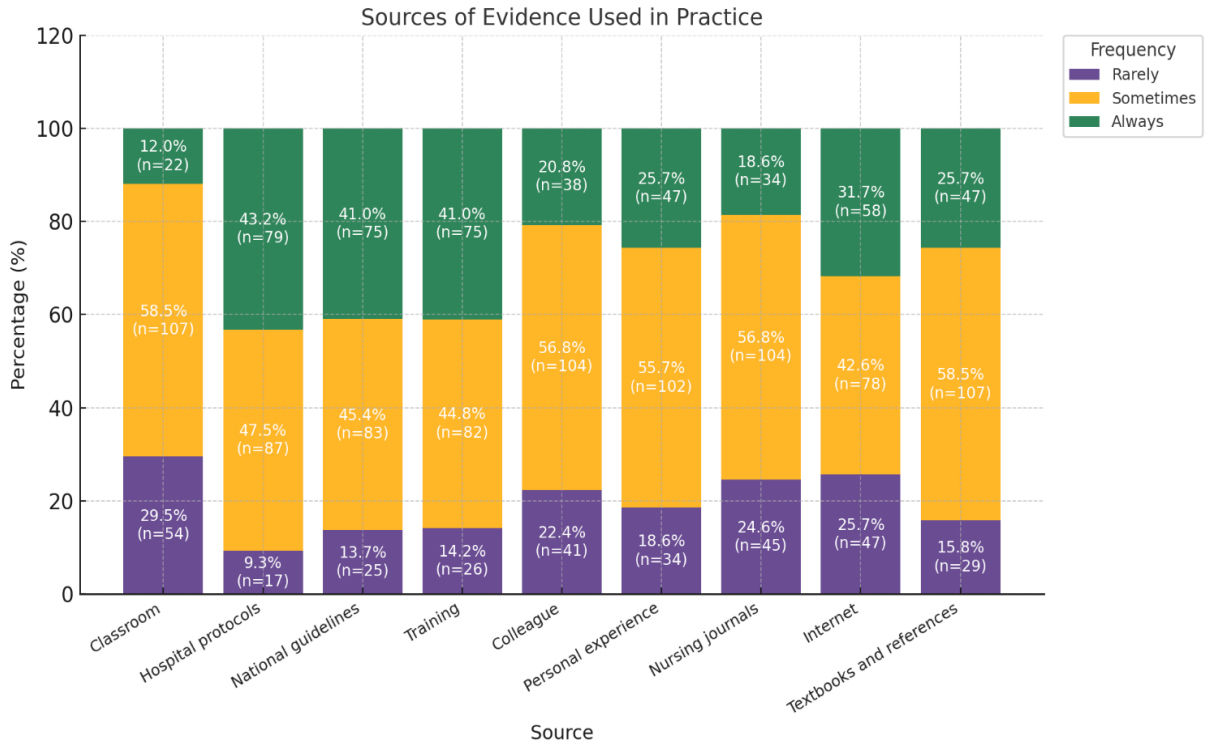


Figure 2: Sources Utilized by Nurses for Evidence and Practice-Related Information

As shown in Figure 2, nurses reported varying frequencies of use across different sources of evidence in clinical practice. The most frequently used sources ("always") were hospital protocols (43.2%), national guidelines (41.0%), and training (41.0%), indicating strong reliance on institutional and formal guidance. In contrast, classroom learning was least frequently used as a primary source, with only 12.0% reporting "always" use, while the majority reported using it "sometimes" (58.5%). Informal sources such as colleagues (20.8%) and personal experience (25.7%) were moderately utilized, whereas nursing journals (18.6%) and the internet (31.7%) showed variable but notable usage. Textbooks and references were used consistently, with 25.7% reporting "always" use and the majority (58.5%) using them "sometimes."

Table 3: Level of Engagement in Evidence-Based Practice Activities Among participants

Activity	Never		Sometimes		Usually		Often	
	N	%	N	%	N	%	N	%
Asked clinical questions related to your nursing care practice	46	25.1%	99	54.1%	8	4.4%	30	16.4%
Looked for information, research, or evidence to support your nursing practice	47	25.7%	90	49.2%	21	11.5%	25	13.7%
Evaluated the outcome of using current evidence (First entry)	37	20.2%	111	60.7%	13	7.1%	22	12.0%
Used/integrated current evidence/guidelines to guide nursing care	45	24.6%	105	57.4%	21	11.5%	12	6.6%
Evaluated the outcome of using current evidence (Repeated entry – use this one instead)	33	18.0%	108	59.0%	25	13.7%	17	9.3%
Shared or taught others about new practices (e.g., current guidelines)	26	14.2%	102	55.7%	22	12.0%	33	18.0%

As shown in Table 3, participants demonstrated generally low-to-moderate engagement in evidence-based practice (EBP) activities. The majority reported "sometimes" engaging in most activities, including asking clinical questions (54.1%, n = 99), searching for evidence (49.2%, n = 90), evaluating outcomes of evidence use (59.0%, n = 108), and integrating current evidence into practice (57.4%, n = 105). A considerable proportion also reported never performing key EBP activities, such as searching for evidence (25.7%, n = 47) and integrating evidence into care (24.6%, n = 45). Only a small percentage of participants reported frequent engagement, with 16.4% (n = 30) often asking clinical questions, 13.7% (n = 25) often searching for evidence, and 18.0% (n = 33) often sharing or teaching new practices.

Table 4: Barriers to Evidence-Based Practice (EBP) among participants

Barrier	Rarely		Sometimes		Always	
	N	%	N	%	N	%
Lack of autonomy to change practice	37	20.2%	110	60.1%	36	19.7%
Inadequate understanding of research terms	32	17.5%	127	69.4%	24	13.1%
Inability to understand statistical terms used in research	40	21.9%	117	63.9%	26	14.2%

Barrier	Rarely		Sometimes		Always	
	N	%	N	%	N	%
Difficulty in judging the quality of research	49	26.8%	126	68.9%	8	4.4%
Inability to properly interpret the results of research	45	24.6%	130	71.0%	8	4.4%
Insufficient time at the workplace to implement EBP	41	22.4%	108	59.0%	34	18.6%
Insufficient resources (e.g., equip-(ment, internet	42	23.0%	116	63.4%	25	13.7%
Lack of authority in the workplace to implement EBP	45	24.6%	117	63.9%	21	11.5%
Insufficient proficiency in the English language	58	31.7%	112	61.2%	13	7.1%
The nurse is isolated from ex-perienced colleagues to discuss research	75	41.0%	96	52.5%	12	6.6%
Physicians are not cooperative with EBP implementation	41	22.4%	114	62.3%	28	15.3%
Unclear implications of EBP for practice in nursing	33	18.0%	125	68.3%	25	13.7%
The culture of my team is not receptive to EBP implementation	55	30.1%	112	61.2%	16	8.7%
Uncertainty to believe the results of the research are relevant to nurses' practice	55	30.1%	108	59.0%	20	10.9%

Table 4 demonstrates that most barriers to evidence-based practice (EBP) implementation were reported as occurring "sometimes." The most frequent individual barriers were difficulty interpreting research results (71.0%), inadequate understanding of research terms (69.4%), and difficulty judging research quality (68.9%). Key organizational barriers included lack of authority to implement EBP (63.9%), insufficient resources (63.4%), lack of autonomy (60.1%), and insufficient time (59.0%). Additionally, over 62.3 % cited noncooperative physicians, unsupportive team culture, and language barriers. A smaller proportion reported experiencing these barriers "always," notably lack of autonomy (19.7%) and insufficient time (18.6%).

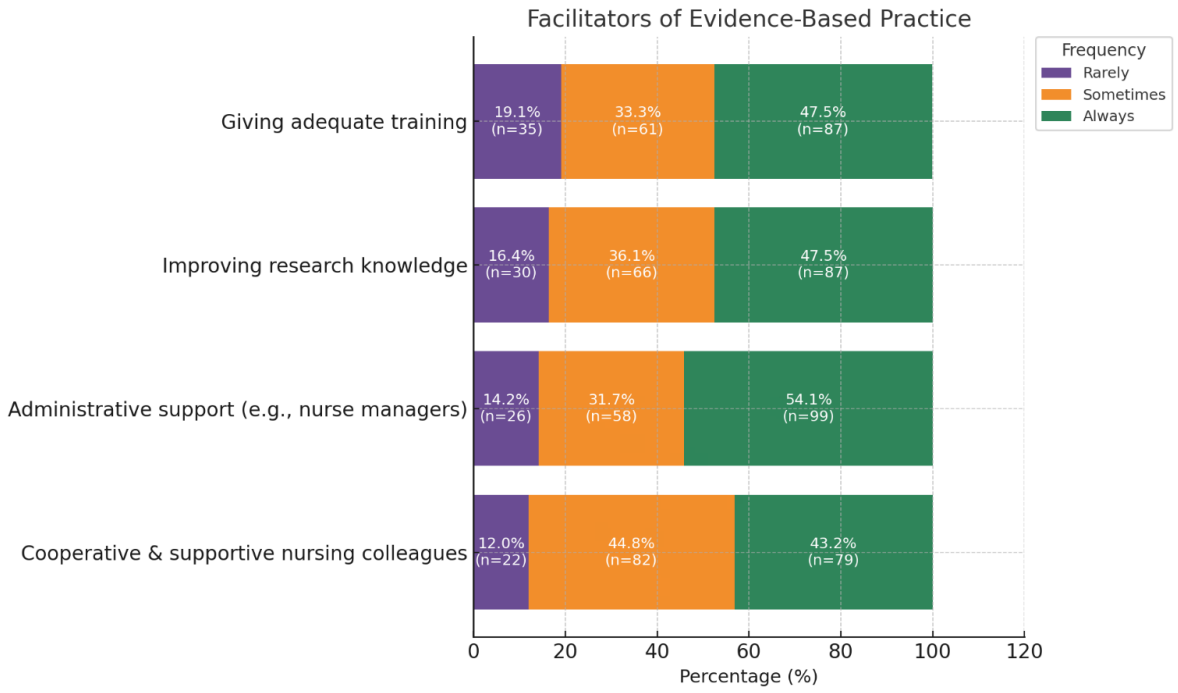


Figure 3: Factors that Facilitate the Implementation of Evidence-Based Practice (EBP)

As shown in Figure 3, several factors were identified as key facilitators of evidence-based practice (EBP) implementation among nurses. Administrative support from nurse managers was the most frequently reported facilitator, with more than half of participants indicating that it "always" supports EBP implementation (54.1%, n = 99). Similarly, both providing adequate training and improving research knowledge were highly endorsed, with 47.5% (n = 87) of participants reporting that these factors "always" facilitate EBP. Additionally, cooperative and supportive nursing colleagues were recognized as important, with 43.2% (n = 79) reporting consistent support. Across all facilitators, a substantial proportion of participants also reported "sometimes" support, highlighting variability in the availability of enabling conditions

Table 5: Distribution of Overall Knowledge about Evidence-Based Practice Among Participants

EBP utilization	Frequency	Percent
Poor	22	12.0
Good	161	88.0
Total	183	100.0

As shown in Table 5, most participants demonstrated good knowledge of evidence-based practice (EBP), with 88.0% (n = 161) classified as having good knowledge, while only 12.0% (n = 22) had poor knowledge. This indicates a high overall level of awareness and understanding of EBP among the study participants.

Table 6: Overall Evidence-Based Practice Utilization Among Participants

Category	Frequency (n)	Percent (%)
Poor	152	83.1
Good	31	16.9
Total	183	100.0

As shown in Table 6, most participants demonstrated poor utilization of evidence-based practice (EBP), with 83.1% (n = 152) classified as having poor utilization, while only 16.9% (n = 31) demonstrated good utilization.

Table 7: Association Between Knowledge and Overall Evidence-Based Practice Utilization

Knowledge Level	Poor Utilization	Good Utilization	P-value	Cramér's V
Poor	22 (100.0%)	0 (0.0%)	0.029*†	0.167
Good	130 (80.7%)	31 (19.3%)		

*** Statistically significant at p < 0.05**
† Fisher's Exact Test was used

As shown in Table 7, there was a statistically significant association between knowledge level and EBP utilization (p = 0.029), with participants with good knowledge demonstrating higher utilization than those with poor knowledge. However, the effect size indicated a weak association (Cramér's V = 0.167), suggesting that although knowledge is statistically related to EBP utilization, its practical influence on actual implementation is limited.

Table 8: Association of Demographic and Professional Characteristics with Knowledge Level

Variables	Category	Overall, Knowledge Level		P. value	Cramér's V
		Poor	Good		
Age group	20–24 years	4 (8.7%)	42 (91.3%)	0.001*	0.329
	25–30 years	0 (0.0%)	29 (100.0%)		
	31–35 years	4 (6.9%)	54 (93.1%)		
	36–40 years	9 (24.3%)	28 (75.7%)		
	>40 years	5 (38.5%)	8 (61.5%)		
Gender	Male	0 (0.0%)	8 (100.0%)	0.599†	0.079
	Female	22 (12.6%)	153 (87.4%)		
Work unit	ER	8 (21.6%)	29 (78.4%)	0.103	0.158
	ICU	0 (0.0%)	9 (100.0%)		
	Labor room	0 (0.0%)	12 (100.0%)		
	Maternity ward	1 (20.0%)	4 (80.0%)		
	OPD	0 (0.0%)	8 (100.0%)		
	Others	13 (11.6%)	99 (88.4%)		
Marital status	Single	4 (5.6%)	67 (94.4%)	0.186	0.203
	Married	17 (15.9%)	90 (84.1%)		
	Divorced	1 (20.0%)	4 (80.0%)		
Work experience	1–4 years	4 (5.3%)	71 (94.7%)	0.088	0.189
	5–8 years	1 (7.7%)	12 (92.3%)		
	9–12 years	4 (19.0%)	17 (81.0%)		
	> 12 years	13 (17.6%)	61 (82.4%)		
Educational level	BSc	13 (14.1%)	79 (85.9%)	0.323	0.138
	Diploma	8 (14.3%)	48 (85.7%)		
	MSc	1 (3.3%)	29 (96.7%)		
	PhD	0 (0.0%)	5 (100.0%)		
Current role	Midwife	0 (0.0%)	12 (100.0%)	0.294	0.116
	Staff nurse	13 (11.4%)	101 (88.6%)		
	Managerial nurse	9 (15.8%)	48 (84.2%)		

*** Statistically significant at p < 0.05**
† Fisher's Exact Test was used

Table 8 shows a statistically significant association between age group and knowledge level (p = 0.001, Cramer's V = 0.329), indicating a moderate association, which suggests a meaningful but not strong relationship between the variables

in practical terms. The highest level of knowledge was observed in the 25–30 age group (100%), while the lowest was among participants aged over 40 years (61.5%). In contrast, no statistically significant associations were found between knowledge level and gender, work unit, marital status, years of experience, educational level, or current role, and all showed weak effect sizes, indicating negligible or limited practical relationships.

