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A behaviourally informed digital framework for safety culture transformation in the oil and gas industry

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Occupational safety within the oil and gas industry continues to face persistent behavioural and cultural challenges despite advances in engineering and management systems. Many existing digital safety systems are primarily structured around compliance-oriented functions, such as incident reporting, audit documentation, and checklist monitoring, with comparatively limited integration of behavioural reinforcement mechanisms and user engagement strategies. This study presents a behaviourally informed digital intervention framework for safety culture transformation, operationalised through the Behavioural Occupational Safety Culture Application (BOSCA). Using a six-step framework grounded in behavioural-change theory, BOSCA's architecture was structured into four layers; Application, Control, Security & Integration, and Data Storage each ensuring secure, real-time interaction between users and the backend system. System functionality validation demonstrated stable performance, with accurate data processing, reliable notification triggering, and secure data handling observed under simulated operational conditions. Usability testing involving ten industry practitioners indicated high user acceptance, with participants reporting clear interface navigation, intuitive module integration, and effective motivational feedback mechanisms that supported continuous engagement. The BOSCA model represents a scalable digital framework that bridges behavioural science with safety management, transitioning from reactive compliance toward proactive, data-driven behavioural engagement in high-risk industrial environments.

Keywords Occupational safety, Behavioural intervention, Mobile application, Safety culture, Oil and gas industry

Occupational safety remains a critical concern in high-risk industries such as oil and gas, where human behaviour and organisational culture profoundly influence accident prevention and operational resilience[1,2]. Despite decades of investment in engineering controls and safety management systems, behavioural and cultural dimensions of safety continue to lag behind, often emerging as root causes in major industrial incidents[3,4]. Conventional safety training and compliance mechanisms typically delivered through audits, briefings, and paper-based reporting struggle to sustain worker engagement or translate safety awareness into consistent safe practices[5]. This gap underscores the pressing need for adaptive, behaviourally informed digital interventions capable of driving continuous participation and reinforcing safety values at all organisational levels. Many existing digital safety systems, including iSafe Work, Safety+, and e-Safety Training, are primarily structured around compliance-oriented functions such as incident reporting, audit documentation, and hazard tracking, rather than behavioural transformation[6,7]. While these systems are effective in supporting regulatory compliance and data documentation, previous studies have highlighted their limitations in sustaining user engagement and influencing long-term behavioural change within organisational safety culture. These tools also provide limited integration of motivational and cognitive constructs, resulting in short-term engagement and minimal

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long-term impact on safety culture. In contrast, the growing success of mobile health (mHealth) applications in influencing health-related behaviour provides a relevant conceptual foundation for the development of behaviourally informed digital interventions[8]. mHealth platforms have demonstrated effectiveness in promoting sustained user engagement, facilitating real-time feedback, and reinforcing behavioural change through personalised and interactive features. These systems integrate behavioural theories into digital environments, enabling continuous monitoring, feedback, and adaptive intervention strategies. Drawing from these principles, the BOSCA framework adopts a similar approach by embedding behavioural constructs such as motivation, communication, and competency development within a mobile-based safety management system. In this study, behavioural science serves as the foundational framework guiding the design of the BOSCA system. Rather than functioning solely as a technological tool, the platform is structured to translate behavioural theories into actionable digital mechanisms. The Information–Motivation–Behavioural Skills (IMB) model and behavioural-based safety principles are applied to define how information delivery, motivational reinforcement, and skill development can influence worker behaviour within organisational safety systems. This theoretical grounding ensures that each system component is purposefully designed to support behavioural engagement, rather than merely facilitate data collection or compliance monitoring. This alignment highlights how behaviour-change mechanisms successfully applied in health contexts can be translated into occupational safety settings to enhance safety participation and organisational engagement[9]. However, unlike conventional mHealth applications that focus primarily on individual health outcomes, BOSCA extends these principles to organisational safety culture, where behavioural change must occur across multiple levels of the workforce. This distinction underscores the novelty of the proposed framework in adapting behaviourally informed digital strategies to complex industrial environments.

Safety culture is widely recognised as a critical determinant of safety performance in high-risk industries such as oil and gas, where complex operations, hazardous environments, and human–system interactions increase the likelihood of catastrophic incidents[10]. A strong safety culture reflects shared organisational values, beliefs, and practices that prioritise safety over competing operational demands, thereby influencing how individuals perceive risks and respond to unsafe conditions[11]. Empirical evidence has consistently demonstrated that organisations with well-established safety cultures experience lower accident rates, improved compliance with safety procedures, enhanced communication, and greater workforce engagement in safety-related activities[12]. The core elements of safety culture typically include management commitment, safety communication, training and competency development, employee involvement, and safety ownership. These elements function as interconnected behavioural drivers that shape individual and collective safety practices within the workplace. For instance, visible management commitment reinforces safety priorities and accountability, while effective communication ensures timely dissemination of hazard information and promotes shared situational awareness[13]. Similarly, continuous training and competency development enhance workers' ability to recognise and respond to risks, while safety ownership encourages proactive reporting and participation in safety initiatives. These components collectively influence worker behaviour through cognitive, motivational, and social mechanisms. When safety culture is strong, employees are more likely to internalise safety values, engage in safe work practices, and actively contribute to hazard identification and risk mitigation. Conversely, weak safety culture has been linked to unsafe behaviours, communication breakdowns, and increased incident rates[14]. Despite the recognised importance of safety culture, translating these behavioural constructs into practical, scalable interventions remains a significant challenge, particularly within digital safety management systems. This gap underscores the need for innovative approaches that operationalise safety culture elements into actionable and measurable components within digital platforms.

Problem statement

Despite the growing adoption of digital safety technologies, a critical gap remains in the integration of behavioural safety theory within digital safety management systems. Most existing platforms emphasise compliance monitoring and administrative reporting rather than addressing the behavioural determinants that shape organisational safety culture[15]. Consequently, many digital safety tools function primarily as data collection platforms rather than behavioural intervention systems capable of influencing worker motivation, engagement, and safety ownership. Within Malaysia's oil and gas sector, this limitation is particularly significant due to complex operational hierarchies, diverse workforce composition, and the need for continuous safety communication across organisational levels. Although previous research has identified key behavioural determinants influencing safety culture in this industry, these insights have rarely been translated into practical digital interventions capable of supporting real-time behavioural engagement. Therefore, there is a need for a behaviourally informed digital framework that integrates safety training, communication, incident reporting, motivational reinforcement, and competency development within a unified mobile platform capable of strengthening organisational safety culture.

Study motivation and contribution

To address this gap, the present study introduces the Behavioural Occupational Safety Culture Application (BOSCA), a theory-driven digital framework designed to operationalise behavioural safety constructs within a mobile-enabled ecosystem[16]. BOSCA translates behavioural determinants identified in previous safety culture research into interactive digital modules that promote continuous engagement, feedback, and organisational learning. In this study, the mobile application serves as an implementation platform for translating behavioural theory into practice, rather than being the sole focus of the research. This study contributes to the literature in several key ways. First, it provides a theoretical contribution by operationalising behavioural science, specifically the Information–Motivation–Behavioural Skills (IMB) model and behavioural-based safety principles, into a structured digital intervention framework for occupational safety. Second, it introduces a methodological contribution through the application of a Design and Development Research (DDR) approach to systematically translate behavioural constructs into functional system modules. Third, it presents a system-level contribution by proposing a multi-layered architecture integrated with real-time feedback mechanisms that enable continuous behavioural reinforcement. Finally, the study offers an applied contribution by demonstrating how behavioural pathways; cognitive, motivational, and behavioural skills can be embedded within digital safety systems to support proactive safety engagement rather than passive compliance monitoring.

Importantly, the BOSCA framework is conceptualised as a behaviourally driven safety intervention rather than merely a technological solution. The system operationalises key safety culture elements, including management commitment, communication, training, safety ownership, and reward mechanisms, into structured digital processes that directly influence worker behaviour. These safety interventions exert their impact through three primary pathways. First, cognitive pathways enhance safety knowledge and risk awareness through continuous training and real-time communication alerts. Second, motivational pathways reinforce positive safety behaviours through gamified rewards, feedback loops, and performance recognition. Third, behavioural skill pathways strengthen competency through structured audits, assessments, and practice-based learning modules. Through the integration of these pathways, BOSCA facilitates a shift from passive compliance toward active safety participation, enabling workers to engage in hazard identification, reporting, and continuous improvement. This behavioural reinforcement mechanism represents a critical advancement in translating safety culture theory into practical and measurable interventions within digital environments.

