SYNERGY
PUBLISHING PTE. LTD.
Tel: +65 65881289
E-mail: contact@s-p.sg
Website: ojs.s-p.sg

Macro Management & Public Policies

Volume 7 · Issue 1 · March 2025 ISSN 2661-3360

SYNERGY
PUBLISHING PTE. LTD.

Volume 7
Issue 01
March 2025
ISSN 2661-3360

Macro Management & Public Policies

Google Scholar
J-Gate
WorldCat
Crossref
VIP 维普资讯
cnki 中国知网 cnki.net

ISSN 2661-3360

Volume 7 Issue 1 • March 2025 • ISSN 2661-3360 (Online)

Macro Management & Public Policies

Editor-in-Chief

Dr. Sang-Bing Tsai

SYNERGY
PUBLISHING PTE. LTD.

Volume 7 | Issue 1 | March 2025 | Page1-78
Macro Management & Public Policies

Contents

SYNERGY PUBLISHING PTE. LTD.

Macro Management & Public Policies

https://ojs.s-p.sg/index.php/mmpp

ARTICLE

An Integrated Framework for Behavioural Safety Improvement Strategies in the Construction Industry: A Systematic Review

Kweku Bedu Simpson[1] Nongiba Alkanam Kheni[2]

[1.] *Department of Construction Technology and Management Education, Akenten-Appiah Menka*

[2.] *University of Skill Training and Entrepreneurial Development, P. O. Box 1277 Kumasi-Ghana*

ABSTRACT

Despite the importance of behavioural safety (BS) in construction, there are few comprehensive frameworks that define measures for improvement. This work fills the gap via a systematic analysis, offering direction for future research and practical improvements to BS performance. A comprehensive database search encompassing literature published between January 1997 and September 2022 was carried out across EBSCOhost, Emerald Insight, Google Scholar, JSTOR, PubMed, SAGE, SCIRP, Scopus, Taylor & Francis, and Wiley-Blackwell. Key phrases including "construction workers", "risk perception", "safety behaviour", "safety compliance", “safety participation”, “safety citizenship behaviours” “construction industry” and other related terms were used for the search. The initial 2,427 records were trimmed to 2,267 after language and title keyword filters were applied. After excluding 2,156 records based on title, abstract, and content analysis, 111 relevant papers were chosen for further review. The selected papers underwent a thorough screening procedure that included title, abstract and full-text analyses and 41 were finally chosen on the basis of their results, conclusions, or recommendations explicitly included BS improvement techniques. QSR NVivo 10 software was used to examine and code the chosen articles. Five levels—organisational, management, leadership, workgroup, and individual—as well as related sub-themes were used to comprehensively classify improvement techniques. An integrated six-level framework was established, incorporating an external component that includes regulatory, economic, and sociological impacts based on these results. This framework clearly connects external and internal factors, enhances the theoretical comprehension of behavioural safety, and offers a practical framework for academics, regulators, and industry professionals aiming to enhance safety outcomes in the construction industry.

Keywords: Behavioural safety improvement strategies; external factors; organisational factors; management factors; leadership factors; workgroups factors; individual factors; systematic review; framework; construction industry.

*CORRESPONDING AUTHOR:
Kweku Bedu Simpson, Email: kwekusimpson48@gmail.com

ARTICLE INFO
Received: 11 March 2025 | Accepted: 20 March 2025 | Published Online: 30 March 2025
DOI: http://doi.org/10.26549/mmpp.v7i1.26831

CITATION
K.B.S, 2025. An Integrated Framework for Behavioural Safety Improvement Strategies in the Construction Industry: A Systematic Review. Macro Management & Public Policies. 7(1): 1–22. DOI: http://doi.org/10.26549/mmpp.v7i1.26831

1. Introduction

Despite continued efforts to reduce the number of accidents, the construction industry continues to be seen as an exceptionally dangerous sector [1], with an elevated rate of workplace mishaps [2]. Accidents in the construction business culminate in large, both direct and indirect, expenses for employers and society, according to Haupt and Pillay [3]. Despite worldwide advances, workplace injuries and deaths in the construction industry remain common and devastating [4, 5], yet there remains much that can be done to improve construction safety [6]. Generally, safety management systems must be established with the goal of improving BS performance, particularly at the end user, the worker, where most failures occur [5].