Table 9: Association of Demographic and Professional Characteristics with Overall Evidence-Based Practice Utilization

	Category	Overall Evidence-Based Practice Utilization		P. value	Cramér's V
		Poor	Good		
Age (years)	20–24	41 (89.1%)	5 (10.9%)	0.225	0.176
	25–30	24 (82.8%)	5 (17.2%)		
	31–35	45 (77.6%)	13 (22.4%)		
	36–40	29 (78.4%)	8 (21.6%)		
	>40	13 (100.0%)	0 (0.0%)		
Gender	Male	8 (100.0%)	0 (0.0%)	0.355†	0.097
	Female	144 (82.3%)	31 (17.7%)		
Marital status	Single	61 (85.9%)	10 (14.1%)	0.372	0.104
	Married	86 (80.4%)	21 (19.6%)		
	Divorced	5 (100.0%)	0 (0.0%)		
Work unit	ER	28 (75.7%)	9 (24.3%)	<0.001*	0.538
	ICU	0 (0.0%)	9 (100.0%)		
	Labor room	12 (100.0%)	0 (0.0%)		
	Maternity ward	5 (100.0%)	0 (0.0%)		
	OPD	8 (100.0%)	0 (0.0%)		
	Others	99 (88.4%)	13 (11.6%)		
Work experience	1–4 years	65 (86.7%)	10 (13.3%)	0.467	0.118
	5–8 years	9 (69.2%)	4 (30.8%)		
	9–12 years	17 (81.0%)	4 (19.0%)		
	>12 years	61 (82.4%)	13 (17.6%)		
Educational level	BSc	82 (89.1%)	10 (10.9%)	<0.001*	0.434
	Diploma	52 (92.9%)	4 (7.1%)		
	MSc	14 (46.7%)	16 (53.3%)		
	PhD	4 (80.0%)	1 (20.0%)		
Current role	Midwife	8 (66.7%)	4 (33.3%)	0.126	0.150
	Staff nurse	99 (86.8%)	15 (13.2%)		
	Managerial nurse	45 (78.9%)	12 (21.1%)		

*** Statistically significant at p < 0.05**
Fisher's Exact Test was used

As shown in Table 9, statistically significant associations were observed between work unit and overall evidence-based practice (EBP) utilization ($p < 0.001$, Cramér's $V = 0.538$), indicating a large effect size, which reflects a strong and practically meaningful relationship between workplace setting and EBP utilization. Similarly, a statistically significant association was found between educational level and EBP utilization ($p < 0.001$, Cramér's $V = 0.434$), indicating a moderate effect size, suggesting a clear but not strong practical relationship between higher education and improved EBP utilization.

Participants working in the ICU demonstrated the highest level of good utilization (100.0%), whereas those in labor rooms, maternity wards, and outpatient departments exhibited entirely poor utilization (100.0%). Regarding educational level, participants with a master's degree showed the highest proportion of good utilization (53.3%), while those with bachelor's and diploma qualifications demonstrated predominantly poor utilization.

No statistically significant associations were found between EBP utilization and age ($p = 0.225$, Cramér's $V = 0.176$), gender ($p = 0.355$, Cramér's $V = 0.097$), marital status ($p = 0.372$, Cramér's $V = 0.104$), work experience ($p = 0.467$, Cramér's $V = 0.118$), or current role ($p = 0.126$, Cramér's $V = 0.150$), with all showing weak effect sizes, indicating minimal or negligible practical relationships.

4. Discussion:

This study aimed to assess the utilization and predictors of evidence-based practice among nurses and midwives working at the maternity and children's hospital in Al-Jouf, Saudi Arabia

4.1 Knowledge Level regarding (EBP)

The findings indicate that most participants had good knowledge and positive perceptions of evidence-based practice (EBP), which aligns with the EBP theoretical framework emphasizing the integration of research evidence, clinical expertise, and theory to improve the quality of care (Dabak et al., 2024; Melnyk & Fineout-Overholt, 2022). Although awareness of EBP was high, less than half of the participants reported receiving formal EBP training, reflecting a gap between knowledge and educational preparation that has been similarly reported in previous studies (Ominyi et al., 2025). Most nurses recognized EBP as a problem-solving approach that enhances care quality, consistent with earlier research linking EBP to improved clinical decision-making and patient outcomes (Halili et al., 2024). Additionally, the understanding that EBP is important for both educators and clinical nurses reinforces the need for collaborative academic–clinical models, which are crucial for successful EBP implementation. These results underscore the need for ongoing educational initiatives, the incorporation of EBP throughout the nursing curriculum, and the creation of supportive clinical environments that promote research literacy and critical appraisal skills to strengthen evidence-based decision-making in practice.

4.2 Sources Utilized by Nurses for Evidence and Practice-Related Information

The findings indicate that nurses primarily relied on institutional resources such as hospital protocols, national guidelines, and training programs. Within the diffusion of innovation theory of the Evidence-Based Practice model, this pattern reflects the strong influence of the practice environment and organizational readiness on evidence utilization, particularly when evidence is translated into accessible tools such as protocols and guidelines. (Dang et al., 2021). International studies similarly report that leadership support, educational preparation, and clinical experience facilitate nurses' engagement with evidence-based resources, whereas time constraints and limited research skills hinder direct research use. (Ominyi et al., 2025) .

Within the Saudi Vision 2030 context, the frequent use of standardized guidelines and institutional resources aligns with national healthcare transformation goals aimed at improving care quality and workforce competency, though continued emphasis on leadership empowerment and research literacy remains essential.(Althuwaybi et al., 2025) .

4.3 Engagement in Evidence-Based Practice Activities

The results revealed low to moderate levels of engagement in EBP-related activities among the participants; the "sometimes" category was most frequently selected, suggesting that EBP is practiced intermittently rather than routinely. These findings imply that although nurses recognize the importance of EBP, it is not yet embedded in everyday clinical decision-making.

This pattern aligns with previous research reporting that nurses often engage with EBP irregularly due to factors such as time constraints, lack of confidence in research skills, and insufficient institutional support. (Alqahtani et al., 2022) . These findings emphasize the need for strategies to enhance the frequency and quality of EBP engagement among clinical nurses.

4.4 Barriers to Evidence-Based Practice

The findings indicate that nurses face multiple barriers to evidence-based practice (EBP), with the most prominent related to research knowledge, including difficulty interpreting results (71.0%), judging research quality (68.9%), and understanding research terminology (69.4%). Organizational constraints, such as lack of authority (63.9%), insufficient resources (63.4%), limited physician cooperation (62.3%), an62.3d time pressures were also frequently reported. These barriers align with the Johns Hopkins EBP Model, where deficits in evidence appraisal and contextual support hinder the translation of research into practice. (Alqahtani et al., 2022; Alruwaili et al., 2025; Mortada, 2024). Social, cultural, and language challenges further limit nurses' confidence and engagement in EBP, consistent with international studies highlighting the impact of leadership, mentorship, and organizational culture on EBP adoption. (Connor et al., 2023). Addressing these barriers through targeted training, leadership empowerment, protected time, and resource provision is essential to strengthening EBP

implementation and aligning nursing practice with the quality-driven goals of Saudi Vision 2030. Althuwaybi et al., 2025

4.5 Facilitators of Evidence-Based Practice

Several facilitators were identified that could strengthen EBP implementation. The most significant enablers were interpersonal and organizational support. Cooperative and supportive colleagues were perceived as highly influential, with 43.2% of nurses indicating that their colleagues were always supportive and 44.8% indicating that they were sometimes supportive. Similarly, 54.1% of the respondents reported consistent administrative support from nurse managers. These findings suggest that teamwork, mentorship, and leadership commitment are vital for cultivating an evidence-based culture in healthcare.

Moreover, improving research knowledge and providing adequate training were recognized as key facilitators, each reported as "always helpful" by 47.5% of the participants. This emphasizes the importance of continuous professional development, workshops, and mentorship programs that equip nurses with the skills to evaluate and apply evidence. Previous studies have similarly confirmed that structured EBP education and leadership involvement significantly enhance EBP competencies and patient care outcomes. (Dabak et al., 2024). Collectively, these findings underscore the need to foster a supportive clinical environment that values collaboration, managerial engagement, and continuous learning as critical factors for advancing EBP.

4.6 Factors Associated with Good Utilization of Evidence-Based Practice

A statistically significant association was found between knowledge level and EBP utilization ($p = 0.029$), indicating that participants with good knowledge were more likely to implement evidence-based practice than those with poor knowledge. Knowledge is a key factor that enables healthcare professionals to understand, evaluate, and apply research evidence in clinical decision-making. Previous studies similarly report that higher EBP knowledge is associated with greater use of evidence in practice (Dabak et al., 2024). Also, the findings indicate that organizational and social factors strongly facilitate evidence-based practice (EBP) among nurses, with supportive colleagues, administrative backing, targeted training, and improved research knowledge being key enablers (Alqahtani et al., 2022). When considered alongside the findings on knowledge, the results suggest that both individual knowledge and organizational factors influence EBP utilization. Although age was the only demographic factor significantly associated with knowledge level, with younger nurses (25–35 years) demonstrating higher levels of good knowledge, age itself was not significantly associated with EBP utilization. This indicates that while younger nurses may possess stronger theoretical knowledge of EBP, it is likely due to more recent education that integrates research appraisal, clinical inquiry, and EBP principles; they may not necessarily translate this knowledge into practice without supportive clinical environments (Reynolds et al., 2026). Younger nurses' greater familiarity with digital tools and online databases may enhance access to evidence, while older nurses may rely more on traditional practices and experiential knowledge, which can limit engagement with contemporary research (Bissett et al., 2025; Halili et al., 2024).

In contrast, the present results showed that work unit and educational level were the strongest factors associated with EBP utilization. Nurses working in high-acuity settings such as the ICU demonstrated the highest level of EBP utilization, likely due to greater reliance on protocols, multidisciplinary collaboration, and continuous monitoring. Similarly, nurses with higher educational qualifications, particularly those with master's degrees, demonstrated greater utilization, highlighting the role of advanced education in strengthening research literacy and evidence-based decision-making.

Together, these findings suggest that although younger nurses may possess better EBP knowledge, the actual application of EBP is more strongly influenced by organizational context and educational preparation rather than demographic characteristics alone. The lack of significant associations between utilization and variables such as gender, marital status, work experience, or role further supports the idea that system-level support, mentorship, and institutional facilitation are key drivers of EBP implementation. (Connor et al., 2023). Therefore, targeted professional development programs especially for older nurses and organizational strategies that foster a culture of evidence-based care are essential to bridge knowledge gaps and promote consistent EBP utilization across all clinical settings.

5. Conclusion:

This study shows that although nurses and midwives have positive attitudes and high knowledge about evidence-based practice, its everyday application is still restricted. The use of EBP is greatly aided by organizational and social factors, especially access to training, collegial collaboration, and leadership support. In line with the objectives of Saudi Vision 2030's healthcare reform, our findings emphasize the significance of bolstering institutional regulations, empowering leaders, and launching training and educational programs to incorporate EBP into routine practice. Future studies should use interventional and longitudinal designs in a variety of contexts to assess strategies that support long-term EBP implementation and raise the quality of care.

6. Recommendations

Healthcare institutions should provide continuous educational and training programs to improve evidence-based practice (EBP) knowledge and utilization among nurses and midwives, particularly in departments with lower utilization levels. Access to evidence-based resources and mentorship programs should also be strengthened to support EBP implementation in clinical settings.

6.1 Implications for Nursing Practice and Research

The findings highlight the importance of promoting EBP competencies among nurses and midwives to enhance the quality of patient care and clinical decision-making. The study also emphasizes the need for organizational support and educational advancement to improve EBP utilization. Future research should include larger and more diverse samples from multiple healthcare settings across Saudi Arabia to improve the generalizability of findings and further explore barriers to EBP implementation.

6.2 Limitations:

The study has several limitations that should be considered when interpreting the findings. Data were collected using self-administered online questionnaires, which may have introduced response and social desirability bias, as participants may have overestimated their knowledge or utilization of evidence-based practice (EBP). In addition, the use of nonprobability sampling may have increased the likelihood that more motivated staff members participated in the study, which limits generalizability. Also, the study was conducted in a single hospital and included only a small number of male staff members, which limits the generalizability of the findings to other healthcare settings, professional groups, or regions in Saudi Arabia. The cross-sectional design captured participants' perceptions at a single point in time and therefore could not assess changes or long-term effects related to EBP utilization. Additionally, the relatively small number of midwives (n = 12) limited the statistical power for comparisons between nurses and midwives and restricted the applicability of subgroup-specific conclusions. The combination of Likert-scale responses (e.g., agree/strongly agree and disagree/strongly disagree) may have resulted in a loss of detail and reduced the ability to capture nuanced differences in participants' responses. Future studies should adopt longitudinal approaches and include larger, more diverse, and balanced samples to validate and broaden these findings across different professional groups and settings.

1. Declaration of Conflicting Interest:

- No conflict of interest to declare in this study.

2. Funding:

- None.

3. List of Abbreviations:

- EBP = Evidence-Based Practice
- SA = Saudi Arabia
- ICU = Intensive Care Unit

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Strategies for Reconstructing Historic Buildings in Saudi Arabia: Balancing Authenticity, Sustainability, and Community Identity

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Abstract
This research addresses the relationship between communities' need to restore damaged historic structures and the limits imposed by international heritage conservation charters, especially the Venice Charter (1964)2 and the Nara Document on Authenticity (1994). 3,4 The study is based on a descriptive-analytical comparative technique, relying on specialist academic literature and examining three Saudi case studies (Diriyah, Historic Jeddah, and AlUla) in comparison to three overseas models.
The research revealed that the tension between international charters and communities' desire to reestablish their visual identity is structurally anchored, but partially bridged by the recognition of genuine plurality in the Nara Document. 3,4 The introduction of advanced digital technology, such as Historic Building Information Modelling (HBIM) and Digital Twins, has changed reconstruction decisions from subjective evaluations to data-driven choices. 10,11 The findings indicate that the major heritage projects in Saudi Arabia represent an emerging regional model, informed by the King Salman Charter for Architecture and Urbanism (2026). 20 Main recommendations are the need for specialized national historic construction rules, the need for community involvement and adoption of sustainable productive heritage model.

Keywords: Heritage Reconstruction - Architectural Authenticity - HBIM - Saudi Urban Heritage - Vancouver Citation Style.

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1. Introduction

Architectural heritage is a fundamental expression of human civilization - a repository of collective memory and a record of past modes of living, thought, and aesthetics. This heritage is today under unprecedented threat from natural disasters, armed conflict, and the pressures of urban expansion. Within the broader debate on intervention in heritage, the reconstruction of historic buildings is the most contested form of intervention. It raises fundamental questions about the possibility of recovering what has been lost, the nature of authenticity, and the boundary between genuine preservation and falsification. These questions have shaped international frameworks such as the Venice Charter (1964) and the Nara Document on Authenticity (1994), which represent the two principal poles of contemporary conservation practice. In the Saudi context, the diversity of urban heritage, together with Vision 2030 and the King Salman Charter for Architecture and Urbanism (2026), has driven a marked rise in heritage projects. Against this background, this study examines the strategies applied in the reconstruction of historic buildings and seeks to identify a balance between respecting the past and preparing for the future.