The innovative contribution of this study lies in its integration of behavioural science, digital system architecture, and real-time feedback mechanisms into a unified framework for safety culture transformation. Unlike conventional digital safety systems that primarily focus on compliance monitoring and data reporting, BOSCA embeds behavioural constructs directly within system functionalities, enabling continuous interaction between users and safety processes. This approach transforms digital safety tools from passive monitoring systems into active behavioural intervention platforms. Furthermore, the framework introduces a modular and scalable architecture that allows safety culture elements to be operationalised as measurable, interactive components within a mobile ecosystem. This integration provides a novel pathway for bridging the gap between theoretical safety models and practical implementation in high-risk industrial environments.

Assumptions and limitations

The present study focuses on the design and development of the BOSCA system architecture and the prototype interface. The platform was evaluated under simulated operational conditions with representative industry users. It is assumed that digital engagement mechanisms such as real-time notifications, gamified reward systems, and competency tracking can positively influence behavioural participation in workplace safety activities. However, the long-term impact of the BOSCA platform on safety performance, incident reduction, and organisational culture requires further validation through real-world implementation and longitudinal evaluation. Future research should therefore assess the effectiveness of the system in operational environments across different high-risk industries.

The objective of this study is to design, develop, and validate the BOSCA mobile application interface and system architecture as a functional model for digital safety transformation. Specifically, the study aims to (i) operationalise behavioural constructs such as motivation and communication into interactive digital modules, (ii) establish a secure, multi-layered architecture for continuous monitoring and feedback, and (iii) evaluate the system's usability, functionality, and behavioural alignment. By merging behavioural science with digital innovation, BOSCA represents a new paradigm for strengthening safety culture in Malaysia's oil and gas sector transitioning from reactive compliance monitoring toward proactive, data-driven behavioural engagement.

Results

The results of this study are presented in terms of system functionality validation and usability evaluation, reflecting the design and development scope of the BOSCA framework.

Conceptual framework of the intervention

The conceptual framework of the BOSCA intervention (Fig. 1) illustrates the theoretical underpinnings linking *motivation*, *behavioural skills*, *moderating factors*, and *health outcomes*. Grounded in the principles of behaviour-change theory, the model emphasises that motivation and behavioural competence are precursors to sustainable safety culture transformation. Moderating factors such as leadership commitment, communication, and reward systems shape these behavioural outcomes, which in turn influence the overall health and safety performance within oil and gas organisations.

This conceptual framework served as the theoretical blueprint for the design and digital translation of the BOSCA system architecture. Each construct within the framework; motivation, behavioural skills, moderating factors, and health outcomes was systematically operationalised into functional modules within the mobile application. Motivational elements were embedded through gamified reward systems and real-time feedback notifications; behavioural skills were translated into interactive training and competency assessment features; moderating factors such as leadership engagement and communication flow were integrated through managerial dashboards and alert systems; while health outcomes were represented as measurable performance indicators within the user analytics layer. This theoretical-to-digital alignment ensured that every component of BOSCA was grounded in behavioural science and organisational safety principles, providing a structured pathway from conceptual understanding to practical implementation. The resulting multi-layered architecture thus embodies

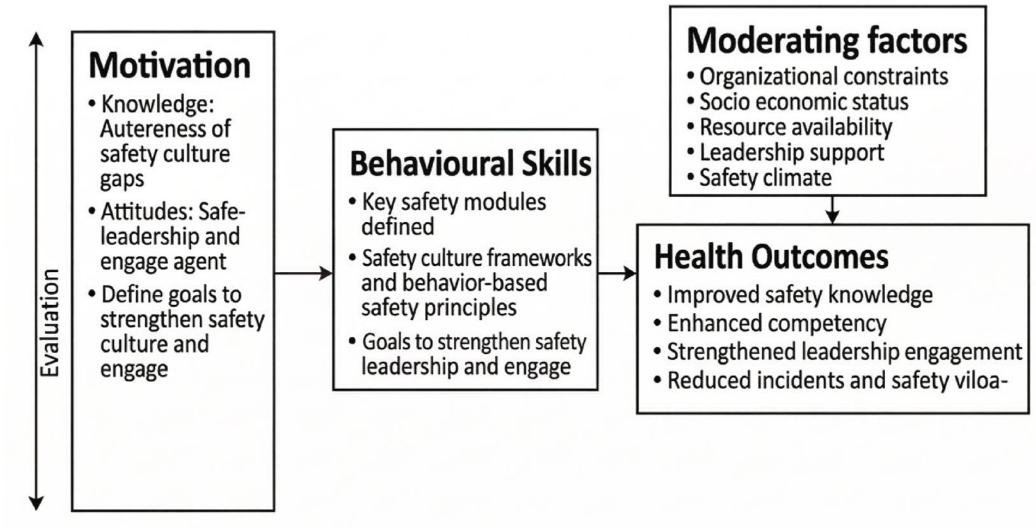

Fig. 1. Conceptual framework of the intervention model illustrating the relationship between motivation, behavioural skills, moderating factors, and health outcomes for enhancing safety culture in the oil and gas industry.

the behavioural mechanisms illustrated in Fig. 1, enabling dynamic feedback loops and continuous monitoring that drive progressive improvement in safety culture across the oil and gas sector.

Software architecture description of BOSCA

The software architecture of the Behavioural Occupational Safety Culture Application (BOSCA) was developed using a structured architecture-description approach that integrates both functional and operational perspectives of the system. This approach combines a use-case view and a logical operation view to provide a comprehensive representation of system capabilities, user interactions, and runtime behaviour.

From a functional perspective, the use-case view (Fig. 1A) defines the core system functionalities and their relationships with different user roles. The BOSCA platform supports four primary user groups: employees (workers), safety officers, safety managers, and system administrators. Each group interacts with the system through a defined set of functions tailored to their operational responsibilities. Employees are primarily engaged in reporting incidents, completing audit checklists, accessing training modules, performing competency assessments, receiving safety alerts, and tracking rewards and achievements. Safety officers oversee operational safety activities, including reviewing incident reports, monitoring audit submissions, assigning training, and tracking employee participation. Safety managers utilise the system for higher-level monitoring, such as analysing safety performance, reviewing trends, and approving recognition and rewards. System administrators manage user access, system configuration, permissions, and audit trails to ensure proper system governance. The use-case model also illustrates functional dependencies within the system, where common functions such as user authentication ("log in") and dashboard access are shared across multiple user roles. This structured representation ensures clarity in defining system boundaries and highlights how BOSCA supports end-to-end behavioural safety management through integrated user interactions.

From an operational perspective, the logical operation view (Fig. 2B) describes how system components interact dynamically during key processes. Two primary workflows are modelled: incident reporting and training and competency management. In the incident reporting workflow, the process begins with the employee initiating a report through the mobile application interface. The request is authenticated using secure authentication mechanisms (OAuth and role-based access control), after which the incident data are transmitted to the incident service for processing. The workflow orchestrator validates and coordinates the process before storing the report in the incident database. Subsequently, the notification service triggers real-time alerts to safety officers, enabling timely response and review via the system dashboard. In the training and competency workflow, users access training modules through the mobile interface, and content is retrieved via the training service. Upon completion of training, assessment results are processed by the competency service and evaluated by the workflow orchestrator. The resulting competency scores are stored in the database and used by the reward service to assign performance points or badges. These updates are reflected in the user dashboard, providing continuous feedback and reinforcing positive safety behaviour.

The interaction between system components demonstrates a coordinated flow of data and control across the application, supported by modular services and central orchestration logic. The architecture follows a service-oriented approach in which individual functional modules (e.g., incident reporting, training, competency, and rewards) operate as interconnected services, enabling scalability, maintainability, and flexibility. Security mechanisms, including authentication, access control, and secure data handling, are embedded within the operational workflows to ensure data integrity and system reliability. Collectively, the integration of the use-case view and logical operation view provides a structured and reproducible description of the BOSCA architecture,