Choudhry [7], citing Cooper (1994), describes "behavioural safety" as the systematic application of psychological studies on human behaviour to the subject of safety. Cooper [8] and [9] have both referred to behaviour-based safety (BBS) as a behavioural safety process and BS. Several writers have called it BBS, including [7], [10], and others. A variety of safety interventions have employed this strategy for modifying behaviours on front-line workers' safety behaviour (SB) [11]. According to Cooper [8], the BS process, which calls for concerted activities, reduces occurrences caused by risky or unsafe behaviours.

According to Zhang et al. [12], citing Blackmon and Gramopadhye (1995), workers' risky behaviour generates more than 80% of workplace occurrences. Unsafe behaviours, according to [13], are risky or harmful actions that violate safety laws and can result in accidents. Prior behavioural investigations revealed that violations of safety regulations and procedures are common among construction workers [14].

Given the aforementioned, it is argued that any deliberate effort to foster good H&S behaviour in the construction sector is referred to in this review as BS improvement strategies. This might involve H&S management techniques, safety climate and culture, safety compliance (SC) and participation (SP), safety citizenship behaviours (SCB), safety motivation and commitment, safety communication, safety knowledge, and safety education and training techniques including related terms.

Hinze et al. (2013), as cited in [15], describe SB as "safety-related acts performed by employees within an organisation." This behaviour is an important predictor of safety performance. According to [16], analysing safety-related behaviours is a highly efficient method for forecasting workplace safety. Organisational norms, legislative frameworks, ethos, work environment, and cultural traits were identified as the top individual human environment elements impacting construction workers' health and safety behaviour. When public policy components were considered together, they had the largest effect. These findings underline the importance of the work environment in affecting employee behaviour [17].

Distal context-related elements such as leadership and safety climate and proximal person differences such as safety awareness and motivation [18], as well as multiple factors like colleague connections and management team initiatives, influence workers' safety-related behaviours [12]. According to Turner et al. (2012), cited in [19], workers will widen their vision to include safety (i.e., safety citizenship) in fulfilment of an obligation or loyalty to their superiors. Workers' safety attitudes are favourably connected with safety leadership [20]. Workers on construction sites will almost certainly communicate with management teams, and these interactions may have an important effect on how they perceive safety and how they act as a result [21].

Recent systematic reviews in the construction sector have focused on improving Health and Safety (H&S) performance. Studies such as [22] on safety barrier identification and classification, [23] on safety leading indicators, and [24] on the link between safety culture, climate, and performance all give useful insights. Furthermore, [25] investigate variables influencing construction workers' risky behaviours, whereas [26] evaluate safety strategies for accident prevention. These studies cover key areas of construction safety, such as obstacles, indications, culture, interventions, and worker behaviour. Nevertheless, none of these studies thoroughly examined the range of strategies for improving behavioural safety (BS), which are essential to proactive safety management in the construction sector. These techniques include external and internal factors. While [27] investigated behavioural safety in Qatari megaprojects and [28] introduced a framework categorising 16 elements into organisational, safety climate, and individual dimensions, their geographic and contextual breadth is constrained, underscoring the importance of an exhaustive evaluation of programmes and systems that improve BS outcomes worldwide.

This study is unique because it takes a detailed and organised approach that goes beyond prior assessments of BS in construction. First, it does a bibliographic analysis to investigate the sources of published publications as well as their publication dates, following the history, trends, and patterns in BS research in the construction sector. Second, it synthesises the methodological techniques used in previous research, highlighting both best practices and shortcomings to present a more complete view of how BS has been examined. Third, the study delves deeper into the behavioural improvement drivers by identifying and assessing the important elements impacting BS management and performance. Finally, it presents a comprehensive theoretical framework that incorporates a variety of evidence-based methodologies and practices designed to improve BS management in the construction sector. This research fills a significant gap in the literature by offering a comprehensive view on enhancing safety behaviour in construction contexts. It provides a workable implementation roadmap, filling a crucial gap in academic research and industrial practice, thus significantly contributing to the construction BS literature.

Against this backdrop the study is guided by the following objectives:

- To conduct a bibliographic analysis of the selected articles on behavioural safety in construction.
- To identify and synthesise the methodological approaches previously employed in BS related research.
- To examine the key factors influencing behavioural safety improvement within the construction industry.
- To develop an integrated theoretical framework aimed at enhancing behavioural safety management in the construction industry.