2. Research Problem

Historic buildings play a profound role in shaping the cultural identity of communities and reinforcing their sense of civilizational belonging. Their reconstruction after destruction or deterioration, however, creates a deep tension between two conflicting demands that are difficult to reconcile. On one hand, there is a growing social and national demand to restore the visual symbolism of demolished buildings. On the other hand, international charters for architectural conservation place strict limits on this direction. The Venice Charter (1964) states that restoration must cease where conjecture begins, and that reconstructing the missing parts of ancient buildings may compromise historical authenticity rather than preserve it. Under UNESCO guidelines and recommendations, any materials used in an intervention must be visually distinguishable from the original and must be reversible. This requirement effectively contradicts the notion of 'exact reconstruction' often sought by public will and political decision-making.

2.1 Core Research Question

How can a comprehensive strategy for the reconstruction of historic structures reconcile society's expectations for restoring visual symbolism and national identity with the conservation constraints imposed by international conservation charters? Sub-questions:

- What are the internationally recognized categories (levels) of architectural intervention, and what conceptual criteria distinguish each?
- How have contemporary digital technologies (HBIM, Digital Twins, etc.) helped to bridge the gap between authenticity demands and accurate reconstruction?
- How does the Saudi approach to heritage reconstruction under the King Salman Charter for Architecture and Urbanism differ from, or intersect with, established international practice?

3. Research Objectives

The main purposes of this study are:

- To examine the philosophical foundations and historical evolution of reconstruction concepts.
- To define the methodological controls governing the levels of architectural intervention in accordance with international norms.
- To assess the effectiveness of advanced digital technologies (HBIM, Digital Twins, laser scanning and AI) in balancing authenticity requirements and accurate reconstruction.
- To analyse the Saudi strategy for the reconstruction of national heritage assets under the King Salman Charter (2026).

4. Research Gap

The research gap addressed by this study lies in the absence of a systematic academic examination of historic-building reconstruction in the Arab-Saudi context. While the philosophical basis of authenticity has been examined in relation to international charters (Venice 1964, Nara 1994), and while individual Saudi projects (Diriyah, Historic Jeddah, AlUla) have been documented separately, no prior study has integrated these two strands. Specifically, the literature lacks an analysis that links the conceptual framework of authenticity to the applied Saudi experience under the King Salman Charter for Architecture and Urbanism (2026), and that evaluates the role of modern digital technologies in reconciling authenticity, sustainability, and community participation within a coherent regional model.

5. Research Significance

The significance of this research can be summed up in its contributions, both at the academic and applied levels, as follows:

- Clarifying the tension between the social need for reconstruction and the limits set by international charters, and offering a framework for navigating it.
- Comparing successive international charters to provide a theoretical basis for the concept of authenticity across diverse cultural contexts.
- Documenting and assessing the Saudi experience in the reconstruction of architectural heritage. - Demonstrating the contribution of

digital technologies - including HBIM, Digital Twins, and laser scanning - to the accuracy and objectivity of historic reconstruction projects.

- Enabling local communities to actively participate in the safeguarding of their heritage.

6. Methodology

This research adopted a descriptive-analytical comparative methodology. This design was selected because the research question requires both an interpretive reading of conceptual frameworks - the philosophy of authenticity in international charters - and a structured comparison of applied cases across different contexts. A descriptive-analytical comparative approach is well suited to this dual aim, as it allows theoretical principles to be tested against documented practice. The methodology was structured into three main phases:

1. **Phase I:** Theoretical Framework: Included a survey of specialist academic literature in the field of architectural heritage conservation and reconstruction, with reference to international charters on heritage work.
2. **Phase II:** Data Collection: The research involved the use of several secondary sources, such as academic peer-reviewed studies published between 2013 and 2025, official reports by international bodies including UNESCO and ICCROM, and institutional reports by bodies that oversee Saudi heritage initiatives.
3. **Phase III:** Case Study Selection Criteria: Three Saudi projects (Diriyah, Historic Jeddah, AlUla) were selected based on specific criteria: diversity in architectural intervention style, variation in environmental and historical context, availability of published scientific documentation, and the linkage of each to a different phase of heritage development in the Kingdom. Three international comparisons (Warsaw, Dresden, Mostar) were also used to shed light on reconstruction models with diverse cultural-symbolic motivations. The selected cases were then analysed using a comparative analytical matrix built around consistent authenticity indicators (material, formal, functional, and symbolic authenticity) and the recognised levels of architectural intervention. This matrix enabled a thematic comparison across all six cases, so that each experience could be assessed against the same conceptual criteria rather than described in isolation.

7. Historic Building Reconstruction: Conceptual Overview

The reconstruction of destroyed historic buildings is among the most complex challenges in contemporary architectural conservation. It is not limited to the retrieval of physical fabric, but also involves the recovery of collective memory and the fulfilment of environmental and technical sustainability standards. Intervention in the historic fabric therefore requires a methodology - at once philosophical and technological - centred on the equilibrium between "material authenticity" and "authenticity of meaning". This conceptual tension, which runs through both the Venice Charter (1964) and the Nara Document on Authenticity (1994), has developed over decades of international charters and field practice. Reconstruction thus becomes necessary chiefly where natural disasters, armed conflict, or rapid urban change have damaged a community's visual identity. [7]

8. Philosophical Frameworks and the Historical Evolution of Reconstruction Concepts

8.1 Introduction

The reconstruction of historic buildings reflects two centuries of intellectual debate over the nature of heritage, the meaning of authenticity, and the limits of architectural intervention in the past. This debate has developed through successive historical stages, each responding to and revising the assumptions of its predecessor, leading to the contemporary normative framework [5]

8.2 Origins: From Romantic Restoration to Scientific Critique (Nineteenth Century)

The earliest origins of systematic thought on architectural heritage are to be found in the 19th century, when a romantic revival swept across Europe, restoring prestige to medieval architecture, Gothic churches and historic castles as emblems of developing national identity. Two schools of thought arose that set up the argument that is still alive today.[6]

8.2.1 The school of stylistic restoration - Viollet-le-Duc

The French architect Eugène Viollet-le-Duc led what might be called the bold interventionist school, believing that reconstruction does not mean returning the building to a condition documented in a historical document but restoring it to 'a complete state that may never have existed at any moment of its existence.' On this approach he repaired and rebuilt dozens of French buildings – including the fortress of Carcassonne and Notre-Dame Cathedral, Paris – adding elements that did not previously exist but that he considered as compatible with the 'stylistic spirit' of the building.[5]

8.2.2 The Anti-Restoration School – John Ruskin

The opposing position was held by the British critic John Ruskin, who strongly objected to what he regarded as 'destruction masquerading as restoration'. In Ruskin's view, a historic building derived its value from the reality of its own time rather than from an imagined ideal state; ageing, erosion, and the marks left by time were not defects

to be concealed, but part of the building's authenticity and evidence of its history. He described restoration as a particularly damaging form of intervention, and established a line of thinking that continues to influence heritage practice today.

8.3 International Normative Building: From Athens to Venice (1931–1964)

8.3.1 The Athens Charter, 1931

The first systematic worldwide statement containing standards for the treatment of architectural heritage was the result of the worldwide Conference of Architects and Technicians for Historic Monuments, held in Athens in 1931.8 The Athens Charter set out a series of principles which would become the pillars of global heritage practice: the need to conserve on an ongoing basis rather than intervene intermittently; that modern techniques can be used to support historic structures as long as they are hidden; the emphasis on the value of the urban environment surrounding the building as part of the heritage system. The Athens Charter, despite its obvious limits today, was an important historical precedent in establishing the notion that architectural conservation is an international affair outside the borders of national sovereignty.[6,8]

8.3.2 The Venice Charter, 1964 – The Great Foundation

The Venice Charter of 1964 was a significant breakthrough in the history of international architectural conservation, setting out principles that still form the backbone of contemporary preservation practice six decades after its promulgation.[2] The Charter was based on the premise that historic structures convey cultural meaning from the past and serve as evidence of long-standing traditions, and that their preservation and restoration constitute a shared responsibility.[5] On the question of reconstruction in particular, the Charter laid down a firm barrier that should not be crossed, saying that "the process of restoration must stop where conjecture begins", and that any addition made to a historic building must carry the imprint of its own time to be distinguishable from the original, and must be removable so as to leave room for future generations to make their own choices. The Charter also confirmed the legitimacy of the Reassembly of original scattered elements provided original materials and sufficient documentation exist, but every new addition must be marked with a distinctive sign.[2]

8.4 The Crisis of European Centrism and the Plurality of Concepts of Authenticity (1970–1994)

As UNESCO membership grew and Asian, African, and Latin American countries joined the international heritage system, concerns were increasingly raised about the universality of the values anchored in the Venice Charter. The principal point of conflict was the Western concept of authenticity based on 'material authenticity', which in practice marginalised numerous non-European architectural traditions, excluding many from World Heritage Lists or placing them at a disadvantage. These concerns directly prepared the ground for the later Nara Document on Authenticity (1994), which sought to broaden the concept of authenticity beyond its material dimension.[4] Take traditional Japanese architecture, for example. It is based on the principle of rebuilding temples every twenty years using the same materials and techniques-as in the famous Ise Shrine, which has been rebuilt more than sixty times in thirteen centuries. This is not seen as a violation of its authenticity, but rather as an embodiment of "artisanal authenticity" based on the continuity of craft and knowledge rather than the continuity of material. In many African and Islamic civilizations, for example, the social and spiritual function of the building is more important than the literalness of its building elements.[9]

8.5 The Nara Document on Authenticity (1994) – A Conceptual Shift

This growing criticism was directly addressed by the Nara Conference, held in Japan in 1994, which produced a text now regarded as a reference no less significant than the Venice Charter itself. The Nara Document was founded on the principle that 'the assessment of authenticity cannot be based on fixed criteria, but must take into account the cultural context in which the heritage was produced'.[3,4] With this admission, the document opened wide doors to reconsider the idea of authenticity, and to extend the range of its sources to:

- Authenticity of form and design: the visual and aesthetic extension of the building in accordance with its original design logic.
- Authenticity of material and substance: the basis of the Venice Charter and the foundation of the Western concept. - Authenticity of usage and function: the continued execution of a building's social or spiritual mission.
- Authenticity of traditions and techniques: Continuity of craft skills in inherited building processes.
- Authenticity of setting and surroundings: the relationship of the building to its geographical and natural setting.
- Authenticity of spirit and feeling – the intangible dimension, which received limited recognition in earlier material-based approaches, but which carries considerable weight in many non-Western contexts.

The development of the concept of authenticity has been an impetus to the legitimization of reconstruction models previously considered contrary to international conservation principles, and thus the possibility of

recognizing, for example, the reconstruction of the Old City of Warsaw in faithful replication of the original as an exceptional legitimate model rather than a departure from sound methodology.

8.6 Maturity Phase: Digital Documentation and Sustainable Heritage (2000-Present)

At the turn of the third millennium, architectural conservation entered a new era in which three key shifts overlapped, redefining the rules of involvement with heritage:

1. The Digital Revolution and Precision Documentation Technologies: Technologies of laser scanning, drone aerial photography, and Historic Building Information Modelling (HBIM) afforded documentation at a degree of precision inconceivable at the time the Venice Charter was formulated.10 It became possible to digitally capture every millimeter of a historic building and then model several scenarios of renovation and assess their impact before actual execution. Artificial intelligence has introduced a new level to these capabilities by identifying patterns of structural deterioration and suggesting most appropriate materials for restoration based on big datasets.[11]
2. The Heritage Crisis in Times of Armed Conflict The heritage question had an exceptional urgency, in the events at the turn of the millennium, from the destruction of the Mostar Bridge in Bosnia in 1993, to the blowing up of the Bamiyan Buddhas in Afghanistan in 2001, to the enormous destruction that struck archaeological sites in Syria and Iraq. In all these circumstances, the argument increased over the right to rebuild and controls over it, putting practical pressure on the international normative system of providing more flexible and unambiguous responses than existing documents allow.
3. Environmental Sustainability as a New Heritage Dimension: The growing concern for climate change and energy efficiency has given rise to a new philosophical dimension that was not taken into account by the framers of twentieth-century charters. Another reason to reconstruct heritage is the environmental sustainability argument. Research has demonstrated that the process of restoring and modernizing a historic building consumes far less energy than demolishing it and rebuilding it from scratch, thus making heritage conservation an environmentally responsible choice before it is a cultural one.[17,18]

8.7 The Contemporary Philosophical Framework: Between Two Poles

The philosophical framework in which contemporary reconstruction strategies operate may be described as a continual tension between two intellectual tendencies that do not negate one another. These are best understood as broad orientations rather than rigid, mutually exclusive schools: The First Pole – the Philosophy of 'Material Authenticity': embodied in the Western school of Ruskin and formalised in the Venice Charter, this view holds that the value of heritage lies in its literal materials and the marks left on them by time, and that reconstruction tends to produce a reinvention of the past rather than its recovery.[2] The Second Pole – the Philosophy of 'Authenticity of Meaning': represented by non-Western cultures and recognised in the Nara Document, this view holds that authenticity lies in the continuity of a building's social, spiritual, and symbolic function, and that the community which produced the heritage has a primary role in determining how it is treated.[12] The strategies discussed in this research represent practical attempts to reconcile these two tendencies - drawing on current digital technology and respecting the cultural particularity of each context - rather than privileging either pole.

9. Levels of Architectural Intervention in Historic Buildings

Architectural interventions are commonly classified, in the specialist conservation literature and international charters, into seven principal levels - from preventive maintenance to complete reconstruction - according to a building's structural condition and historical significance. These levels and their methodological controls[13] are summarized in Table 1.

Table 1. International Levels of Architectural Intervention and Their Methodological Controls

Level of Intervention	Technical Description	Strategic Objective	Methodological Controls
Prevention	Routine maintenance	Extend building life without change	Minimum physical intervention
Preservation	Stabilize the current condition	Maintain the original state	No additions or modifications
Consolidation	Strengthen the structural system	Ensure structural safety	Use chemically compatible materials
Restoration	Recover a known prior condition	Reveal aesthetic and historical values	Rely on precise historical documents
Rehabilitation	Adapt building for new use	Ensure functional continuity	Preserve architectural character
Reproduction	Copy missing parts from an original	Compensate decorative elements	Visual distinction between old and new
Reconstruction	Completely rebuild a destroyed structure	Restore identity symbolism	Must be an exceptional case only

A closer analysis of these levels indicates that 'reconstruction' remains the most far-reaching form of intervention, generally justified only where the loss of a building has created a substantial and otherwise irreparable gap in the collective identity or national memory of a society - as was the case in Warsaw and Dresden after the Second World War.[12]

10. Collective memories and visual symbols in processes of reconstruction

Historic buildings serve not only a functional purpose but also act as repositories of collective memory, anchoring communal identity in space and time. Architecture provides a central material reference point for this process. In situations of armed conflict, the deliberate destruction of symbolic buildings is frequently intended as a form of cultural erasure aimed at the loss of a people's shared past.