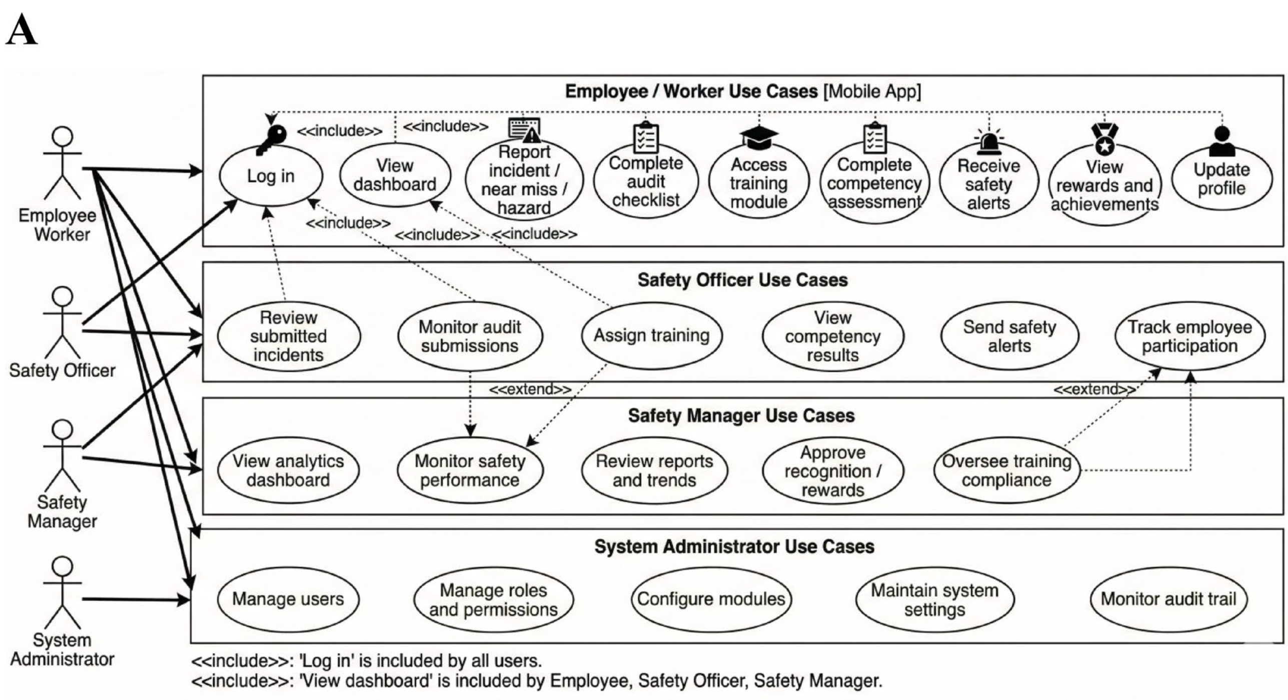

Fig. 2. Software architecture description of the Behavioural Occupational Safety Culture Application (BOSCA). (**A**) Use-case view illustrating the interactions between system actors (employee/worker, safety officer, safety manager, and system administrator) and the core functionalities of the mobile application, including incident reporting, auditing, training, competency assessment, communication, and system management. (**B**) Logical operation view depicting system workflows: (i) incident reporting workflow, showing the sequence of interactions from user input to data processing, storage, and notification; and (ii) training and competency workflow, illustrating content delivery, assessment evaluation, performance tracking, and reward allocation. Together, these views provide a comprehensive representation of BOSCA's functional capabilities and operational behaviour.

clearly illustrating both the system's functional capabilities and its runtime behaviour. This dual-perspective representation addresses previous limitations in architectural clarity and ensures consistency between system design, implementation, and user interaction.

Intervention outcomes and performance objectives

Table 1 presents the matrix of intervention outcomes, performance, and change objectives developed through the Phase 1 needs assessment. Each objective corresponds to specific requirements, expected behavioural changes, and anticipated outcomes aimed at improving safety culture. For instance, strengthening management commitment was linked to enhancing accountability, improving communication, and demonstrating visible leadership. Likewise, improving safety training and communication was intended to enhance knowledge retention and information flow, while the introduction of a digital reward system promoted positive reinforcement and safety ownership.

Wireframe design and module integration

Figure 3 presents the wireframe designs that guided the layout and workflow of BOSCA. The initial schematic was iteratively refined to ensure logical transitions between screens, minimal cognitive load, and visual clarity. The wireframe delineates eight primary interfaces: *Login*, *Dashboard*, *Training*, *Audits*, *Rewards*, *Alerts*, *Enhancement*, and *Profile Management*. The dashboard serves as a central hub linking all modules, while the profile interface summarises individual achievements, completed audits, and training scores. These components collectively reinforce behavioural engagement through continuous feedback loops.

Control-layer algorithm flow

The control-layer algorithmic flow (Fig. 4) comprises three integrated processes that translate user activity into automated system responses. The data collection and validation algorithm (Fig. 4A) captures behavioural safety inputs such as audits, incidents, and training records and verifies their completeness and accuracy before database storage. The automated feedback and notification engine (Fig. 4B) analyses validated data to generate real-time alerts and motivational messages, reinforcing user engagement and timely response to safety tasks. The scheduling algorithm (Fig. 4C) issues reminders for upcoming audits, training, and reporting deadlines, maintaining consistent participation across users. Together, these processes establish a continuous feedback

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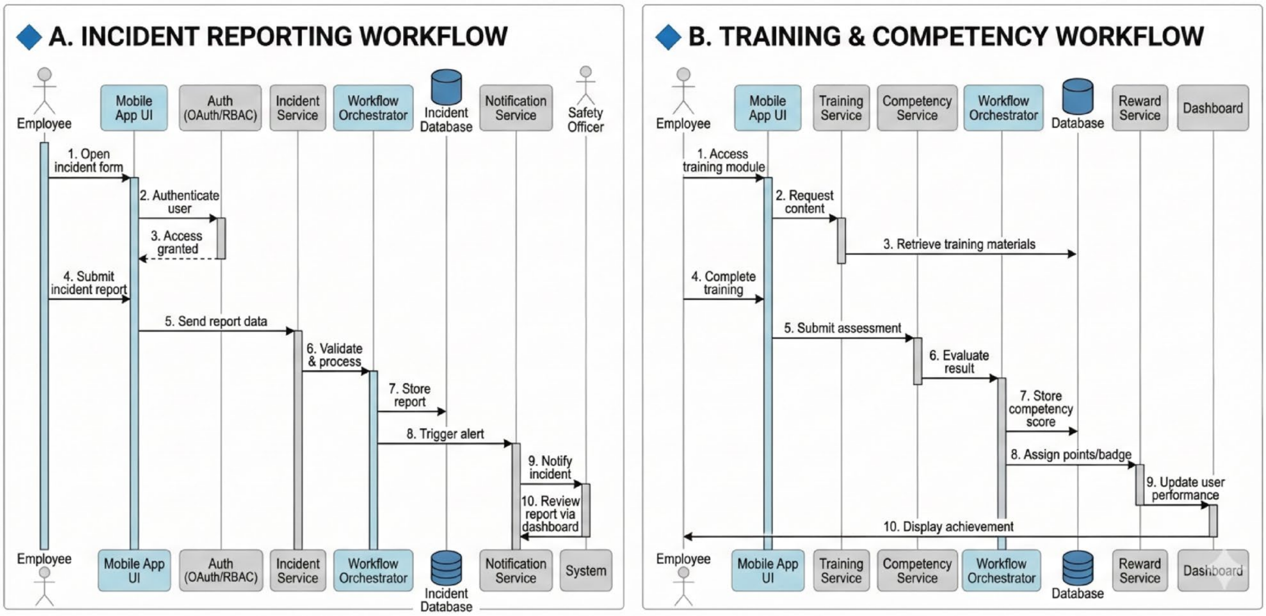

Fig. 2. (continued)

Objectives	Requirements	Behavior	Constraints	Outcomes
Strengthening Management Commitment	Develop leadership-driven safety initiatives Enhance accountability and communication between managers and staff	Demonstrate visible leadership in safety programs and respond to feedback proactively	Limited time commitment from management Hierarchical decision-making	Improved safety leadership and communication culture
Enhancing Safety Commitment	Establish shared safety values and responsibilities Encourage consistent participation in safety activities	Participate actively in reporting, safety talks, and audits	Low motivation and inconsistent engagement	Increased safety awareness and compliance
Promoting Safety Ownership	Encourage employees to take responsibility for workplace safety Create self-reporting and monitoring mechanisms	Report hazards and unsafe acts promptly	Fear of blame or repercussions	Improved accountability and proactive reporting behavior
Improving Safety Training	Provide accessible, interactive digital learning content Conduct periodic refresher modules	Complete in-app safety training and assessments	Connectivity limitations Time availability	Enhanced knowledge retention and training participation
Strengthening Safety Communication	Develop a real-time communication channel for safety alerts and notifications	Share information promptly and provide peer feedback via the app	Technological literacy Information overload	Faster information dissemination and improved situational awareness
Reward and Recognition System	Define measurable safety performance indicators Implement digital recognition and reward badges	Engage consistently in safe practices and mentoring peers	Budget constraints Possible bias in recognition	Reinforced positive safety behavior and motivation
Supporting Safety Investment	Allocate resources for safety innovation and improvement programs Track safety investments digitally	Record and update investment activities through the app	Limited organizational budget Bureaucratic approval delays	Increased transparency in safety investment tracking
Developing Safety Competency	Create competency-based safety assessments and matrix Link training outcomes to performance metrics	Demonstrate skills improvement via assessment results	Variability in user participation Training fatigue	Improved skill competency and continuous learning culture

Table 1. Intervention outcomes, performance, and change objectives matrix based on the needs assessment in Phase 1.

loop in which behavioural data inform training, communication, and recognition systems, fostering adaptive learning and accountability throughout all organisational levels.