2. Research Methodology

2.1 Literature search

The study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram guidelines [33] such as identification, screening, eligibility, and inclusion to arrive at the final selection of the included articles (Figure 1). Articles published in English and contained in their titles, either one or a combination of the following keywords: “safety behaviour”, or “unsafe behaviour”, or “risk perception”, or “safety violation”, or “safety compliance”, or “safety participation”, or “safety citizenship behaviour”, or “safety climate”, or “safety culture”, “construction workers”, “construction industry”, and “leadership”, were used to search from the stated databases. Before screening the publications obtained for the systematic review, duplicate records, reviews, systematic reviews, and meta-analyses were eliminated, since the review focused on research providing empirical data. The screening procedure also entailed the exclusion of conference papers, theses, and other unpublished or non-peer-reviewed materials, as these may lack a stringent peer-review process (Butler & Visser, 2006, as cited in [29, 30, 31], Chai & Wen, 2005, as cited in [32]. The authors utilised the double screening (two-fold screening) technique [33] to ensure that all records were checked twice and only human decisions were used for the evaluation. Authors independently examined titles and abstracts to determine article eligibility, and any disputes were resolved through discussion and consensus in both situations [33]. The procedure for gathering materials included title analysis, abstract analysis, and content analysis. The analysis of the included articles was conducted through a qualitative strategy (Whittemore, 2005, cited in [34]. Using content analysis, the required data was coded into themes and sub-themes, with the use of QSR Nvivo 10 software, by noticing patterns and themes, clustering, counting, and noting similarities and relationships [35]. The decision on the improvement strategies and the probable factors was based on the authors' consensus after independently reviewing thoroughly the articles by considering those that contained sentences that suggested improvement strategies for H&S management and improvement in the construction industry and discussing them. Again, similar strategies were employed to extract the probable factors that influence BH&S management and performance. These were coded into themes and sub themes. Descriptive analysis was used to present the results in the form of texts, tables and figures.

3. Results

3.1 Literature search

A search through 10 databases yielded 2427 records for the identification process. Most of the articles were drawn from the Taylor and Francis database (630), followed by Google Scholar (392), then Scopus (369), with the least drawn from EBSCO Host (13) (Figure 2). The last search dates from the databases were: EBSCO Host (25/2/22), Emerald Insight (14/4/22), Google Scholar (11/3/22), JSTOR (6/3/22), PubMed (8/4/22), Sage (1/4/22), Scirp (2/4/22), Scopus (13/4/22), Taylor and Francis (18/3/22) and Wiley and Blackwell (31/3/22).