10.1 Sociology of the Reclamation of Demolished Buildings Identity

The societal impulse to bring back the visual symbolism of the demolished structures is rooted in the drive to reclaim the national identity, where the reconstructed building acts as 'memory itself' for the generations that did not witness this historical period, as demonstrated in Table 2.[1]

Table 2. Comparative Analysis of Symbolic Reconstruction Cases

Case Study	Symbolic Motivation	Methodology Adopted	Societal Impact
Old City of Warsaw	Challenging Nazi cultural annihilation	Faithful reconstruction based on Canaletto paintings	UNESCO inscription as exceptional model of national will
Church of Our Lady - Dresden	Symbol of German unity and reconciliation	Original remaining stones (anastylosis) with new stone	Transformed into world shrine embodying peace and memory
Old Mostar Bridge	Restore connection between ethnic components	Traditional Ottoman techniques, stone from same original quarry	Symbol of reconciliation despite ongoing political tensions

Figure 1 show Warsaw before and after reconstruction and Faithful Reconstruction Figure 2 show The church in Dresden and its reconstruction, with the use of original and new stones Figure 3 show The Old Bridge Mostar and the use of stone from the same

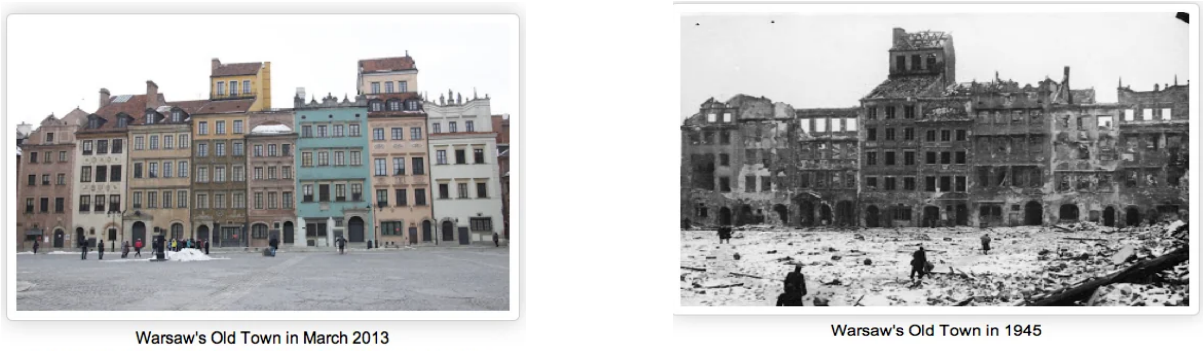


Figure 1: Old Warsaw before and after reconstruction. Source[37]



Figure 2: The Frauenkirche church in Dresden, Germany before and after reconstruction. Source[38]

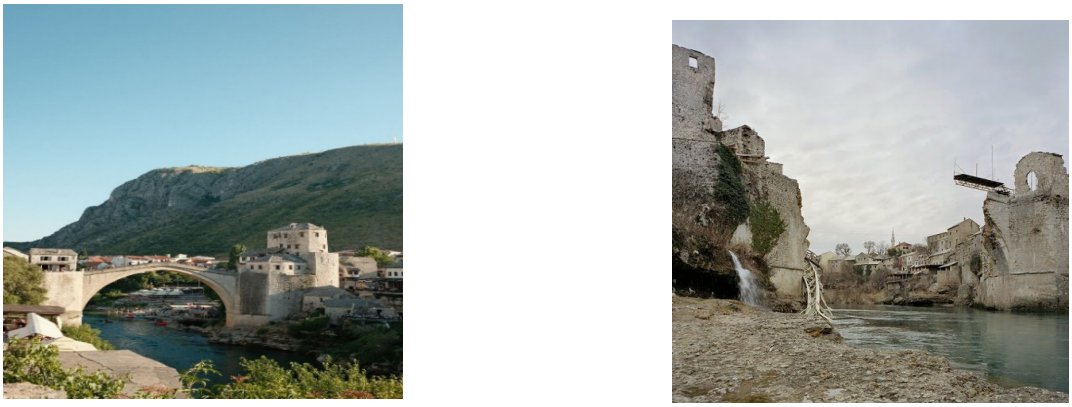


Figure 3 Old Bridge Mostar before and after reconstruction Source

The psychological process of the recovery of identity via architecture needs participation of the society at large so that the process of rehabilitation does not degenerate into commercial 'heritagisation' aimed at tourists exclusively, but remains connected to its living social roots.[14]

11. Balancing Authenticity and Contemporary Sustainability Standards

Sustainability in the architectural heritage presents a double challenge: conservation of ancient buildings is, in principle, a sustainable act, since it maintains 'embodied energy' and avoids demolition and construction waste. At the same time these structures often have poor energy efficiency by current standards and require precise technical interventions.

11.1 Resource Efficiency and Renewable Energy

Studies have demonstrated that it can take between 10 and 30 years for a new structure constructed to high green standards to compensate for the energy used in their original erection, relative to a historic building that has been repaired and modernised.[15] Therefore, the rehabilitation strategy should seek to harness the climate solutions inherent in traditional design including:

- High thermal mass: thick walls of clay or stone that naturally regulate heat exchange.
- Passive ventilation: Natural cooling without using power, through wind catchers and courtyards.
- Local sustainable materials: the use of local clay and timber decreases the carbon impact from travel and assures biological compatibility with the environment. Modern research confirms these old tactics as suitable responses to today's environmental challenges.[16]

11.2 Integrating Sustainability Systems in Historic Buildings

Contemporary methods can be included into the reconstruction or restoration of old structures to enhance their energy efficiency without losing architectural authenticity. Some of these strategies[17] are shown in Table 3.

Table 3. Strategies for Integrating Modern Sustainability in Historic Buildings

Modern Technology	Application in Heritage	Technical Challenge	Authenticity Standard
Internal thermal insulation	Adding insulating layers of natural materials (e.g. cork)	Preventing moisture accumulation inside walls (vapor barriers)	Preserving the original exterior appearance
Photovoltaic cells (solar)	Integrating in non-visible surfaces or as building materials (BIPV)	Visual interference with historic fabric	Reversibility
Smart control systems	Motion sensing and lighting to reduce consumption	Routing cables without destroying historic elements	Minimum intervention principle

To find a balance between authenticity and sustainability, a 'conscious recovery' process is required, in which the outward form is not only simulated, but the environmental logic on which the original structure was designed is comprehended and improved using modern instruments.[18]

12. Advanced Digital Technologies: HBIM, Digital Twins, and Artificial Intelligence

The digital revolution has substantially changed the ways in which heritage assets are documented and reconstructed. Conventional paper-based documentation has been largely superseded by Historic Building Information Modelling (HBIM) - a digital modelling approach that integrates engineering, historical, and material data within a single parametric model.

12.1 HBIM for Accurate Re-construction

The HBIM technology allows the construction of parametric 3D models capable of accurately represent the structural deformations, the deterioration patterns and the historical changes happening in a structure. Digital workflow comprises:[10] • Laser Scanning – captures millions of points to form a 'point cloud' of the building showing measures to the millimeter. • Photogrammetry: Using high-resolution photos to wrap the digital models with realistic texture and hues. • Digital Twin – Develop a live model that interfaces with IOT sensors to monitor the stability of the building and its reaction to environmental conditions in real time. These instruments help to take data informed judgments and so minimize the risks of wrong intervention.[11]

12.2 The Added Value of Technology in Heritage Management

For example, in the Tousson Palace project in Egypt, the application of BIM and Digital Twins led to: reduction of carbon emissions by 2.8 tons per year per building; the provision of visitor behavioral simulation models to improve the management of the tourist site; and the development of technical employment opportunities in the survey and modelling fields for local populations. Furthermore, Artificial Intelligence (AI) is turning into a tool for the prediction of degradation patterns of structures and suggesting the most suitable materials for restoration based on a huge database of historic and modern materials.[19] These technologies are not without limitations, however. HBIM and Digital Twin workflows require significant initial investment, specialised expertise, and sustained data management, and the accuracy of any model remains dependent on the quality of the underlying survey and archival evidence. In contexts of incomplete documentation, digital tools can support but cannot fully resolve the uncertainties inherent in reconstruction decisions.

13. Cultural Tourism and Heritage: Prospects for Vision 2030

Vision 2030 aims to increase the contribution of tourism to GDP to 10% by 2030, supporting economic diversification beyond oil dependency. Heritage sites occupy a central place in this strategy as a significant national asset that can generate renewed economic value when managed appropriately. A central challenge for decision-makers and specialists alike is to maintain a balance between the economic use of heritage and the preservation of its authenticity. The over-commercialisation of historic sites can lead to what the heritage literature terms 'heritagisation' - a process in which a living cultural inheritance is gradually reframed as a tourist commodity, with a corresponding loss of social meaning and depth. Conversely, conservation that disregards the needs of use and investment can result in functional rigidity, which may in turn lead to neglect and the slow deterioration of these assets.

14. King Salman Charter for Architecture and Urbanism:

A National Vision for Authenticity and Innovation In the Saudi context, the King Salman Charter for Architecture and Urbanism provides a national framework intended to define an architectural identity grounded in authenticity. The Charter sets out six core values, presented in Table 4, which serve as a reference guide for reconstruction and development processes at Saudi historic sites. While the Charter articulates these values within a national vision, it can also be read in relation to established international conservation principles: its emphasis on authenticity and continuity is broadly consistent with the Venice Charter and the Nara Document, although its explicit linkage of heritage to contemporary social needs and national identity gives it a distinct orientation. Examining this relationship critically - rather than treating the Charter solely in descriptive terms - helps locate the Saudi approach within the wider discourse on heritage conservation.[20]

Table 4. The Six Values of the King Salman Charter and Their Heritage Applications

Value	Concept in Reconstruction Context	Practical Application
Authenticity	Core of creativity and design logic connected to place	Avoid superficial imitation; focus on design spirit
Continuity	Community growth while respecting the past and celebrating identity	Link traditional architecture to contemporary social needs
Human-centricity	Making the individual and community the centre of the design process	Create social spaces that reinforce bonds between residents and heritage

Value	Concept in Reconstruction Context	Practical Application
Liveability	Improving quality of life and creating a safe, attractive environment	Transform heritage zones into living centres for residence, work, and leisure
Innovation	Exploring new horizons and non-traditional solutions	Use advanced digital technologies to enhance conservation
Sustainability	Protecting environmental, social, and economic objectives	Use local materials and enhance energy efficiency

These values manifest in major projects such as Diriyah and Historic Jeddah, where the goal is not limited to restoring buildings, but extends to building a sustainable urban environment that reflects national pride and supports Vision 2030.

15. Saudi Arabia Heritage Reconstruction Case Studies

Saudi Arabia has embraced heritage rehabilitation practices that strive for a balance of authenticity, symbolism and sustainability.

15.1 Diriyah: 'City of Earth' and Al-Turaif Quarter

The Al-Turaif Quarter – included on the UNESCO World Heritage List - is a difficulty in conserving mudbrick ruins. The Diriyah Gate Development Authority (DGDA) devised a strategy that integrated:

- Rigorous history documentation: recreate missing elements with precision using archival pictures and surveys.
- Traditional materials improved: reuse of clay and straw with natural additions to increase durability and tensile strength.
- National symbolism: reconstruction of Diriyah as a cultural capital to reinforce the feeling of Saudi identity.
- Al-Bujairi Terrace: a model of urban growth that reflects the topography of Najd (small lanes, cubic masses) and provides a luxury and sustainable tourism experience.

The Diriyah project is an innovative model for identity-based reconstruction based on scientific evidence and national symbolism.[21,14] Figure 4 shows The Al-Turaif area, one of the historic Diriyah communities before and after reconstruction.

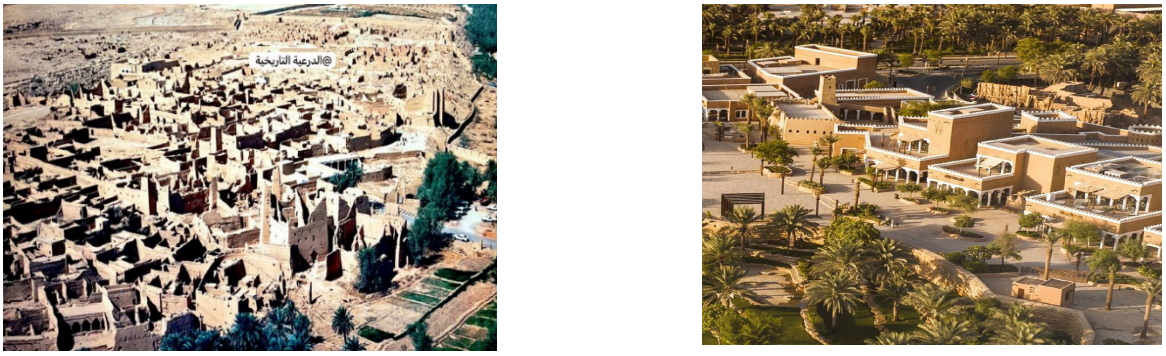


Figure 4: Al-Turaif neighborhood in historic Diriyah before and after reconstruction

15.2 Al-Balad (Historic Jeddah) Adaptive Reuse as a Model of Living Conservation

15.2.1 Heritage and Historical Significance

Historic Jeddah, or 'Al-Balad', is one of the oldest cities in Hijaz, and one of the most architecturally diverse cities in Hijaz. The city developed as the gateway to the Two Holy Mosques and as a foremost station on maritime trade routes between the Arabian Peninsula, Africa and South Asia for over fourteen uninterrupted centuries, which created a unique urban fabric that reflects the depth of cultural exchange and civilizational diversity the city witnessed through the ages.[22] In 2014, UNESCO listed Historic Jeddah as a World Heritage Site for its exceptional value expressed in three integrated aspects: first, the cohesive urban fabric based on a branching network of lanes, markets and tall residential buildings; second, the unique Hijazi architectural style with its distinctive decorative elements - especially the carved wooden balconies and coral stone extracted from the Red Sea As shown in Figure 5, third, continuity of the city's social and commercial activity, making it living heritage rather than mere museum ruins.[23].



Figure 5: The authentic Hijazi architectural style in historic Jeddah - wooden Roshan-window and coral stones

15.2.2 Challenges to Heritage

1. Environmental and Structural Challenges The buildings of Al-Balad are subject to a double threat of humid coastal circumstances and the particularity of traditional construction materials. The coral stones, the raw material for most of these buildings, are excellent insulators against heat but are greatly affected by the salinity and high humidity that prevails throughout the year in the Red Sea climate, which accelerates the fragmentation of these stones and the collapse of historic walls.[23] To this is added the potential of excessive amounts of ground water that cause ongoing corrosion in the building foundations, an engineering challenge that defies conventional traditional remedies. Figure 6. Effect of the restoration method to a Historical-building.