BOSCA mobile application interface

The BOSCA mobile application interface (Fig. 5) integrates six core modules; Audit, Training, Reward Recognition, Incident Reporting, Competency, and Communication Alerts to support continuous behavioural engagement and organisational safety monitoring. The Audit module enables digital inspections and automated scoring; the Training and Competency modules deliver interactive learning and assess skill proficiency; the Incident Reporting module streamlines hazard and near-miss submissions with real-time notifications; the Reward Recognition module reinforces motivation through digital badges and points; and the Communication

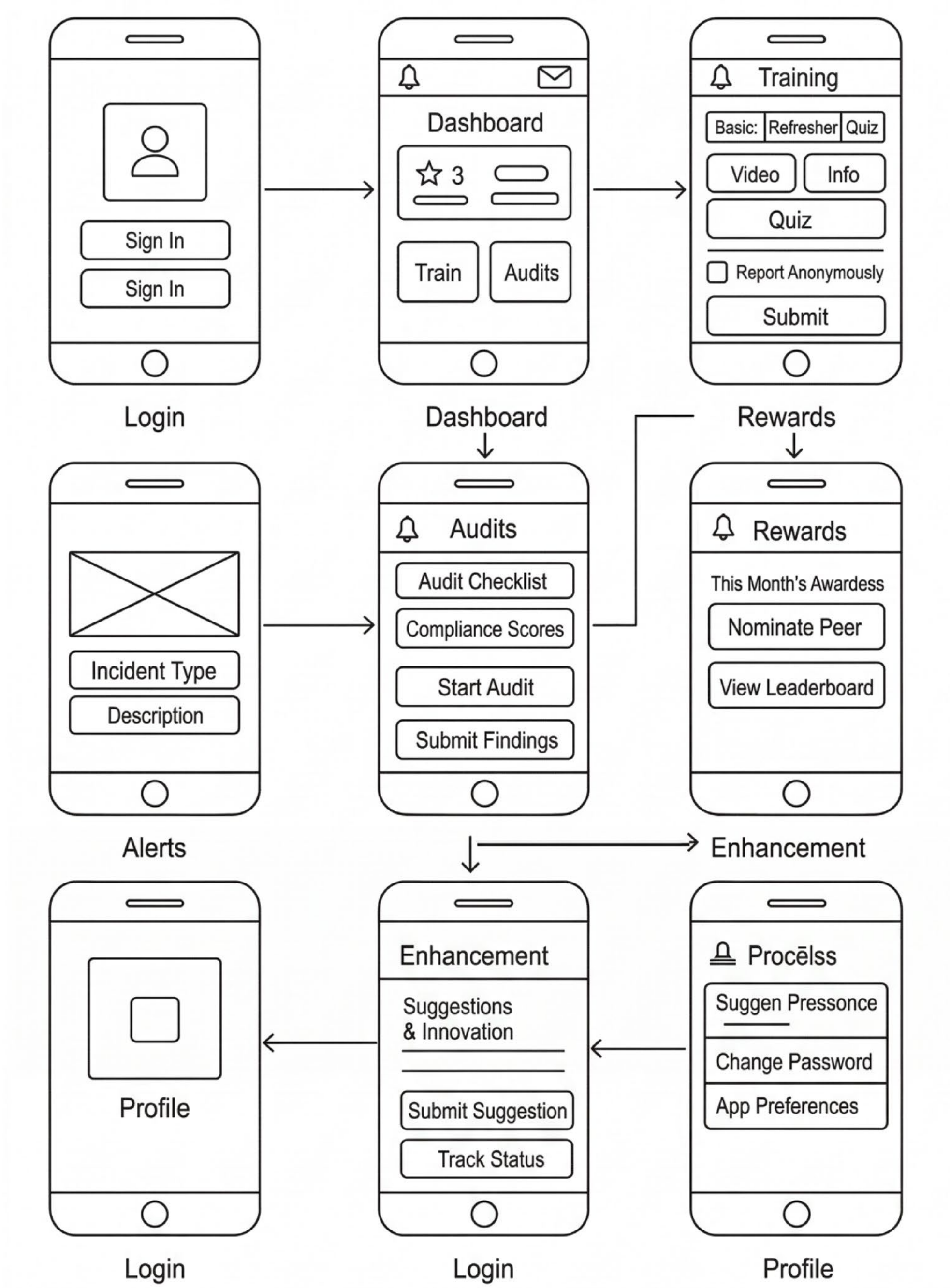

Fig. 3. Wireframe designs for the behavioural occupational safety culture application (BOSCA). *Note* The wireframe illustrates the functional flow of BOSCA modules, including *Login*, *Dashboard*, *Training*, *Audits*, *Rewards*, *Alerts*, *Enhancement*, and *Profile Management.* Each module was designed to enhance behavioural safety engagement and compliance among oil and gas industry employees.

Alerts module ensures timely dissemination of safety messages and updates. Collectively, these modules provide a user-friendly, interactive platform that transforms behavioural theory into practice, fostering proactive participation, accountability, and continuous improvement in workplace safety culture.

Discussion

This study introduces the Behavioural Occupational Safety Culture Application (BOSCA), a digitally integrated intervention designed to enhance safety culture in the oil and gas industry through a theory-driven behavioural approach. The system combines behavioural science, digital innovation, and organisational learning into a cohesive framework that supports motivation, skill development, feedback, and accountability. The contribution

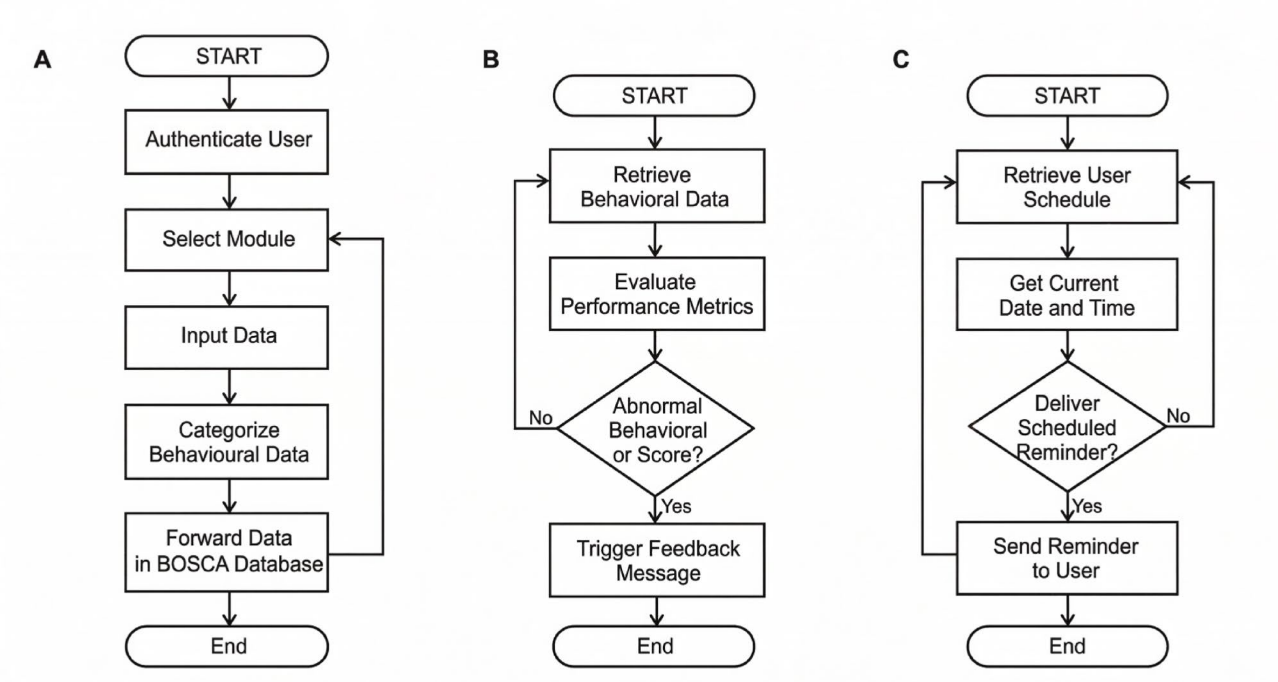

Fig. 4. Flowcharts of algorithms implemented in the control layer of the BOSCA application, where (**A**) presents the data collection and validation process for behavioural safety input; (**B**) describes the automated feedback and notification engine that reinforces user engagement; and (**C**) represents the scheduling algorithm that notifies users of upcoming training, audit, or reporting deadlines.