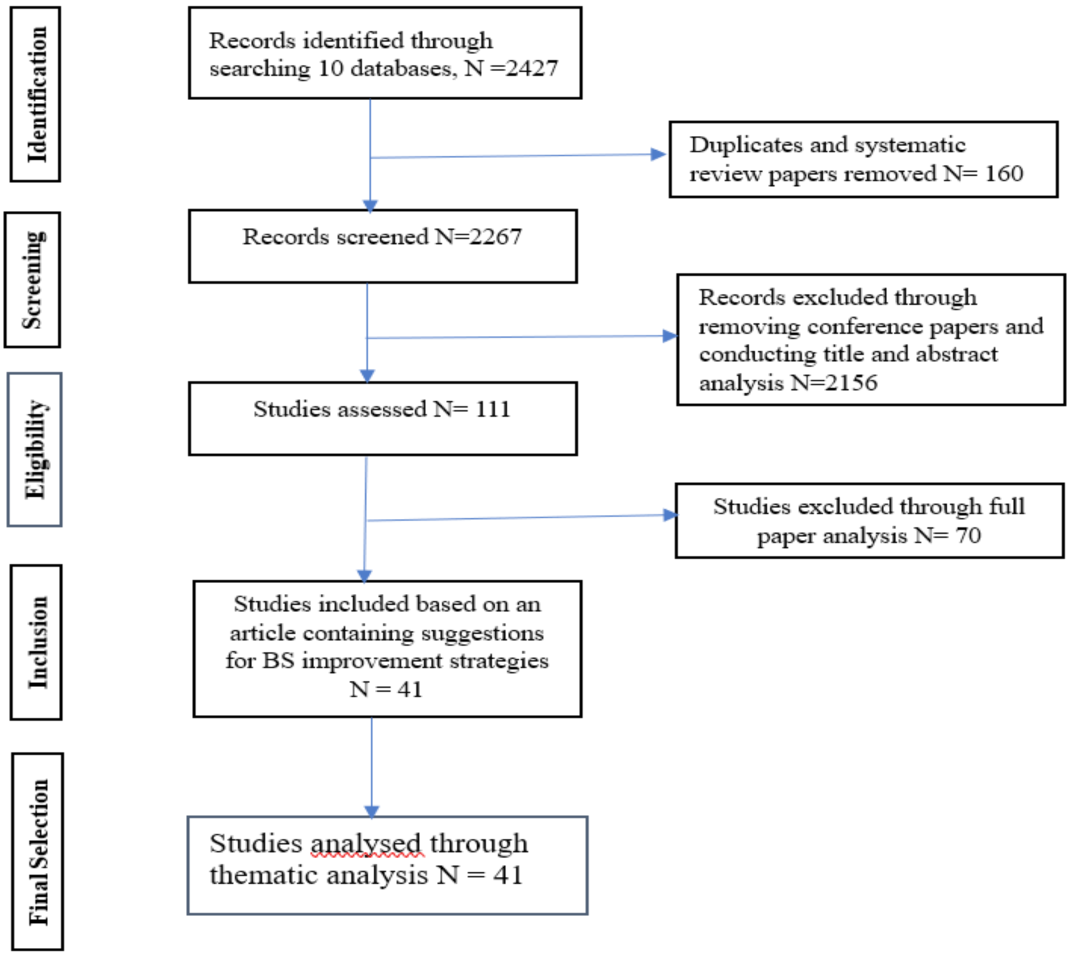

Figure 1: PRISMA study screening flow chart

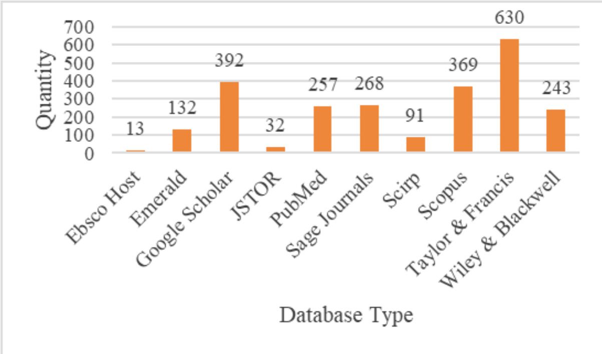

Figure 2: Statistics on the result of the electronic databases searched

Prior to the primary screening process, 160 publications were excluded, of which 77 were duplicates and 83 were reviews, systematic reviews, or meta-analyses, as the focus was on empirical research. 2,267 records were then looked at, removing conference papers, theses, and other unpublished works, since they might not have been properly reviewed by experts (Butler & Visser, 2006, as cited in [29], [30, 31], Chai & Wen, 2005, as cited in [32].

The screening process included many stages: title analysis, abstract analysis, and complete content analysis. The first stage, title analysis, determined if the titles were consistent with the study objectives and topic area. This was followed by abstract analysis, which comprised a thorough review of each study's goal, methods, and main findings. Finally, a content analysis was performed to guarantee relevancy and rigour. After this procedure, 2,156 records were removed, resulting in a more focused collection of articles for future study. Resultantly, 111 studies were accessed for eligibility, out of which 70 records were removed after conducting full paper analysis. In all, 41 articles were included for the analysis (**Figure 1**). These were papers that contained suggestions for improvement strategies aimed at enhancing holistic BS performance in the construction industry.

The study used thematic analysis to categorise articles into various categories, such as country of study, journal types, yearly publications, and methodological approaches. Thematic analysis was used to extract improvement strategies and code them into themes and sub-themes using QSR Nvivo 10 software. Factors influencing BS were coded into organisational, management, leadership, workgroup, and individual factors, and the results were descriptively analysed and presented in texts, tables and figures.

3.2 Analysis of sources of published articles and years of publications

3.2.1 Bibliographic analysis of the journal papers included

The results present the country of study and number of papers obtained (**Figure 3**), types of journals, quantity, and impact factor (**Table 1**), and the yearly publications of the reviewed papers (**Table 2**).