Figure 6: Historical-building-restoration-before and after

2. Social and Demographic Challenges: Over the past decades, historic Jeddah has witnessed an accelerating wave of population exodus, as many original residents abandoned their traditional homes in search of modern housing more comfortable and suitable for contemporary life, leaving behind towering buildings and ancient lanes slowly collapsing in the absence of those to preserve and care for them .[22] This residential vacuum created a painful reality in which some historic homes became abandoned warehouses or temporary housing that lacked the minimum standards of conservation.
3. Legal and Development Challenges: Al-Balad is situated in the midst of one of the most vibrant and expanding Saudi cities, and therefore constantly faces the pressures of real estate development and urban expansion. In earlier phases, the lack of specific heritage building codes resulted in the defacement of sections of the historic fabric with inappropriate additions, and traditional owners could not balance the high costs of restoration with the low economic return of their heritage buildings.[24]

15.2.3 Adaptive Re-Use Strategy

In the face of these multi-branching challenges, the Historic Jeddah Programme has chosen a core methodology based on the concept of "Adaptive Reuse" – an approach that refuses the two extreme options: museum mummification which freezes the building in a particular historical moment and deprives it of vitality, and radical renewal which keeps the external shell and empties the heritage core. This strategy rather seeks a fine balance between the preservation of historical architectural values and the providing of a new use to the building, which pumps current vitality into it, insuring its life and assuring ongoing maintenance resources.[22]

This technique is reflected in a number of interconnected axes:

1. Functional Conversion with Architectural Conservation: Historic Jeddah has seen pioneering efforts in turning traditional residential structures into boutique hotels, heritage cafés, cultural and arts centres, and specialized local museums. All these experiments are founded on the same constant principle: that functional conversion should not impact on the original structural system or the distinctive decorative elements; rather, it uses these elements as an added value that sets the new establishment apart and increases its commercial and tourist attraction.[22]
2. Facing Structural Challenges, Technical Intervention: Engineers working on Al-Balad projects have devised novel engineering solutions to confront the specific challenges of this site. To address the problem of eroded coral stones, specialized injection techniques were developed to consolidate the structure of the stone without changing its appearance or texture, and reversible moisture-proofing materials were also tested to meet the 'reversibility' principle required by the Venice Charter.[23] The groundwater problem was caused by installing underground drainage systems that took water away from the historic foundations, thereby avoiding the necessity for excavations that could harm the historical fabric.
3. Reviving Traditional Crafts as a Pillar of Sustainability the Al-Balad strategy quickly learned that protecting a heritage structure is not complete without keeping the craft that generated it. Carved wooden balconies are a traditional talent, requiring years of training and expertise, and sculpting coral stones demands a careful grasp of the qualities of this fragile material. As a result, specific craft training programmes were initiated for young generations from local communities, offering them sustainable economic opportunities tied to continuing restoration initiatives.[25]
4. Socio-economic Sustainability: An essential pillar in the Al-Balad strategy is the re-settling of original residents and their involvement in the economic activity of the cultural zone. These include providing financial benefits and concessional loans to the owners of heritage buildings in return for their commitment to approved standards of restoration; creating economic platforms that allow craftsmen and local producers to benefit from the growing tourist movement; and the periodic hosting of cultural events that reconnect residents to their architectural heritage.[26]

15.2.4 Results and lessons learned

The tangible results of the Historic Jeddah experience are the following: increased tourist occupancy rates in the historical zone; proof of the viability of the "productive heritage" model, which relies on creating economic income from the historic building itself, instead of depending solely on government funding for maintenance[22]; the creation of a model that can be duplicated in comparable heritage zones that combine high historical value with complex environmental and social challenges[23]; and the discovery of the limits of approaches that focus on tourist attraction at the expense of social continuity.

15.2.5 Historic Jeddah and King Salman Charter

The values of the King Salman Charter for Architecture and Urbanism (2026)[20] are evident in the Historic Jeddah experience: it manifests the value of 'Continuity' by connecting traditional architecture with current social needs; the value of 'Human-centricity' by putting the resident and visitor alike in the center of the development process; and the value of 'Livability' by making the historic zone a living urban environment that integrates residence, work and leisure in a single urban fabric.

15.3 The 'Light Touch' Methodology in alUla

15.3.1 Documentation and Planning First Survey Phase

The restoration of the Old AlUla town (Al-Deira) was initiated with the stage of detailed and accurate documentation, which served as the foundation for all subsequent intervention decisions. In 2019, the Royal Commission for AlUla commissioned HCC Heritage Conservation Consulting[28] to undertake a comprehensive conservation program. This program began with a comprehensive 3D laser survey of the entire site, to identify priority areas for study, and to identify the factors contributing to deterioration and to implement preventive conservation measures to address these issues. This investigation resulted in an extraordinary digital database that documents all the houses, lanes and walls of the urban fabric covering an area of around 67,286 square meters, consisting of more than 900 residential and urban units crossed by a network of lanes over 3,135 meters long.

15.3.2 The Multidisciplinary Approach

HCC's proposed plan was characterized by the innovative methodology of bringing together all professionals and stakeholders at the same time on the same site to test methodologies and define precise protocols for each phase of intervention. Conservators, heritage architects, engineers, archeologists, materials specialists and social scientists worked simultaneously.[28] The MUDUD project partnership with the French Agency for Alula Development (AFALULA) brought a comparative academic dimension with the use of a multidisciplinary methodology combining architectural

archaeology and materials and mortar analysis to date buildings and understand traditional construction patterns through the ages.

15.3.3 Principles of Intervention: Light Touch and Real Materials

Work that is focused on the notion of Light Touch Interventions that highlight the vast cultural heritage and natural landscape, repair natural ecosystem systems and safeguard heritage and nature within a 'living museum'.[28,29] At the technical level, architects promised to use tamarisk trunk and palm trunk as structural supports, to restore palm-woven roofs and to make mudbrick by the same ancient techniques to rebuild walls. As indicated in Figure 7, while attempting to make use of natural airflow as much as possible in order to lessen the dependence on electricity using air conditioning.[27.]



Figure 7: Al-Ula Old Town - The condition of the mud-brick buildings (A) before the restoration project & (B) after the restoration

15.3.4 Use of the Living Memory of Residents

The most unusual characteristic of the AlUla technique, compared to other historical initiatives, is the use of human memory as the major source of technical information. When researcher Noura Ghobra came in AlUla, she spoke with the elders who have memories of how these buildings were cared for and preserved. Their testimonies told more about the real building methods. They highlighted that not only were the people using local resources in the construction but they were also maintaining and restoring their houses every year using the clay that was gathered from their surrounding farms.[27] This living memory revealed interesting architectural features such as 'al-Tayyara' the lofty air passage between two houses that contains an amazing temperature management mechanism that shades the lanes and directs the air movement for natural ventilation.[27]

15.3.5 Geological and environmental hazards

The range of the technical intervention was not just restricted to the walls and roofing, but also to the geological context of the site. To reduce the risk of landslides, engineering measures were taken, such as the construction of retaining walls with an inclination on the eastern edge of the old town, whose work began in 2023 and are constantly monitored, in order to reduce the slope angles and avoid possible collapses that could endanger the neighboring heritage buildings, all under constant archaeological supervision.

15.3.6 International Partnership and Attainment Standards

The repair was carried out pursuant to the principles of UNESCO and international standards for the protection, restoration and reconstruction of heritage sites.[30] These efforts lead to an excellent international partnership. The Royal Commission for AlUla and the Archaeological Park of Pompeii continue their joint collaboration in the preservation of the Old Town, within the framework of the cooperation agreement signed in January 2025, with the aim of advancing protection research and developing techniques of conservation that support long-term sustainability.[31]

16. Legal and Administrative Challenges and the Community Participation Principle.

Reconstruction does not occur in a legal vacuum, and UNESCO requirements for conservation often conflict with local building laws about fire safety and accessibilities.[24]

16.1 Reconciling Conflicting Codes

Architects often adopt 'performance-based engineering' solutions - an approach in which compliance is demonstrated by meeting defined safety performance objectives (for example, a required level of fire safety or structural stability) rather than by applying prescriptive code provisions designed for modern concrete buildings. Examples include the use of water mist systems in place of standard sprinklers to reduce water damage to historic fabric, and ramps and

lifts that are concealed or integrated into the architecture to provide accessibility for people with disabilities. Such solutions require close collaboration between conservation specialists and local regulatory bodies to create context-sensitive compliance approaches.[32]

16.2 The Centrality of Community Participation in Heritage Sustainability

Effective heritage conservation tends to occur where residents act as active custodians of their heritage rather than as passive observers of externally managed projects.[33] Comparative research on community engagement in historic Cairo and Jeddah reports that active community involvement can increase residents' sense of ownership by more than 70%, with associated reductions in vandalism and improved maintenance of buildings after project completion.[25] Models of participation include: * Co-design workshops: Residents are involved in identifying new roles for restored buildings. • Craft training: establishing economic pathways for local craftsmen (carpenters, clay builders, etc.) that assure sustainability of crafts associated to the building; Community involvement is not just an ethical obligation but also a practical assurance for the long-term viability and sustainability of any historic repair project.[26]

17. Results:

- Structural tension between international charters and actual reality, based on basic philosophical disputes about what authenticity means and who determines it.
- The Nara Document (1994) marked a significant conceptual shift, recognising that authenticity of craft and socio-spiritual significance are valid heritage values alongside material authenticity. This broadening of the concept of authenticity is what makes a structured reconciliation between charters and community expectations possible.
- The seven levels of intervention represent strategic decisions based on historical and symbolic significance, the degree of damage, and the available evidence. Complete reconstruction remains exceptional and is generally justified only where the loss of a building constitutes a substantial and otherwise irreversible breach in community identity.
- Digital documentation tools (HBIM, laser scanning, Digital Twins) help convert conjecture into verifiable evidence. Within the limits of available documentation, technical precision can strengthen the evidentiary basis for reconstruction decisions rather than constrain them.
- AI and Digital Twins can be used to predict structural degradation, propose compatible materials and simulate interventions in real-time before they are implemented.
- Heritage conservation is an environmentally friendly act, saving embodied energy and minimizing demolition trash.
- Three international models demonstrate that symbolic reconstruction is feasible if social purpose is unambiguous: Warsaw (united popular will), Dresden (original stones making anastylosis possible), Mostar (technical authenticity compensating for political difference).
- Complementary methods of three Saudi models:

1. Diriyah: Reconstruction rooted on identity with rigorous documentation and traditional materials.
2. Historic Jeddah: Adaptive reuse between authenticity and economic and social renewal.
3. AlUla: light touch approach, landscape, clay architecture and living memory.

- King Salman Charter (2026): a significant development at the national level, introducing a comprehensive value system (authenticity, continuity, human-centricity, liveability, innovation, sustainability) that seeks to balance commitment to heritage with contemporary requirements.

18. Summary Finding.

The reconstruction of historic buildings is not a purely technical decision determined by material properties and structural codes. It is a multidimensional process that requires the convergence of scientific method, social will, and long-term vision. As the case studies in this research indicate, an effective strategy is one that draws on the available tools - digital documentation technologies, international conservation frameworks, and comparative case experience - to determine when material authenticity should take precedence, when authenticity of meaning should, and when the two can be integrated. The aim is an approach that respects the past without freezing it, and engages with the future without losing continuity with its origins.

19. Recommendations.

Based on the results of study and comparative analysis of international and local experience, the research proposes an integrated system of recommendations at four levels:

19.1 Policy and Legislation:

- Develop and issue a national code for heritage buildings, based on the King Salman Charter (2026), translating its six values into binding technical requirements that respect regional architectural diversity (Najdi, Hijazi, Asiri, Gulf).
- Develop a national classification system for heritage buildings, based on objective criteria:

historical/symbolic significance, architectural authenticity, social importance and available evidence.

- Connecting international charters to the Arab environment: Participation in global heritage conferences and the integration of references to Arab-Islamic values in future normative frameworks.

19.2 Documentation & Technology:

- Demand HBIM and Digital Twins for big national heritage reconstruction projects and create a centralized national digital repository for scholars and future generations
- Support preemptive and wide-ranging surveying of heritage buildings before threats emerge, including a nationwide campaign targeting less-documented places, such as historic villages and small cities.

19.3 Project Management and Professional Practice:

- Use a multidisciplinary approach including heritage architects, structural engineers, archaeologists, materials experts, social scientists and local craftspeople.
- Investment was put into upgrading traditional materials, which were preferred to imported new materials and were compatible with original materials.
- Apply the idea of reversibility to all modern modifications or interventions. - Regular methodological reports documenting and sharing knowledge across Saudi and Arab heritage projects.

19.4 Economy and Community:

- Require community participation in the feasibility studies for each heritage project, ensuring that the original inhabitants have a real say in the decision making process.
- Adopt the 'productive heritage' approach through adaptive reuse options that achieve a balance between authenticity and sustained economic rewards.
- Balance tourism needs with local community needs and ensure heritage projects benefit original residents first.

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Classification of Complemented Subspaces in $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$ for Spaces with Few Operators

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Abstract
Building on Acuaviva's work, which characterizes operators on injective tensor products (Acuaviva, 2026), we extend the classification of complemented subspaces from $C_0(\omega \times \mathcal{K}_{\mathcal{A}})$ to $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$, where $\mathcal{K}_{\mathcal{A}}$ is generated by an almost disjoint family $\mathcal{A}$ of continuum cardinality with few operators. In addition, we adapt Benyamini's extension theorem for separable spaces (Benyamini,1978) to show that any infinite dimensional complemented subspace is isomorphic to C_0, $C_0(\mathcal{K}_{\mathcal{A}})^n$ for $n \in \mathbb{N}$, or $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$. We use inductive arguments on Cantor-Bendixson indices and tensor decompositions, and we confirm uniqueness follows from the structural decomposition and separable-range analysis. This addresses a technical gap in handling transfinite ordinals exceeding ω, with applications to lattices of operator ideal and potential generalizations to non-scattered spaces.

Keywords: Injective tensor products, operator ideals, complemented subspaces, few operators, transfinite ordinals, scattered compact spaces.

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1. Introduction

The study of Banach spaces with restricted operator structures has been a central theme in modern functional analysis. A Banach space $\mathcal{X}$ is said to have few operators if every bounded linear operator $\mathcal{T}:\mathcal{X}\to\mathcal{X}$ admits a decomposition $\mathcal{T}=\lambda I+\mathcal{S}$, where $\lambda\in\mathbb{k}$ is a scalar and $S:\mathcal{X}\to\mathcal{X}$ is an operator with separable range. This structural rigidity, first established in ZFC-independent contexts by Shelah (1978) and later refined by Shelah & Steprāns (1988), reduces the complexity of the operator algebra $B(\mathcal{X})$ significantly: the non-scalar part is restricted to operators with separable range.