of behavioural science within the BOSCA framework lies in its role as the underlying mechanism that shapes system design and user interaction. Unlike conventional digital safety systems that prioritise data collection and compliance monitoring, BOSCA integrates behavioural constructs into its functional architecture. Each module is designed to reflect specific behavioural principles: training and communication modules support cognitive engagement, reward and recognition systems enhance motivation, and audit and competency modules strengthen behavioural skills through practice and feedback. This integration enables the system to function as a behaviourally informed intervention rather than a passive monitoring tool, providing a structured pathway for influencing safety-related behaviour in high-risk environments. Importantly, the contribution of this study extends beyond conventional software or API design. While the BOSCA platform incorporates standard digital system components, its novelty lies in the integration of behavioural science principles into the system architecture and operational logic. Unlike typical application development studies that focus primarily on functionality and system performance, this study demonstrates how behavioural constructs can be systematically translated into interactive digital processes that influence user behaviour. This positioning distinguishes BOSCA as a behaviourally informed intervention framework rather than a purely technical solution, contributing to both the theoretical advancement and practical implementation of digital safety systems.

Compared with existing digital safety systems, BOSCA demonstrates a more comprehensive integration of behavioural principles within its design. Previous digital tools have largely focused on compliance monitoring, incident reporting, or training delivery, with limited emphasis on sustained behavioural engagement[16–19]. In contrast, BOSCA embeds motivational reinforcement, competency development, and real-time feedback directly into system functionalities, enabling continuous interaction between users and safety processes. This aligns with findings from behavioural safety research, which highlight that interventions incorporating feedback and reinforcement mechanisms are more effective in promoting long-term behavioural change compared to passive information-based approaches[20,21]. Early digital safety tools such as e-Safety Training, iSafe Work, and Safety+ were primarily designed for digital checklists, incident reporting, or compliance documentation, often neglecting intrinsic motivational factors that sustain behavioural change[3,22]. In contrast, BOSCA was developed to address this critical gap by embedding the motivational, cognitive, and contextual components of behavioural theory directly within its system architecture[18]. Similar to the mHealth intervention model, which employed intervention mapping to develop a hypertension self-management app, BOSCA aligns each digital function with the core constructs of the Information–Motivation–Behavioural Skills (IMB) framework. This theoretical grounding ensures that BOSCA not only delivers safety content but also facilitates active behavioural engagement through continuous feedback, reinforcement, and performance analytics. The significance of the BOSCA framework lies in its ability to transform workplace safety management from a compliance-driven approach into a behaviourally driven system. By integrating real-time feedback, continuous communication, and competency-based learning within a unified digital platform, the framework enables organisations to actively influence worker behaviour rather than merely monitor safety outcomes. This shift is critical in high-risk industries

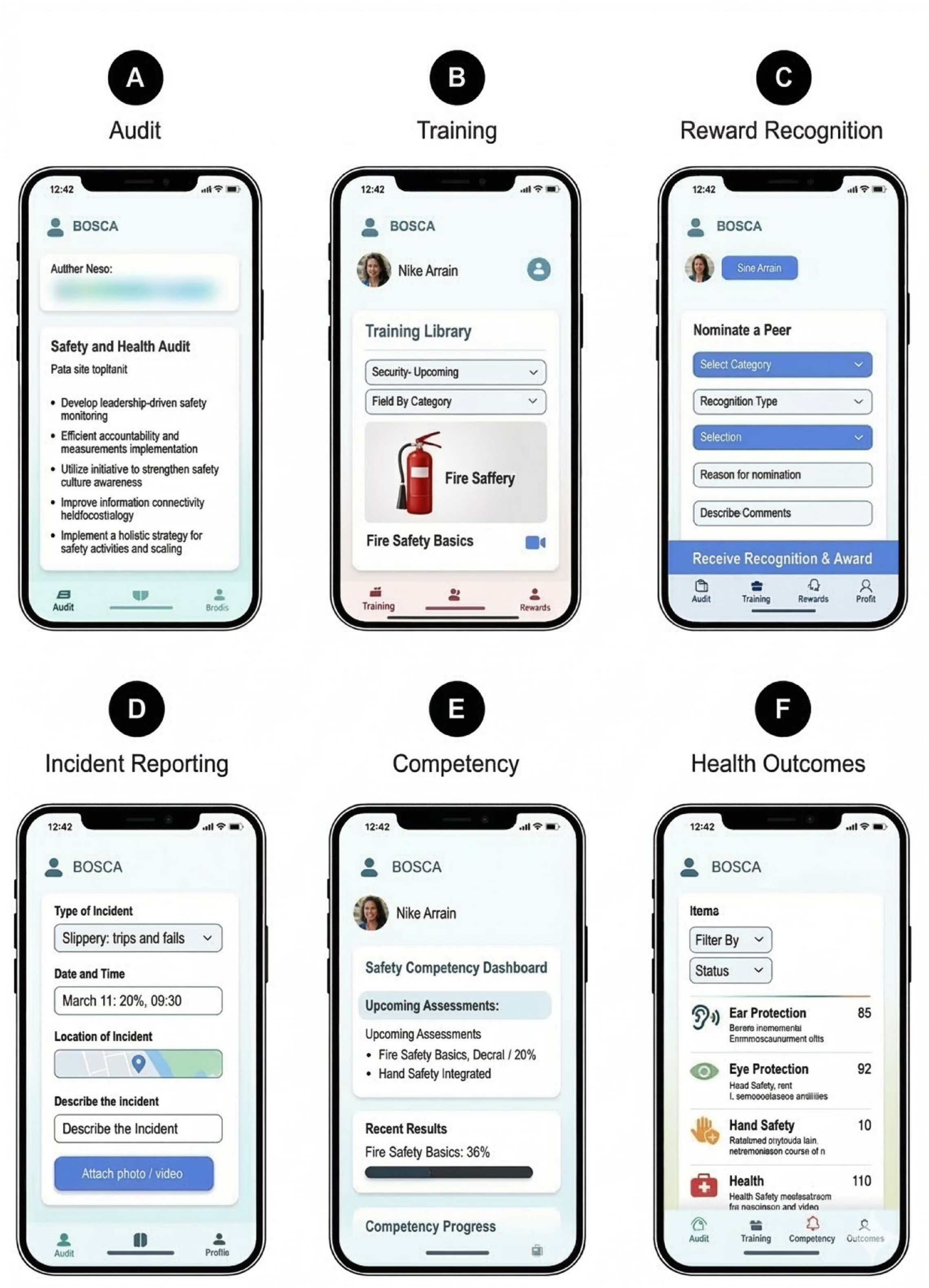

Fig. 5. BOSCA mobile application interface showcasing six core modules: (**A**) Audit, (**B**) Training, (**C**) Reward Recognition, (**D**) Incident Reporting, (**E**) Competency, and (**F**) Communication Alerts designed to promote proactive safety management, competency tracking, and real-time engagement within the oil and gas industry.

such as oil and gas, where unsafe behaviours are a major contributing factor to incidents. The integration of behavioural mechanisms within BOSCA supports proactive hazard identification, increased reporting, and sustained engagement, ultimately contributing to improved safety performance and organisational resilience.