On a separate track, Benyamini (1978) showed that every infinite-dimensional complemented subspace of $C(\omega^\omega)$ is isomorphic to either c_0 or the entire space $C(\omega^\omega)$, relying on an extension theorem designed for separable scattered compacta. In parallel, Candido (2021) analyzed spaces of the form $C_0(\alpha\times L)$, demonstrating that finite-power complements $C_0(L)^n$ can arise under the auxiliary set-theoretic ♣-principle. Later, Acuaviva (2026) studied tensor-product structures for spaces of the form $C_0(\omega \times \mathcal{K}_{\mathcal{A}})$. Extending this work transfinitely to $C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})$, however, poses new challenges specifically, one needs finer control over separable-range perturbations at limit ordinal stages. The present paper tackles this setting within ZFC, combining transfinite decomposition techniques with the few-operator framework. This extends Candido's finite-power results to the transfinite ordinal ω^ω while eliminating the dependence on combinatorial axioms.

The main result is established using a transfinite induction framework together with the operator decomposition methods developed in Section 3:

Theorem 1.1.

Assume that $\mathcal{K}_{\mathcal{A}}$ is a locally compact Hausdorff space, with the generating almost disjoint family $\mathcal{A}\subseteq[\mathbb{N}]^\omega$ of continuum cardinality, and that the function space $C_0(\mathcal{K}_{\mathcal{A}})$ admits only few operators. Then, every infinite dimensional complemented subspace of $C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})$ must be isomorphic to one of the following spaces:c_0, $C_0(\mathcal{K}_{\mathcal{A}})^n$ for some finite $n\in\mathbb{N}$; or $C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})$.

This resolves the question raised in (Acuaviva, 2026) concerning transfinite extension beyond ω. We also discuss applications to operator ideals and indicate possible broader extensions, motivated by more developments, including. Candido's extensions of $C_0(L\times L)$,(Candido,2004).

2. Preliminaries

We adhere to standard notation used in Banach space theory. All spaces are taken over field $\mathbb{K}$, where $\mathbb{k}\in\{\mathbb{R},\mathbb{C}\}$. An operator always refers to a bounded linear map between normed spaces. For Banach space $\mathcal{X}$, we denote its unit ball by $B_{\mathcal{X}}$. For Banach spaces $\mathcal{X}$ and $\mathcal{Y}$, we write $\mathcal{X}\sim=\mathcal{Y}$ if they are (linearly) isomorphic, i.e., there exists a bounded linear bijection $\mathcal{T}:\mathcal{X}\to\mathcal{Y}$ with bounded inverse. We write $\mathcal{X}\sim\mathcal{Y}$ if they are isometrically isomorphic, i.e., there exists a linear bijection $\mathcal{T}:\mathcal{X}\to\mathcal{Y}$ such that $\|\mathcal{T}\mathcal{X}\|=\|\mathcal{X}\|$ for all $\mathcal{X}\in\mathcal{X}$. Additional specialized notation will be given when necessary.

2.1 Tensor Products and Few Operators

We give a brief overview of well-known results regarding tensor products of Banach spaces, focusing particularly on the injective tensor product, as discussed in (Ryan, 2002). We will assume standard knowledge of the algebraic tensor product, denoted $\mathcal{X}\otimes\mathcal{Y}$, of vector spaces $\mathcal{X}$ and $\mathcal{Y}$; see Ryan (2002, Chapter 1) again for the elementary definitions. Note that if E,F,$\mathcal{X}$ and $\mathcal{Y}$ are vector spaces and U:E→F,R:$\mathcal{X}\to\mathcal{Y}$ are linear maps, the tensor product of U and R is a linear map

$$U\otimes R: E\otimes\mathcal{X}\to F\otimes\mathcal{Y}$$

that satisfies the usual properties:

$$(U\otimes R)(e\otimes x)=(Ue)\otimes(Rx),\ \ \forall\, e\in E \text{ and } x\in\mathcal{X}.$$

Let $\mathcal{X}$ and $\mathcal{Y}$ be two Banach spaces. For these spaces, we may consider their algebraic tensor product $\mathcal{X}\otimes\mathcal{Y}$, that is, the vector space consisting of finite sums of the form $\mathcal{X}\otimes\mathcal{Y}$, with $x\in\mathcal{X}$ and y$\in\mathcal{Y}$. The algebraic tensor product can be equipped with different norms, and different norms may yield different Banach spaces upon completing the spaces with respect to the norms. The theory of tensor products of Banach spaces investigates the definition of tensor product norms and the resulting properties of the completed Banach spaces.

If $\alpha(\cdot)$ is a norm defined on the algebraic tensor product $\mathcal{X}\otimes\mathcal{Y}$. The completion of $\mathcal{X}\otimes\mathcal{Y}$ with respect to α is denoted by $\mathcal{X}\hat{\otimes}_\alpha\mathcal{Y}$. Two of the most commonly used norms are the projective norm $\pi(\cdot)$ and the injective norm $\varepsilon(\cdot)$ (see Chapters 2 and 3 in Ryan,2002). If an element $u\in\mathcal{X}\otimes\mathcal{Y}$ can be written as

$$u=\sum_{i=1}^{n} x_i\otimes y_i,$$

then it follows that

$$\varepsilon(u)=\sup\left\{\left|\sum_{i=1}^{n}\varphi(x_i)\,\psi(y_i)\right| : \varphi\in B_{\mathcal{X}^*},\psi\in B_{\mathcal{Y}^*}\right\},$$

and this norm is well-defined and does not depend on the particular representation chosen for u. Another fundamental property is

$$\varepsilon(x\otimes y)=\|x\|\|y\| \quad \text{for each } x\in\mathcal{X} \text{ and } y\in\mathcal{Y},$$

(see Proposition 3.1 in Ryan, 2002).

A key fact that will be used later is that the injective tensor product preserves subspaces. Moreover, we have the following result:

Proposition 2.1

If U:E→F and R:$\mathcal{X}\to\mathcal{Y}$ are linear operators. Then there exists a unique operator

$$U \widehat{\otimes} R: E \widehat{\otimes}_{\varepsilon} \mathcal{X} \to F \widehat{\otimes}_{\varepsilon} \mathcal{Y}$$

such that

$$(U \widehat{\otimes} R)(e \otimes x) = (Ue) \otimes (Rx), \text{ for all } e \in E \text{ and } x \in \mathcal{X}.$$

Moreover, the operator norm satisfies

$$\| U \widehat{\otimes} R \| = \| U \| \| R \|.$$

Observe that, U$\widehat{\otimes}$R is obtained as the continuous extension of the linear map U⊗R:E⊗$\mathcal{X}$→F⊗$\mathcal{Y}$. Additionally, recall the following standard result. (see Section 3.2 in Ryan, 2002).

Proposition 2.2

Let $\mathcal{X}$ be a Banach space, and K and L be two compact Hausdorff spaces. Then we have the canonical isometric isomorphism

$$C(K) \widehat{\otimes}_{\varepsilon} \mathcal{X} \sim= C(K, \mathcal{X}),$$

where elementary tensors are identified via

$$(f \otimes x)(k) = f(k)x \quad \text{for all} \quad f \in C(K), x \in \mathcal{X}, \quad \text{and } k \in K.$$

Likewise, we obtain the isometric isomorphism

$$C(K) \widehat{\otimes}_{\varepsilon} C(L) \sim= C(K \times L).$$

As observed above, the injective tensor product satisfies the following:

If U:E→F and R:$\mathcal{X}\to\mathcal{Y}$ are two bounded operators, then the algebraic tensor U⊗R extends to a bounded operator

$$U \widehat{\otimes} R: E \widehat{\otimes}_{\varepsilon} \mathcal{X} \to F \widehat{\otimes}_{\varepsilon} \mathcal{Y},$$

It is natural to ask for which norms α(·) on the algebraic tensor product such an extension exists; that is, for which tensor norms the linear map U⊗R extends to a bounded operator

$$U \widehat{\otimes} R: E \widehat{\otimes}_{\alpha} \mathcal{X} \to F \widehat{\otimes}_{\varepsilon} \mathcal{Y},$$

where we highlight the fact that the map is defined from the α-tensor product E$\widehat{\otimes}_{\alpha}\mathcal{X}$ into the injective tensor product F$\widehat{\otimes}_{\varepsilon}\mathcal{Y}$.

The present paper takes a closer look at certain well-behaved norms (see Section 6.2 in Ryan, 2002), which, in particular ensure the existence of such operator extensions.

Definition (Ryan,2002) 2.3

Let $\mathcal{X}$ and $\mathcal{Y}$ be Banach spaces. A reasonable cross-norm α(·) on $\mathcal{X}\otimes\mathcal{Y}$ is a norm that satisfies:

(1) $\alpha(x \otimes y) \le \|x\|\|y\|, \ \forall\, x \in \mathcal{X}$ and $y \in \mathcal{Y}$,

(2) For every bounded linear functional φ in $\mathcal{X}^*$ and ψ in $\mathcal{Y}^*$, the elementary tensor φ⊗ψ , regarded as a linear functional on $\mathcal{X}\otimes$Y, is bounded, and moreover

$$\|\varphi \otimes \psi\| \le \|\varphi\|\|\psi\|.$$

Definition (Ryan,2002) 2.4

A uniform cross-norm α(·) is an assignment of a reasonable cross-norm to each pair of Banach spaces (E,$\mathcal{X}$), such that for every bounded linear operator U:E→F and R:$\mathcal{X}\to\mathcal{Y}$, the tensor product operator U⊗R:E⊗$\mathcal{X}$→F⊗$\mathcal{Y}$ satisfies

$$\|U \otimes R\| \le \|U\|\|R\|,$$

where ‖U⊗R‖ is taken with respect to the cross-norms on the spaces E⊗$\mathcal{X}$ and F⊗$\mathcal{Y}$.

It is a fact that α(·) is a reasonable cross-norm if, and only if,

$$\varepsilon(u) \le \alpha(u) \le \pi(u), \forall\, u \in \mathcal{X} \otimes \mathcal{Y},$$

as demonstrated in Proposition 6.1 of Ryan (2002). This implies that, in case α(·) is a uniform crossnorm and U:E→F and R:$\mathcal{X}\to\mathcal{Y}$ are operators, the product operator

$$U \widehat{\otimes} R: E \widehat{\otimes}_{\alpha} \mathcal{X} \to F \widehat{\otimes}_{\varepsilon} \mathcal{Y},$$

is well-defined, satisfies that

$$\|U \widehat{\otimes} R\| \le \|U\|\|R\|$$

and acts on elementary tensors as

$$(U \widehat{\otimes} R)(e \otimes x) = (U \otimes R)(e \otimes x) = (Ue) \otimes (Rx)$$

for each e∈E and x∈X.

Finally, we observe that ε(·) is itself a uniform cross-norm. That property is required for the purposes of the theory of tensor products of Banach spaces developed here.

A space $\mathcal{X}$ is said to have only a few operators, if all operators $\mathcal{T}$:$\mathcal{X}\to\mathcal{X}$ are of the form $\mathcal{T}$=λI+$\mathcal{S}$ where λ is a scalar in the field $\mathbb{K}$ and $\mathcal{S}$ has separable range (Shelah, 1978).

According to the findings presented in (Acuaviva, 2026): If E and F are separable spaces, and $\mathcal{X}$ is a non-separable space with few operators,

$$\mathcal{T}: E \widehat{\otimes}_\alpha \mathcal{X} \to F \widehat{\otimes}_\varepsilon \mathcal{X},$$

can be represented as $\mathcal{T}=U\widehat{\otimes}I+\mathcal{S}$, where $U:E\to F$ is a bounded operator and $\mathcal{S}$ is an operator, whose range is separable. This theorem utilizes the elementary structure of operators on $\mathcal{X}$, establishing a connection to Shelah's constructions within the framework of the diamond axiom (which subsequently became ZFC-independent (Shelah & Steprāns, 1988)) and the reflexive examples presented in (Wark, 2001).

Standardization of Notation. To ensure consistency throughout the manuscript, we fix the following conventions. Let $\mathcal{X}$ be a Banach space. We denote by $B(\mathcal{X})$ the algebra of bounded linear operators, by $K(\mathcal{X})$ the closed ideal of compact operators, by $\mathcal{S}(\mathcal{X})$ the closed ideal of operators with separable range, and by $G_E(\mathcal{X})$ the ideal of operators factoring through a Banach space E. The symbol $\bigoplus_\infty$ denotes the ℓ_∞-direct sum equipped with the maximum norm. For compact spaces K we write $C(K)$, and for locally compact non-compact spaces L we write $C_0(L)$. Throughout this work, the phrase "$\mathcal{X}$ has few operators" strictly means that every $\mathcal{T}\in B(\mathcal{X})$ decomposes as $\mathcal{T}=\lambda I+\mathcal{S}$ with $\lambda\in\mathbb{K}$ and $\mathcal{S}\in\mathcal{S}(\mathcal{X})$ (Shelah, 1978). All subsequent references to operator ideals, tensor products, and ordinal derivatives follow this standardized notation

2.2 Almost Disjoint Families and $C_0(\mathcal{K}_\mathcal{A})$

We use $[\mathbb{N}]^{<\omega}$ and $[\mathbb{N}]^{<\omega}$ to denote the families of subsets of $\mathbb{N}$, finite or infinite respectively. A subfamily $\mathcal{A}\subseteq[\mathbb{N}]^\omega$ is called almost disjoint if the intersection of any two distinct elements $A,B\in\mathcal{A}$, is finite; that is, $A\cap B\in[\mathbb{N}]^{<\omega}$ (Hjorth, 2005).

In this section, we follow the notation presented in (Koszmider & Laustsen, 2021) and denote by $\mathcal{K}_\mathcal{A}$ the locally compact Hausdorff space corresponding to the almost disjoint collection $\mathcal{A}\subseteq[\mathbb{N}]^\omega$, as given in Definition 3 of Koszmider and Laustsen (2021). For convenience, we recall the following definition:

Definition 2.5

(Koszmider & Laustsen, 2021) Assume that $\mathcal{A}\subseteq[N]^\omega$ is an almost disjoint family. The space $\mathcal{K}_\mathcal{A}$ is defined as the set of points

$$\{x_n : n\in\mathbb{N}\}\cup\{y_A : A\in\mathcal{A}\},$$

where each x_n is an isolated point.

For each $A\in\mathcal{A}$ and finite subset $G\subseteq\mathbb{N}$, we define the sets

$$U(A,G)=\{x_n : n\in A\setminus G\}\cup\{y_A\},$$

These sets form a neighbourhood basis at the point y_A. We also denote $U(A)$ simply by $U(A,\varphi)$.

We first summarize key properties of these spaces (see Koszmider & Laustsen, 2021) and extend certain results from the same work to their natural analogues in $C_0(M\times\mathcal{K}_\mathcal{A})$ where M is a compact metric space.

Lemma 2.6 Suppose that $\mathcal{A}\subseteq[\mathbb{N}]^\omega$ is an almost disjoint family. Then:

- $\mathcal{K}_\mathcal{A}$ is a locally compact, scattered and Hausdorff space.
- Compactness of $\mathcal{K}_\mathcal{A}$ occurs if and only if both $\mathcal{A}$ and $\mathbb{N}\setminus\bigcup\mathcal{A}$ are finite.
- The set $\{\mathcal{X}_n : n\in\mathbb{N}\}$, which consists of isolated points of $\mathcal{K}_\mathcal{A}$, is dense in $\mathcal{K}_\mathcal{A}$ so $\mathcal{K}_\mathcal{A}$ is separable. Consequently $\mathcal{K}_\mathcal{A}$ is metrizable if and only if it is second countable, which occurs precisely when $\mathcal{A}$ is countable.
- The family of points $\{y_A : A\in\mathcal{A}\}$ forms a closed and discrete subspace of $\mathcal{K}_\mathcal{A}\setminus\{x_n : n\in\mathbb{N}\}$.
- For every $A\in\mathcal{A}$, the sequence $(x_n)_{n\in A}$ converges to y_A in $\mathcal{K}_\mathcal{A}$.

Definition 2.7 Suppose that $\mathcal{A}\subseteq[\mathbb{N}]^\omega$ is an almost disjoint family. For a function $f\in C_0(M\times\mathcal{K}_\mathcal{A})$ and a set of functions $X\subseteq C_0(M\times\mathcal{K}_\mathcal{A})$, we define the following support sets

1. $s(f)=\{A\in\mathcal{A}:$ there exists $k\in M$ with $f(k,y_A)\neq 0\}$
2. $s(X)=\{s(f): f\in X\}$, where $s(f)$ is defined as above.

Lemma 2.8 For every function $f\in C_0(M\times\mathcal{K}_\mathcal{A})$, the set

$$s(f)=\{A\in\mathcal{A}:\exists k\in M \text{ such that } f(k,y_A)\neq 0\}$$

is countable.

Proof. We fix a countable dense subset $M_0\subseteq M$. We claim that

$$s(f)=\{A\in\mathcal{A}:\exists k\in M_0 \text{ such that } f(k,y_A)\neq 0\}=\bigcup_{k\in M_0}\{A\in\mathcal{A}: f(k,y_A)\neq 0\}.$$

Indeed, suppose $A\in s(f)$. By definition, there exists $k\in M$ such that $f(k,y_A)\neq 0$. Since M_0 is dense in M, there exists a sequence $(k_n)\subset M_0$ with $k_n\to k$. By continuity of f in the first variable, we have

$$f(k_n,y_A)\to f(k,y_A)\neq 0.$$

Hence, there exists $N\in\mathbb{N}$ such that $f(k_N,y_A)\neq 0$. This shows that it suffices to consider only $k\in M_0$ when defining $\mathcal{S}(f)$.

Now, it remains to demonstrate that the set

$$\{A\in\mathcal{A}: f(k,y_A)\neq 0\}$$

is countable for all $k\in M_0$.

Fix $k \in M_0$. Observe that the set $\{(k,y_A): A \in \mathcal{A}\}$ is discrete and closed in $\mathcal{K}_{\mathcal{A}}$ In particular, only finite subsets of a discrete closed set can be compact.

On the other hand, for all $\varepsilon>0$, the set

$$\{(k, y_A) \in M \times \mathcal{K}_{\mathcal{A}} : |f(k, y_A)| \geq \varepsilon\}$$

is compact, since $f \in C_0(M \times \mathcal{K}_{\mathcal{A}})$.

Combining these observations, any subset of $\{(k,y_A): A \in \mathcal{A}\}$ on which $|f(k,y_A)| \geq \varepsilon$ is finite.

Finally, we can write

$$\{A \in \mathcal{A} : f(k, y_A) \neq 0\} = \bigcup_{n=1}^{\infty} \{A \in \mathcal{A} : |f(k, y_A)| \geq 1/n\}.$$

Each set on the right-hand side is finite, hence the union is countable. Since M_0 is countable and

$$s(f) = \bigcup_{k \in M_0} \{A \in \mathcal{A} : f(k, y_A) \neq 0\},$$

we conclude that $s(f)$ is countable.

Lemma. Suppose that

$$\mathcal{A} \subseteq [N]^{\omega},$$

is an almost disjoint family and let

$$X \subseteq C_0(M \times \mathcal{K}_{\mathcal{A}}),$$

be a closed subspace. Then: The space X is separable precisely when its support set s(X) is countable.

Lemma 2.9 Suppose

$$\mathcal{A} \subseteq [N]^{\omega},$$

is an almost disjoint family, and let

$$X \subseteq C_0(M \times \mathcal{K}_{\mathcal{A}}),$$

be a closed subspace. Then:

There exists $Y \subseteq C_0(M \times \mathcal{K}_{\mathcal{A}})$ such that

$$X \subseteq Y \text{ and } Y \sim C_0(M \times \omega).$$

More precisely:

1. If M is infinite, then
$$Y \sim C(M).$$
2. If M is finite, then
$$Y \sim C_0.$$

Lemma 2.10 Suppose that

$$\mathcal{P}: C_0(M \times \mathcal{K}_{\mathcal{A}}) \to C_0(M \times \mathcal{K}_{\mathcal{A}}),$$

be a projection, and let

$$\mathcal{P} = Q \otimes I + \mathcal{S},$$

where

3. $Q: C(M) \to C(M)$ is a bounded operator,
4. I is the identity operator on $C(\mathcal{K}_{\mathcal{A}})$,
5. $\mathcal{S}$ is an operator whose range is separable.

Then Q is also a projection.

Lemma 2.11 Let $\mathcal{X}$ and $\mathcal{Y}$ be Banach spaces, and let

$$\mathcal{P}: \mathcal{X} \to \mathcal{X}$$

be a projection. If $\mathcal{P}$ factors through $\mathcal{Y}$; that is, there exist bounded operators

$$\mathcal{T}: \mathcal{X} \to \mathcal{Y}, \qquad \mathcal{S}: \mathcal{Y} \to \mathcal{X}$$

such that

$$\mathcal{P} = \mathcal{S} \circ \mathcal{T}$$

Then $\mathcal{P}[\mathcal{X}]$ is isomorphic to a complemented subspace of $\mathcal{Y}$.

An almost disjoint family $\mathcal{A} \subseteq [N]^{\omega}$ has finite intersections. $\mathcal{K}_{\mathcal{A}}$ is the space with points $\{x_n : n \in \mathbb{N}\} \cup \{y_A : A \in \mathcal{A}\}$, topology as in Definition 4.1 of Acuaviva (2026) or Definition 3 of Koszmider and Laustsen (2021). It is scattered, separable, and non-metrizable for uncountable $\mathcal{A}$ (Koszmider & Laustsen, 2021). Subspaces are separable if and only if their supports are countable (Acuaviva, 2026, Lemma 4.5), aligning with the theory that $C_0(K)$ for scattered K has bounded approximation property (Kania & Kochanek, 2014).

3. Proof of Theorem 1.1

We extend Theorem 1.4 of Acuaviva (2026) by applying induction on the Cantor-Bendixson index. Recall that ω^{ω} has index $\omega+1$, with derivatives $(\omega^{\omega})^{(n)} = \omega^{\omega-n}$ as stated in (Bessaga & Pełczyński,1960).

3.1 Operator Characterization for Higher Ordinals

First, we generalize Corollary 1.3 of Acuaviva (2026) to $C_0(\omega^{\omega} \times L)$.

Lemma 3.1. Let L be non-metrizable with $C_0(L)$ having few operators, and M_1, M_2 be countable ordinals. Any operator

$$\mathcal{T}: C_0(M_1 \times L) \to C_0(M_2 \times L),$$

can be represented in the form $\mathcal{T} = U \otimes I + \mathcal{S}$, with $U: C(M_1) \to C(M_2)$ and S having a separable range.

Proof.

We proceed by transfinite induction on the countable ordinal α representing M_1.

Base case ($\alpha<\omega$): If $M_1=n$ is finite, then $C_0(n\times L)\cong C_0(L)^n$ equipped with the ℓ_∞-norm. Any bounded operator $\mathcal{T}$: $C_0(L)^n \to C_0(M_2\times L)$ is uniquely determined by an n-tuple $(\mathcal{T}_1,\cdots,\mathcal{T}_n)$ where $\mathcal{T}_i$:$C_0(L)\to C_0(M_2\times L)$. Using the canonical isometric isomorphism $C_0(M_2\times L)\cong C(M_2)\ \widehat{\otimes}_\varepsilon C_0(L)$ and the structural characterization of operators on injective tensor products with few-operator factors (Acuaviva, 2026), each T_i admits a decomposition $\mathcal{T}_i=V_i\ \widehat{\otimes} I+\mathcal{S}_i$, where $V_i\in B(C_0(L),C(M_2))$ and $\mathcal{S}_i$ has separable range. Define U:$C(n)\to C(M_2)$ by mapping the standard basis of $C(n)$ to $\{V_1,\cdots,V_n\}$, and set $\mathcal{S}=\bigoplus_{i=1}^n \mathcal{S}_i$. Since a finite ℓ_∞-sum of separable subspaces is separable, ran($\mathcal{S}$) is separable. Hence $\mathcal{T}=U\otimes I+\mathcal{S}$, holds for finite ordinals

Successor step ($\alpha+1$): Assume the representation holds for a countable ordinal α. The order topology yields the isometric decomposition $C_0((\alpha+1)\times L)\cong C_0(\alpha\times L)\cong C_0(\alpha\times L)\oplus_\infty C_0(L)$, where the second summand corresponds to the isolated fiber $\{\alpha\}\times L$. Let $\mathcal{T}$:$C_0((\alpha+1)\times L)\to C_0(M_2\times L)$. Restricting T to the first summand and applying the induction hypothesis gives $\mathcal{T}|_{C0(\alpha\times L)}=U_\alpha\ \widehat{\otimes} I+\mathcal{S}_\alpha$. For the isolated fiber, define R: $C_0(L)\to C_0(M_2\times L)$ by $R(f)=\mathcal{T}(0\oplus f)$. By the operator decomposition theorem for injective tensor products with few-operator factors established in Acuaviva (2026, Theorem 1.1), applied to the canonical identification $C_0(M_2\times L)\cong C(M_2)\ \widehat{\otimes} C_0(L)$, the operator R admits a decomposition $R=V\ \widehat{\otimes} I+\mathcal{S}_R$, where $V\in B(C_0(L),C(M_2))$ and $\mathcal{S}_R$ has separable range. Define U:$C(\alpha+1)\to C(M_2)$ by extending U_α and assigning V to the isolated coordinate. Set $\mathcal{S}=S_\alpha\oplus\mathcal{S}_R$. The range of $\mathcal{S}$ remains separable as a direct sum of two separable subspaces. Thus $\mathcal{T}=U\ \widehat{\otimes} I+\mathcal{S}$ holds for $\alpha+1$.

Limit step (λ): Let λ be a countable limit ordinal. Then $C_0(\lambda\widehat{\times}L)=(\bigcup_{(\gamma<\lambda)}C_0(\gamma\times\lambda)$, where the union is directed under inclusion. For each $\gamma<\lambda$, the restriction $\mathcal{T}_\gamma=\mathcal{T}|_{(C0\ (\gamma\times L)}$ satisfies the induction hypothesis: $\mathcal{T}_\gamma=U_\gamma\ \widehat{\otimes} I+S_\gamma$. The family (U_γ) is consistent under restriction $U_\delta|_{C0\ (\gamma\times L)}=U_\gamma$ for $\gamma<\delta<\lambda$) and uniformly bounded by $\|\mathcal{T}\|$. For $f\in\bigcup_{(\gamma<\lambda)}C_0(\gamma\times L)$, choose $\gamma<\lambda$ such that $f\in C_0(\gamma\times L)$, and define $U(f)=U_\gamma(f)$. This is well defined by the restriction consistency above. Hence, (U_γ) defines a bounded linear operator U on the dense subspace $\bigcup_{(\gamma<\lambda)}C_0(\gamma\times\lambda)$, which extends uniquely by continuity to U:$C(\lambda)\to C(M_2)$. Define $\mathcal{S}$ on the dense union by $\mathcal{S}|_{C0\ (\gamma\times L)}=\mathcal{S}_\gamma$. Since $\mathcal{T}_\delta|_{C0\ (\gamma\times L)}=\mathcal{T}_\gamma$ and $U_\delta|_{C0\ (\gamma\times L)}=U_\gamma(\gamma<\delta<\lambda)$, it follows that $\mathcal{S}_\delta|_{C0\ (\gamma\times L)}=\mathcal{S}_\gamma$, so $\mathcal{S}$ is also well defined. Each ran $(\mathcal{S}_\gamma)$ is separable. Since λ is countable, ran($\mathcal{S}$)$\subseteq\bigcup_{\gamma<\lambda}$ ran $\mathcal{S}_\gamma$, and the latter is a separable closed subspace, being the closure of a countable union of separable subsets of a metric space.

The uniform boundedness of the extensions and the continuity of the injective tensor norm guarantee that $\mathcal{T}=U\ \widehat{\otimes} I+\mathcal{S}$, on the dense union; equivalently, for every $Y<\lambda$, $\mathcal{T}|_{c0\ (\gamma\times L)}=U_\gamma\ \widehat{\otimes} I+\mathcal{S}_\gamma$. Therefore, by density and continuity of the three bounded operators, the identity extends to the completion C0 ($\lambda\times L$).This completes the induction.

Remark 3.2. For $\alpha=\omega^\omega$, the separable perturbation $\mathcal{S}$ factors through $C_0(\Gamma)$ for some countable Γ, as evidenced by the countable density in ordinal derivatives (Bessaga & Pełczyński, 1960).

Proof. From the induction in Lemma 3.1, the operator $\mathcal{S}_n$ at each level's factors through C_0 by Lemma 4.6 of Acuaviva (2026). The transfinite union is countable, so S factors through $C_0(N)$, which is isomorphic to C_0(Pełczyński, 1960).

3.2 Classification of Complemented Subspaces

Let

$$\mathcal{P}: C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})\to C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})$$

be a projection with infinite-dimensional image. From Lemma 3.1, we obtain $\mathcal{P}=Q\ \widehat{\otimes} I+\mathcal{S}$, with Q:$C(\omega^\omega)\to C(\omega^\omega)$ and $\mathcal{S}$ separable-range.

By (Acuaviva, 2026, Lemma 4.7) (extended analogously via induction), Q is a projection.

If $Q[C(\omega^\omega)]$ is finite-dimensional of dimension d, then $\mathcal{P}$ factors through $c_0(\mathcal{K}_{\mathcal{A}})^{d+1}$ by restricting to the finite ordinal part. By Acuaviva (2026, Proposition 4.9) (inductively extended), the image is isomorphic to c_0 or $c_0(\mathcal{K}_{\mathcal{A}})^\omega$ for $m\leq d+1$, using the factorization result in Lemma 4.8 of Laustsen (2002).