A clearer comparison between BOSCA and existing digital safety systems highlights its methodological advancement. Conventional systems are predominantly compliance-driven, focusing on incident reporting, checklist completion, and audit tracking, with limited integration of behavioural change mechanisms[23]. In contrast, BOSCA adopts a behaviour-driven approach by embedding behavioural science principles directly into its system architecture. This is achieved through the integration of cognitive (training and communication), motivational (reward and feedback), and behavioural skill (audit and competency) pathways, which collectively influence user behaviour. Furthermore, while existing systems often operate as static data collection tools, BOSCA introduces dynamic feedback loops through real-time notifications, performance tracking, and adaptive reinforcement. This distinction demonstrates that BOSCA is not merely an extension of existing digital tools, but represents a shift toward behaviourally informed and interactive safety management systems. The BOSCA system architecture's four interconnected layers; Application, Control, Security & Integration, and Data Storage represent a major advancement in digital safety management. This multi-layered architecture enables seamless communication between users and the backend while maintaining high levels of data integrity and privacy[24,25]. The control-layer algorithm, with its automated feedback, notification, and scheduling mechanisms, transforms user activity into adaptive system responses that sustain engagement and accountability[26]. This continuous feedback loop parallels the real-time data validation and automated reinforcement systems used in validated health management applications but is uniquely adapted here for industrial safety operations. The architecture's modularity also facilitates scalability, allowing BOSCA to be tailored for different operational environments without compromising functionality or security[27]. The interface and wireframe designs further demonstrate BOSCA's emphasis on usability and behavioural reinforcement. The integration of six core modules; Audit, Training, Reward Recognition, Incident Reporting, Competency, and Communication Alerts creates a user-friendly ecosystem that enables two-way communication between employees and management. By combining automated training, hazard reporting, and gamified recognition features, BOSCA promotes consistent behavioural participation while cultivating a shared sense of ownership in workplace safety. Such features address one of the key limitations identified in previous digital safety systems: low long-term engagement and poor data feedback mechanisms[28]. The use of real-time notifications and reward-based reinforcement enhances motivation, mirroring findings from mobile health studies where gamified engagement significantly improves adherence and task completion rates[29,30].

In comparison with earlier digital interventions, BOSCA represents a paradigm shift from passive compliance monitoring to proactive behavioural transformation. Previous applications in industrial safety, including those developed for construction and manufacturing sectors, primarily served as reporting tools with limited behavioural analytics[3,31]. BOSCA, however, integrates data-driven feedback and competency-based reinforcement into its control logic, allowing organisations to monitor progress, identify gaps, and adapt training based on real-time performance metrics. This integration of feedback, analytics, and motivational psychology reflects an evolution toward personalised, adaptive digital safety systems aligned with Industry 4.0 objectives.

Beyond technical innovation, BOSCA contributes conceptually to the evolution of safety culture theory by demonstrating how motivation and behavioural skills can be continuously reinforced through digital feedback ecosystems. The dynamic interaction between the application's modules replicates the cyclical nature of behavioural change where performance outcomes feed back into motivation and skill development. By converting these theoretical constructs into functional digital processes, BOSCA advances the practical implementation of behavioural safety interventions at scale. Overall, this study highlights the potential of behaviourally informed digital technologies to transform occupational safety management. BOSCA demonstrates that when behavioural theory, feedback algorithms, and user-centred design converge within a secure mobile platform, the result is a sustainable system that not only monitors safety compliance but actively cultivates a culture of continuous improvement. Future research should evaluate the system's usability, longitudinal engagement, and measurable impacts on incident rates and workforce attitudes toward safety. With appropriate validation and cross-sector adaptation, BOSCA could serve as a model for developing digital interventions that merge behavioural science with data analytics to achieve safer, more resilient industrial work environments. Importantly, this study should not be interpreted as solely describing a mobile application, but rather as presenting a behaviourally grounded digital intervention framework. The BOSCA platform functions as a medium through which behavioural theories are systematically translated into operational mechanisms, enabling continuous feedback, user engagement, and safety performance monitoring within complex industrial environments. The integration of cognitive, motivational, and behavioural skill components provides a structured pathway for influencing worker behaviour an essential determinant of safety performance in high-risk settings. Through features such as digital reporting, automated feedback, and reward-based reinforcement, the system supports proactive participation, enhances communication across organisational levels, and promotes sustained engagement in safety practices.

From a broader perspective, BOSCA contributes to the evolution of digital safety management by embedding behavioural mechanisms within system architecture rather than relying solely on compliance-based functions. This enables a shift toward more dynamic and responsive safety systems capable of adapting to user interactions in real time. The framework aligns conceptually with socio-technical system principles, where individual actions trigger system-level responses through integrated feedback loops. Although not a simulation model, BOSCA reflects a similar logic in which user activities such as reporting, training, and audit participation; generate adaptive system responses that reinforce behavioural change. Its multi-layered architecture further supports modularity, scalability, and interoperability, consistent with contemporary approaches to complex industrial system design. From an evaluation standpoint, the present study focuses on system functionality and usability validation rather than empirical assessment of behavioural outcomes. The findings demonstrate that BOSCA is technically robust and well accepted by users, indicating its feasibility as a platform for implementing behaviourally informed safety interventions. However, the extent to which these mechanisms translate into measurable behavioural change, improved safety practices, or reduced incident rates remains to be established. Future research should therefore prioritise longitudinal and real-world evaluations to assess the effectiveness of the framework in driving sustained safety culture transformation.

Open research questions and future directions

A key limitation of this study is the absence of large-scale empirical validation. The prototype was evaluated using a small sample under simulated operational conditions, which limits the ability to assess behavioural change, safety performance outcomes, and long-term user engagement. Future research should therefore conduct longitudinal and experimental studies to quantify the effectiveness of the BOSCA framework in real-world organisational settings. Despite the promising design and functional capabilities of the BOSCA platform, several open research questions (ORQs) remain that warrant further investigation. First, while the current study demonstrates the feasibility of integrating behavioural safety theory into a digital application, the long-term impact of such systems on safety behaviour, incident reduction, and organisational safety culture remains unclear. Future research should therefore conduct longitudinal studies to evaluate sustained user engagement and behavioural change over time in real operational environments. Second, the scalability and adaptability of the BOSCA framework across different industrial contexts represent another critical research gap. Although the system was designed for the oil and gas sector, its applicability to other high-risk industries such as construction, manufacturing, and transportation requires further validation. Future studies should explore cross-sector implementation and assess how contextual factors influence system performance and user adoption. Third, the integration of advanced data analytics and predictive modelling within the BOSCA platform presents an important opportunity for enhancement. Future research could incorporate machine learning algorithms to analyse behavioural patterns, predict safety risks, and generate adaptive interventions tailored to user behaviour. Such integration would enable the transition from reactive safety management to predictive and preventive safety systems aligned with Industry 4.0 principles. Fourth, user engagement and behavioural sustainability remain key challenges in digital safety interventions. While gamification and feedback mechanisms were incorporated into BOSCA, further research is needed to optimise these features and determine which behavioural strategies are most effective in maintaining long-term participation and motivation among users. Finally, issues related to data governance, privacy, and ethical considerations require further exploration, particularly in large-scale deployments involving sensitive organisational data. Future research should examine secure data-sharing frameworks, compliance with regulatory standards, and user trust in digital safety systems. Addressing these open research questions will not only enhance the effectiveness of the BOSCA platform but also contribute to the broader development of behaviourally informed digital safety systems capable of transforming occupational safety management across diverse industrial environments.

Despite its potential, the implementation of behaviourally informed digital safety systems such as BOSCA may face several practical challenges. These include variability in user engagement over time, resistance to technological adoption among workers, and organisational barriers related to leadership support and resource allocation. In addition, issues related to data privacy, system trust, and ethical management of behavioural data must be carefully addressed, particularly in large-scale deployments. These considerations highlight the need for careful implementation strategies and continuous evaluation to ensure the effectiveness and sustainability of digital safety interventions. Although the BOSCA framework incorporates established behavioural change principles, the current study does not include quantitative evaluation of behavioural outcomes. Future research should therefore assess the effectiveness of the system in producing measurable behavioural transformation, including changes in safety practices, engagement levels, and incident reduction over time.

Conclusion

This study presents the development of the Behavioural Occupational Safety Culture Application (BOSCA), a behaviourally informed digital framework designed to support occupational safety management through an integrated mobile platform. The system architecture was structured using a formal software architecture description approach, incorporating both use-case and logical operation views to represent system functionality and runtime behaviour. This structured representation enhances clarity, consistency, and reproducibility in the design of the application. The BOSCA framework translates key behavioural safety constructs into functional digital modules, including incident reporting, audit management, training, competency assessment, communication, and reward mechanisms. These modules are integrated within a coordinated system architecture that supports continuous interaction between users and management, enabling a structured approach to behavioural safety implementation. The contribution of this study lies in bridging behavioural safety theory with digital system design by providing a scalable and modular framework that can be adapted to different organisational contexts. The architecture demonstrates how behavioural constructs can be operationalised into a coherent digital ecosystem that supports safety engagement and communication. This study focuses on the design and architectural development of the BOSCA framework; therefore, comprehensive system evaluation and real-world implementation are beyond the scope of the current work and will be addressed in future research. Overall, the BOSCA framework provides a foundational model for integrating behavioural safety principles into digital platforms, supporting the advancement of technology-driven safety management systems.