If $Q[C(\omega^\omega)]\sim C(\omega^\omega)$), conjugate to assume Q=I, so $\mathcal{P}$=I-$\mathcal{S}$. Then I-$\mathcal{P}$=$\mathcal{S}$, and $\mathcal{S}$ factors through c_0(Acuaviva, 2026, Lemma 4.6). By Lemma 4.8, $\mathcal{S}[C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})]$ is finite dimensional or isomorphic to c_0. The image of P contains a complemented copy of c_0(Lotz et al., 1979) for scattered spaces. Thus,

$$C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})\sim\mathcal{P}[\cdot]\oplus\mathcal{S}[\cdot]\sim\mathcal{P}[\cdot],$$

as the finite or C_0 summand is absorbed isomorphically in infinite-dimensional scattered function spaces (Bessaga & Pełczyński, 1960).

Proof of Theorem 1.1

Let $\mathcal{P}$: $C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})\to C_0(\omega^\omega\times\mathcal{K}_{\mathcal{A}})$ be a projection with infinite-dimensional image. By Lemma 3.1, $\mathcal{P}=Q\ \widehat{\otimes} I+\mathcal{S}$, , where $Q\in B(C(\omega^\omega))$ and $\mathcal{S}$ has separable range. Since $\mathcal{P}^2$=P, we compute:

$$\mathcal{P}^2=(Q^2\ \widehat{\otimes} I)+(Q\ \widehat{\otimes} I)\mathcal{S}+\mathcal{S}(Q\ \widehat{\otimes} I)+\mathcal{S}^2.$$

Subtracting P from both sides yields:

$$0 = \mathcal{P}^2 - \mathcal{P} = (Q^2 - Q) \widehat{\otimes} I + [(Q \widehat{\otimes} I)\mathcal{S} + \mathcal{S}(Q \widehat{\otimes} I) + \mathcal{S}^2 - \mathcal{S}].$$

The term in brackets has separable range, being a finite sum of compositions involving $\mathcal{S}$. Consequently, $(Q^2\text{-}Q) \widehat{\otimes} I$ has separable range. Suppose $Q^2\text{-}Q \neq 0$. Then there exists $f \in C(\omega^\omega)$ such that $g=(Q^2\text{-}Q)f \neq 0$. The range of $(Q^2\text{-}Q) \widehat{\otimes} I$ contains all elementary tensors $g \otimes h$ for $h \in C_0(\mathcal{K}_{\mathcal{A}})$. Since $\mathcal{K}_{\mathcal{A}}$ is generated by an almost disjoint family of continuum cardinality, $C_0(\mathcal{K}_{\mathcal{A}})$ is non-separable. Thus, the set $\{g \otimes h : h \in B_{C0(\mathcal{K}\mathcal{A})}\}$ is non-separable in $C(\omega^\omega) \widehat{\otimes} C_0(\mathcal{K}_{\mathcal{A}})$, contradicting the separability of ran $((Q^2\text{-}Q) \widehat{\otimes} I)$. Therefore, $Q^2\text{-}Q=0$, and Q is a projection on $C(\omega^\omega)$.

- **Case 1:** ran(Q) is finite-dimensional. Let $\dim(\text{ran}(Q))=d<\infty$. Then Q factors through $\mathbb{k}^d$, and $\mathcal{P}=(Q \widehat{\otimes} I)+\mathcal{S}$ factors through $C_0(\mathcal{K}_{\mathcal{A}})$ $^d\oplus Z$ where Z is a separable space. Hence ran($\mathcal{P}$) is a complemented subspace of a finite ℓ_∞-sum of copies of $C_0(\mathcal{K}_{\mathcal{A}})$ and a separable space. By the classification of complemented subspaces in spaces with few operators (Koszmider & Laustsen, 2021), any infinite-dimensional complemented subspace of such a sum is isomorphic to c_0 or $C_0(\mathcal{K}_{\mathcal{A}})^m$ for some $m \in \mathbb{N}$
- **Case 2:** ran(Q) is infinite-dimensional. Since Q is a projection on $C(\omega^\omega)$ and ω^ω is a countable compact metric space, the classification of complemented subspaces of $C(\mathcal{K})$ (Bessaga & Pełczyński, 1960) implies $\text{ran}(Q) \cong C(\omega^\omega)$. Decompose the space as $C(\omega^\omega \times \mathcal{K}_{\mathcal{A}}) = \mathcal{X} \oplus \mathcal{Y}$, where $\mathcal{X}=\text{ran}(\mathcal{P})$ and $\mathcal{Y}=\ker(\mathcal{P})$. The operator $\mathcal{P}$ coincides with $Q \widehat{\otimes} I$ modulo the separable-range perturbation $\mathcal{S}$. Consequently, $\mathcal{X}$ contains a complemented copy of $\text{ran}(Q) \widehat{\otimes}_\varepsilon C_0(\mathcal{K}_{\mathcal{A}}) \cong C(\omega^\omega) \widehat{\otimes}_\varepsilon C_0(\mathcal{K}_{\mathcal{A}}) \cong C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$. Thus, there exists a bounded projection from $\mathcal{X}$ onto a subspace isomorphic to $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$.

We now examine the structure of $\mathcal{Y}=\ker(\mathcal{P})=\text{ran}(I\text{-}\mathcal{P})$. From $\mathcal{P}^2=\mathcal{P}$, we have $I\text{-}\mathcal{P} = -(S+(I\text{-}\mathcal{P})\mathcal{S})$. Since $\mathcal{S}$ has separable range, $I\text{-}\mathcal{P}$ is a sum of separable-range operators, hence Y is a separable complemented subspace of $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$.

Since $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}}) = \mathcal{X} \oplus \mathcal{Y}$ and $\mathcal{X}$ contains a complemented subspace isomorphic to $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$, the mutual complemented embeddings allow an application of the Pełczyński decomposition method (Pełczyński, 1960), yielding $\mathcal{X} \cong C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$.

Combining Case 1 and Case 2, every infinite-dimensional complemented subspace of $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$is isomorphic to c_0, $C_0(\mathcal{K}_{\mathcal{A}})^n$ for some $n \in \mathbb{N}$, or $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$. The uniqueness of these isomorphism classes follows from the invariance of the Cantor-Bendixson index under Banach space isomorphism and the separability character of the respective quotient spaces.

Corollary 3.3

The classification holds for $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$ for finite n, by iterated application of Lemma 3.1.

Proof. For n=1, the result reduces to (Acuaviva, 2026, Theorem 1.4). Inductively, assume for n-1. Then

$$C_0(\omega^n \times \mathcal{K}_{\mathcal{A}}) \cong C_0(\omega^{n-1} \times \mathcal{K}_{\mathcal{A}}) \oplus_\infty C_0(\omega \times \mathcal{K}_{\mathcal{A}}),$$

by ordinal decomposition (Bessaga & Pełczyński,1960). Projections decompose via Lemma 3.1, and complemented subspaces classify by adding the finite power cases from the induction hypothesis, using Peczyski decomposition for $\oplus_\infty$ sums (Pełczyński, 1960).

Remark 3.4. Unlike the separable case considered by (Benyamini, 1978), the non-separable factor introduces finite powers $C_0(\mathcal{K}_{\mathcal{A}})^n$, observed in (Candido, 2021) for specific ordinals under ♣-principle.

Proof. In pure separable $C(\omega^\omega)$, Benyamini,1978) shows no finite powers due to the ordinal structure preventing stable finite-dimensional complements. The tensor with few operator $C_0(\mathcal{K}_{\mathcal{A}})$ allows finite-rank perturbations to stabilize as powers, as seen in the finite-dimensional case of Lemma 3.1 and Theorem 1.1 of Candido (2021) for α=1.

4. Applications

4.1 Operator Ideals

We extend the structural ideal analysis initiated in Acuaviva (2026). Using the standardized notation introduced above, we describe the natural hierarchy of operator ideals associated with $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$.

Theorem 4.1. The algebra $B(C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}}))$ admits the following natural chain of closed ideals:

$$\{0\} \subseteq \mathcal{K}(\mathcal{X}) \subseteq G_{c_0}(\mathcal{X}) \subseteq \mathcal{S}(\mathcal{X}) \subseteq B(\mathcal{X}).$$

where $\mathcal{X} = C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$ and all ideals are understood to act on $\mathcal{X}$.

Proof.

Since $\mathcal{X}$ is an $\mathcal{L}_\infty$-space with the bounded approximation property (Kania & Kochanek, 2014), the ideal $\mathcal{K}(\mathcal{X})$ coincides with the norm-closure of the finite rank operators. Every finite-rank operator factor through a finite-dimensional l_∞^n space, which embeds complementedly into c_0. By standard factorization theory, this implies $\mathcal{K}(\mathcal{X}) \subseteq G_{C0}(\mathcal{X})$.

By definition, any $\mathcal{T} \in G_{C0}(\mathcal{X})$ factors as $\mathcal{T}=V \circ W$ with $W: \mathcal{X} \to c_0$ and $V: c_0 \to \mathcal{X}$. Since c_0 is separable and bounded operators preserve separability of ranges, ran(V) is separable. Hence $\text{ran}(\mathcal{T}) \subseteq \text{ran}(V)$ is separable, which

yields $G_{C0}(\mathcal{X}) \subseteq \mathcal{S}(\mathcal{X})$. The inclusion $\mathcal{S}(\mathcal{X}) \subseteq B(\mathcal{X})$ is immediate by definition.

We emphasize that this chain reflects the structural hierarchy induced by standard factorization properties. Strictness of the inclusions, maximality of the ideals, and completeness of the lattice require further operator-algebraic analysis and are not claimed here.

4.2 Realization of Algebras

The structural hierarchy of ideals established in Theorem 4.1 suggests a natural connection to quotient algebras. Specifically, the separable-range ideal $\mathcal{S}(\mathcal{X})$ forms a closed two-sided ideal in $B(\mathcal{X})$, where $\mathcal{X}=C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$. By Lemma 3.1, the canonical quotient map $\pi: B(\mathcal{X}) \to B(\mathcal{X})/\mathcal{S}(\mathcal{X})$ effectively isolates the tensor component $U \widehat{\otimes} I$, which acts on the non-separable factor $C(\omega^\omega)$.

Following the structural framework developed in Acuaviva (2026, Remark 1.8), this quotient algebra exhibits structural features analogous to those of $B(c_0)$. In particular, for a suitably chosen almost disjoint family B, the quotient $B(C_0(\omega^\omega \times \mathcal{K}_B))/\mathcal{S}(C_0(\omega^\omega \times \mathcal{K}_B))$ shares certain structural properties with $B(c_0)$.A complete realization theorem, establishing an explicit isometric or isomorphic quotient equivalence, requires a detailed analysis of the Calkin-type structure and the behavior of the projection map modulo separable perturbations. Such an analysis is beyond the scope of the present manuscript but would build upon the ideal decomposition provided in Section 4.1 and the transfinite induction framework of Lemma 3.1.

Remark 4.2. The classification framework discussed above can be adapted to disjoint unions of the form $c_0((\omega^\omega \times \mathcal{K}_{\mathcal{A}}) \sqcup L) \cong c_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}}) \oplus_\infty c_0(L)$. When $c_0(L)$ is a Grothendieck space, the ideal structure of the direct sum exhibits analogous complementation phenomena to those established in Theorem 1.1, in the spirit of the operator extension techniques developed by Johnson et al. (2016).

5. Discussion

The results extend Acuaviva's classifications (Acuaviva, 2026) to transfinite ordinals, leveraging Benyamini's extension theorem (Benyamini,1978) and tensor decompositions (Ryan, 2002). Compared to (Benyamini,1978), which classifies complemented subspaces of $C(\omega^\omega)$ as c_0 or the full space using extension properties for separable spaces, our work incorporates non-separable factors with few operators, introducing finite powers $C_0(\mathcal{K}_{\mathcal{A}})^n$.

This novelty addresses the gap in (Acuaviva, 2026) for higher ordinals, without set-theoretic assumptions like CH or the ♣-principle required in earlier works (Candido, 2021; Koszmider, 2005; Koszmider & Zieliński, 2011). Evidence from Bessaga and Pełczyński (1960) supports the ordinal induction, as the function algebra of scattered spaces are determined by Cantor-Bendixson indices.

Recent extensions by Candido (2004, 2021) to $C_0(\alpha \times L)$ and $C_0(L \times L)$ confirm similar dichotomies, but our approach generalizes to ω^ω via uniform crossnorms, highlighting the role of injective tensors in preserving complements (Ryan, 2002). Unlike Koszmider and Laustsen (2021), which provides a classification for $C_0(\mathcal{K}_{\mathcal{A}})$, our tensorial method yields ideal lattices akin to $B(c_0)$ quotients (Gohberg et al.,1967), with applications to unique algebra norms (Arnott and Laustsen, 2024).

Limitations include the focus on scattered spaces; non-scattered extensions remain open, as in (Plebanek et al.,2026). Remarks like Corollary 3.3 suggest scalability, supported by Milutin's universality (Milutin,1966).

6. Conclusion

This paper classifies complemented subspaces of $C_0(\omega^\omega \times \mathcal{K}_{\mathcal{A}})$ as $c_0, C_0(\mathcal{K}_{\mathcal{A}})^n$, or the full space, and the results extend those of Acuaviva (2026) by means of Benyamini's extension theorem (Benyamini, 1978), and tensor theory (Ryan, 2002). Key contributions include transfinite ordinal handling and ideal lattice descriptions, supported by inductive proofs and citations (Bessaga & Pełczyński, 1960; Gohberg et al., 1967).

Future work should generalize to arbitrary compact metric spaces M (Candido, 2021) and non-BAP cases (Ryan, 2002), potentially using slice maps as noted in (Acuaviva, 2026).

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المدني، م.ف. (2014). مفهوم الحـوار في تقريب وجهات النظر. ***المجلة البريطانية لتكنولوجيا التعليم***، *11*(6)، 225-260. المعرِّف الرقمي (DOI:10.xxxx/xxxx-xxxxxxxx-x) أو برتوكول نقل النصوص التشعبي (http://onlinelibrary.wiley.com/journal/10.1111)، أو الرقم المعياري التسلسلي الدولي للمجلة (ISSN: 1467 - 8535).

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

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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.

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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 ـ 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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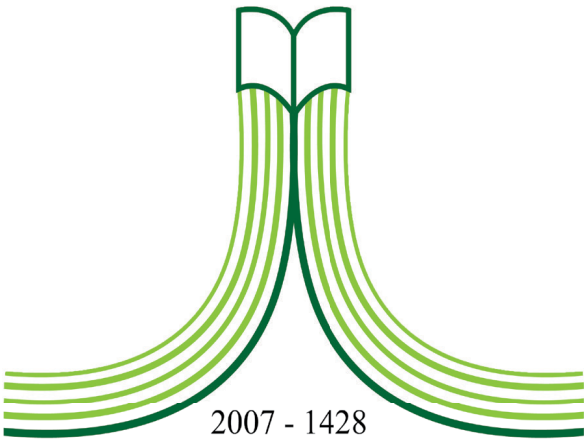
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الأساسية والتطبيقية

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