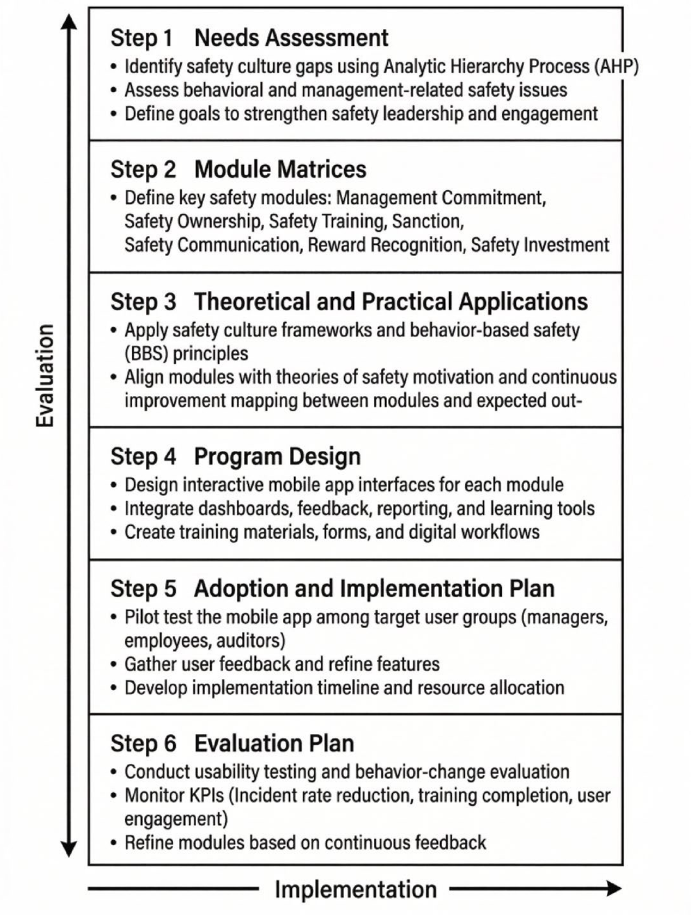

Fig. 6. Six-step framework illustrating the mobile application development and implementation process for enhancing safety culture in the oil and gas industry, integrating assessment, design, implementation, and evaluation phases.

Methods

Study design and development framework

The development of the Behavioural Occupational Safety Culture Application (BOSCA) followed a Design and Development Research (DDR) framework, which is commonly used for the creation and evaluation of technology-based interventions. This approach allows systematic translation of theoretical constructs into functional technological solutions while ensuring iterative validation and refinement. The BOSCA development process consisted of six sequential stages: (1) needs assessment, (2) module matrix development, (3) theoretical framework integration, (4) interface prototyping and software development, (5) prototype implementation and usability testing, and (6) system functionality validation. Each stage was designed to ensure that behavioural safety constructs were effectively translated into operational features within the mobile application (Fig. 6).

Step 1: needs assessment

The needs assessment phase was based on findings from a previously published study that analysed stakeholder priorities for safety culture improvement in the Malaysian oil and gas sector using the Analytic Hierarchy Process (AHP)[10]. That study identified leadership commitment, safety ownership, and safety communication as the most influential behavioural determinants of safety performance. To contextualise these findings for digital implementation, structured consultations were conducted with fifteen industry practitioners, including safety managers, safety officers, and operational engineers working within oil and gas operations. Participants were selected based on their professional experience in occupational safety management. The consultations aimed to identify key functional requirements for a digital safety platform, including user interface expectations, reporting mechanisms, training accessibility, and communication features. The results were translated into system design requirements guiding the development of BOSCA modules.

Step 2: module matrices

The behavioural priorities identified during the needs assessment were subsequently translated into a structured module matrix to define the core functional domains of the BOSCA platform. This matrix served as a design framework that aligned behavioural safety constructs with corresponding digital functionalities within the application. Seven key behavioural domains were identified: management commitment, safety commitment, safety ownership, safety training and sanction, safety communication, reward and recognition, and safety investment. Each domain was systematically mapped to specific behavioural objectives, performance indicators, and corresponding digital features embedded within the BOSCA system. This mapping process enabled the integration of behavioural safety principles into the application architecture and guided the development of interactive modules designed to promote proactive safety engagement, continuous learning, and organisational accountability within the mobile platform.

Step 3: theoretical and design application

The interface design of the BOSCA was guided by the Information–Motivation–Behavioural Skills (IMB) model together with the principles of behavioural-based safety. These theoretical foundations were used to translate behavioural safety constructs into functional design elements within the mobile application. Within the BOSCA platform, the information component of the IMB model was operationalised through interactive training modules and safety communication alerts that deliver safety-related knowledge and updates to users. The motivation component was incorporated through gamified feedback mechanisms, including reward badges, performance scores, and achievement indicators designed to reinforce positive safety behaviours and sustain user engagement. Meanwhile, behavioural skill development was supported through competency assessment tools and digital audit features that allow users to practice, evaluate, and improve safety-related skills in a structured manner. To enhance usability and ensure a consistent user experience, the interface design followed Material Design 3 guidelines, which provide standards for accessibility, layout structure, and visual coherence in mobile applications. In addition, colour-coded indicators were integrated to facilitate intuitive safety-related decision-making within the application, where red represents hazard alerts, green denotes achievement indicators, and blue signifies training and informational content. These design elements collectively ensure that behavioural safety principles are effectively embedded within the BOSCA interface to support continuous engagement and learning.

Step 4: interface prototyping and program design

The interface prototyping phase began with the development of wireframe designs for the BOSCA mobile application using Figma (version 116.2.12). These wireframes were created to visualise the overall navigation structure, module interactions, and dashboard layout of the application before full system development. The wireframe prototypes enabled iterative refinement of the user interface by illustrating the logical flow between different modules and ensuring that the layout supported intuitive navigation and efficient user interaction. Following the prototyping stage, the final application prototype was developed using the Flutter framework with the Dart programming language, allowing the application to be deployed across multiple mobile operating systems, including Android and iOS. The backend infrastructure of the system was implemented using Firebase Cloud Firestore, which provides scalable cloud-based data storage and real-time data synchronisation between the mobile interface and the backend server. The BOSCA system architecture integrates several key development components, including a mobile front-end interface built using the Flutter framework, a backend database managed through Firebase Cloud Firestore, and a secure authentication mechanism based on the OAuth 2.0 protocol. In addition, role-based access control (RBAC) was implemented to regulate user permissions within the system, ensuring that different categories of users can access only authorised functionalities. To safeguard data integrity and confidentiality, secure data transmission was implemented through end-to-end encryption, ensuring that all user interactions and stored data are protected within the BOSCA digital platform.

Step 5: prototype implementation and usability testing

The BOSCA prototype was pilot-tested with ten industry practitioners representing potential end users of the system, comprising safety managers, safety officers, and field engineers with experience in occupational safety operations. The testing sessions were conducted under simulated operational scenarios in which participants interacted with the application to perform typical safety management tasks, including reporting incidents, completing safety audits, accessing training modules, receiving safety alerts, and reviewing performance dashboards. The usability evaluation focused on three main criteria: navigation clarity, interface usability, and responsiveness of system features. Feedback was collected through structured questionnaires and observational checklists, allowing the research team to identify usability issues and make targeted refinements to improve the interface.

Step 6: system functionality and performance testing

To evaluate system reliability and functional performance, a series of validation tests were conducted during the prototype development phase. These tests included data processing validation to ensure that incident reports, audit results, and training records were accurately captured and stored within the database; notification system testing to assess the accuracy and timeliness of automated alerts generated by the scheduling algorithm; security validation to verify the effectiveness of user authentication, role-based access control, and encrypted data transmission; and system responsiveness testing to measure response time during user interactions and data synchronisation between the mobile interface and backend database. The results demonstrated stable system functionality under simulated operational conditions, indicating that the BOSCA platform is capable of supporting real-time behavioural safety monitoring and communication within organisational environments.

Ethical consideration

The interface-development study did not involve clinical data or personally identifiable information. Ethical oversight was not required, but the study adhered to the institutional research ethics standards of Universiti Teknologi MARA (UiTM), ensuring voluntary participation, confidentiality, and responsible conduct of research.

Use of generative AI

The authors used generative artificial intelligence (GenAI) tools for language editing and improvement of manuscript clarity. The use of these tools was limited to grammar refinement, sentence structuring, and readability enhancement. All scientific content, data analysis, interpretation of results, and conclusions were developed and verified solely by the authors. The authors take full responsibility for the content of this manuscript.

Data availability

All data generated or analysed during this study are included in this published article and its supplementary information files. Additional technical documentation related to the BOSCA application architecture and algorithms is available from the corresponding author upon reasonable request.

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References

1. Figueredo, A. J. & Wolf, P. S. A. Assortative pairing and life history strategy: A cross-cultural study. *Hum. Nat.* **20**, 317–330. https://doi.org/10.1007/s12110-009-9068-2 (2009).
2. Egila, A. et al. Highly reliable organisations and sustainability risk management: safety cultures in the Nigerian oil and gas supply chain sector. *Bus. Strategy Environ.* **34** (2), 2680–2701. https://doi.org/10.1002/bse.4091 (2025).
3. Aderamo, A., Taofik, H. C. & Olisakwe Yetunde Adenike Adebayo, and Andrew Emuobosa Esiri. Behavioral safety programs in high-risk industries: A conceptual approach to incident reduction. *Compr. Res. Reviews Eng. Technol.* **2** (1), 64–82. https://doi.org/10.57219/crret.2024.2.1.0062 (2024).
4. Goh, Y., Miang, H., Brown & Spickett, J. Applying systems thinking concepts in the analysis of major incidents and safety culture. *Safety science* **48**, 02–309. https://doi.org/10.1016/j.ssci.2009.11.006 (2010).
5. Hofmann, D. A., Burke, M. J. & Zohar, D. 100 years of occupational safety research: From basic protections and work analysis to a multilevel view of workplace safety and risk. *J. Appl. Psychol.* **102** (3), 375. https://doi.org/10.1037/apl0000114 (2017).
6. Zahid, A., Ferraro, A., Petrillo, A. & Fabio De Felice. Exploring the role of digital twin and industrial metaverse technologies in enhancing occupational health and safety in manufacturing. *Appl. Sci.* **15** (15), 8268. https://doi.org/10.3390/app15158268 (2025).
7. Demikhov, O., Ihorovych, Y. A., Opanasiuk, N. V., Demikhova & Merisalu, E. A digital transformation into occupational health and safety systems: A review of the best practices in Europe. https://doi.org/10.15159/AR.23.083 (2023).
8. Badea, D. O., Darabont, D. C., Chis, T. V. & Alina Trifu. The transformative impact of E-learning on workplace safety and health training in the industry: A comprehensive analysis of effectiveness, implementation, and future opportunities. *Int. J. Educ. Inf. Technol.* **18**, 105–118. https://doi.org/10.46300/9109.2024.18.11 (2024).
9. Istepanian, R. S. H. Mobile health (m-Health) in retrospect: the known unknowns. *Int. J. Environ. Res. Public Health*. **19** (7), 3747. https://doi.org/10.3390/ijerph19073747 (2022).
10. Mearns, K. & Yule, S. The role of national culture in determining safety performance: Challenges for the global oil and gas industry. *Saf. Sci.* **47** (6), 777–785. https://doi.org/10.1016/j.ssci.2008.01.009 (2009).
11. Bisbey, T. M. et al. Safety culture: An integration of existing models and a framework for understanding its development. *Hum. Factors*. **63** (1), 88–110. https://doi.org/10.1177/0018720819868878 (2021).
12. Abeje, M. & Luo, F. The influence of safety culture and climate on safety performance: Mediating role of employee engagement in manufacturing enterprises in Ethiopia. *Sustainability* **15** (14), 11274. https://doi.org/10.3390/su151411274 (2023).
13. Arifin, K., Mansor Ali, M. X., Abas, A. & Juhari, M. L. Communication and coordination as drivers of safety behaviours and outcomes in coal-fired power plants. *PLoS One*. **21** (1), e0341341. https://doi.org/10.1371/journal.pone.0341341 (2026).
14. Reason, J. Safety paradoxes and safety culture. *Injury control Saf. promotion*. **7** (1), 3–14. https://doi.org/10.1076/1566-0974 (2000).
15. Hossain, M., Ismail, M. M. & Hosen Mohammad Aman Ullah Sunny, and Shofiul Azam Tarapder. Implementing advanced technologies for enhanced construction site safety. *Am. J. Adv. Technol. Eng. Solutions*. **1** (02), 01–31. https://doi.org/10.63125/3v8rpr04 (2025).
16. Rahim, H., Dapari, R., Dom, N. C. & Mohd Iqbal Mohd Noor. and. Decoding stakeholder priorities of safety culture preferences in the oil and gas industry. *Sci. Rep.* **14**, 20735. https://doi.org/10.1038/s41598-024-71294-6 (2024).
17. Nævestad, T. O., Hesjevoll, I. S. & Ross Owen Phillips. and. How can we improve safety culture in transport organizations? A review of interventions, effects and influencing factors. *Transp. Res. Part F Traffic Psychol. Behav.* 54: 28–46. https://doi.org/10.1016/j.trf.2018.01.002 (2018).
18. Rahim, H. & Che Dom, N. Design and development of mobile application based on proactive elements of safety culture framework for the oil and gas industry: a conceptual framework. In *IOP Conference Series: Earth and Environmental Science*, vol. 1151, no. 1, p. 012033. IOP Publishing. https://doi.org/10.1088/1755-1315/1151/1/012033 (2023).
19. Vankov, D. Beyond user experience and technology acceptance: Criteria to select a technology for a road safety behavioural change intervention. *Trans. Transp. Sci.* **12**, 53–61. https://doi.org/10.5507/tots.2021.017 (2021).
20. Buckingham, S. et al. and. Mobile health interventions to promote physical activity and reduce sedentary behaviour in the workplace: a systematic review. *Digital health* **5**, 2055207619839883. https://doi.org/10.1177/2055207619839883 (2019).
21. Melzner, J., Heinze, J. & Fritsch, T. Mobile health applications in workplace health promotion: an integrated conceptual adoption framework. *Procedia Technol.* **16**, 1374–1382. https://doi.org/10.1016/j.protcy.2014.10.155 (2014).
22. Park, C., Soltani, M., Pedro, A., Yang, J. & Lee, D. and Rahat Hussain. Transforming construction site safety with iSAFE: An automated safety management platform. In Digitalization in Construction, 213–234. Routledge. https://doi.org/10.36253/979-12-215-0289-3.35 (2023).
23. Oluwaniyi, O. I. Integrating Occupational Safety Management into Enterprise Risk Management (ERM) Frameworks. https://doi.org/10.32628/IJSRST25126505 (2025).
24. Farhaoui, Y. et al. A multi-layered protection system for enhancing data security in cloud computing environments. In *The International Conference on Artificial Intelligence and Smart Environment*, pp. 559–568. Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-88304-0_77 (2024).
25. Joseph, A. A holistic framework for unifying data security and management in modern enterprises. *Int. J. Social Bus. Sci.* **17** (10), 602–609 (2023).

26. Naseri, M., Mehdi, S., Tabibian & Homayounvala, E. Adaptive and personalized user behavior modeling in complex event processing platforms for remote health monitoring systems. *Artif. Intell. Med.* **134**, 102421. https://doi.org/10.1016/j.artmed.2022.102421 (2022).
27. Repetto, M., Carrega, A. & Rapuzzi, R. An architecture to manage security operations for digital service chains. *Fut. Gener. Comput. Syst.* **115**, 251–266. https://doi.org/10.1016/j.future.2020.08.044 (2021).
28. Horrey, W. J. et al. On-board safety monitoring systems for driving: Review, knowledge gaps, and framework. *J. Saf. Res.* **43** (1), 49–58. https://doi.org/10.1016/j.jsr.2011.11.004 (2012).
29. Vergara-Borge Felipe, Diego López-de-Ipiña, Mikel Emaldi, Cristian Olivares-Rodríguez, Zaheer Khan, and Kamran Soomro. Gamifying engagement in spatial crowdsourcing: An exploratory mixed-methods study on gamification impact among university students. *Systems* **13**, 519. https://doi.org/10.3390/systems13070519 (2025).
30. Liao, K. L., Huang, M., Shi, J. & Chen, M. Focus-driven augmented feedback: Enhancing focus and maintaining engagement in upper limb virtual reality rehabilitation. *IEEE Trans. Vis. Comput. Graph.* https://doi.org/10.1109/TVCG.2025.3549543 (2025).
31. Pereira, E., Ali, M., Wu, L. & Abourizk, S. Distributed simulation–based analytics approach for enhancing safety management systems in industrial construction. *J. Constr. Eng. Manag.* **146**, 04019091. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001732 (2020).

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Author contributions
H.R and N.C.D. conceived the study concept, supervised the system design, and drafted the manuscript. H.R., R.D and N.C.D. contributed to the theoretical framework and validation of the intervention model. H.R. and M.O.A. developed the system architecture and wireframe designs, while N.C.D designed and implemented the control-layer algorithms and conducted the data integration testing. All authors contributed to data interpretation, critically reviewed the manuscript for intellectual content, and approved the final version for publication.

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Competing interests
The authors declare no competing interests.

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