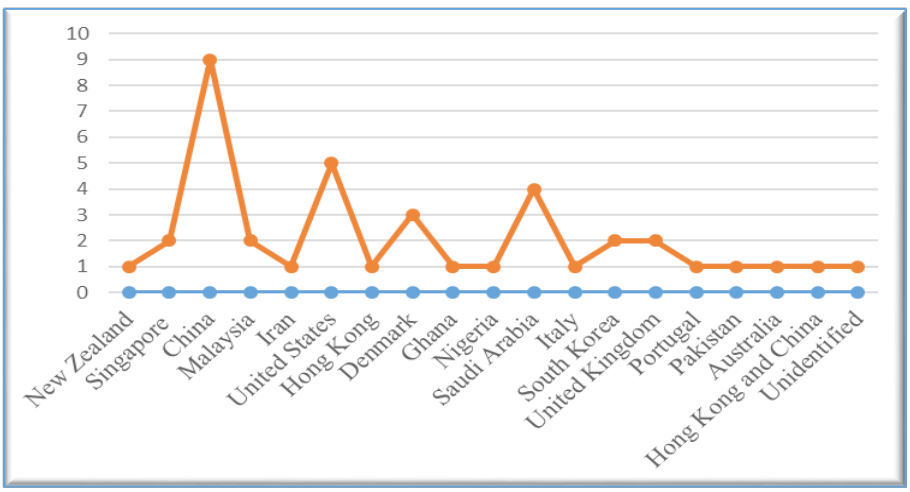

Figure 3: Statistics on the country of study and number of papers obtained

The 41 reviewed articles came from studies conducted in 19 countries, with China (9; 22.5%) having the most publications, followed by the US (5; 12.5%), Saudi Arabia (4; 10%), Denmark (3; 7.5%), South Korea (2; 5%), Malaysia (2; 5%), Singapore (2; 5%), and the United Kingdom (2; 5%). Most (57.9%) of the countries had only one publication each. This includes Iran, Hong Kong, Ghana, Nigeria, and others (Figure 3). This conclusion contradicts the findings of [22], [24], and [25], all of which found the United States to be the most prolific publishing country, rather than China. Other studies, such as [32], Osei-Kyei and Chan (2015), as cited in [32], and [36], have used sample sizes of 56, 38, and 27, respectively, for their reviews concerning safety in the construction industry, and this justifies the sufficiency of this study's sample size of 41 papers.

The quantity of the peer reviewed papers came from the International Journal of Environmental Research and Public Health 7 (17.07%), followed by Construction Management and Economics 6 (14.63%), Safety Science 5 (12.20%), International Journal of Occupational Safety and Ergonomics 4 (9.76%), Engineering Construction and Architectural Management 2 (4.88%), Journal of Construction Engineering and Management 2 (4.88%), and Open Journal of Safety Science and Technology 2 (4.88%). The rest, such as Accident Analysis and Prevention, the Journal of Management in Engineering, Applied Ergonomics, Buildings, and many others, had one each, forming close to 70% of the total (**Table 1**). This also contradicts the findings of [30], who found that the Journal of Construction and Management had the most publications, followed by Safety Science.

In **Table 2**, most of the papers were published between 2017 and 2022, with 2021 having the highest frequency, meaning that researchers have stepped up their publications over the last 6 years. The impact factors of the journals ranged between 0.692 and 6.537, with the Journal of Management in Engineering recording the highest (6.537), while the Journal of Asian Architecture and Building Engineering recorded the lowest impact factor (0.692) (**Table 1**).

Table 1: Types of journals, quantity and impact factor

No	*Peered reviewed journals*	*Quantity*	*Impact Factor*
1	Accident Analysis and Prevention	1	4.993
2	Journal of Management in Engineering	2	6.537
3	Applied Ergonomics	1	3.94
4	Buildings	1	3.6
5	Journal of Risk Research	1	5.346
6	Construction Management and Economics	6	3.796
7	Engineering Construction and Architectural Management	2	3.531
8	Frontiers in Public Health	1	3.018
9	Information	1	0.78
10	International Journal of Construction Management	1	3.097
11	International Journal of Environmental Research and Public Health	7	4.54
12	International Journal of Occupational Safety and Ergonomics	4	2.141
13	Journal of Asian Architecture and Building Engineering	1	0.692
14	Journal of Construction Engineering and Management	2	3.951
15	Journal of Safety Research	1	3.487
16	Open Journal of Business and Management	1	1.00
17	Open Journal of Safety Science and Technology	2	0.74
18	PLOS ONE	1	3.24
19	Safety Science	5	4.877
	Total	41	

Table 2: Yearly publications of the reviewed papers

No	Year of Publications	Quantity	Percentage	No.	Year of Publications	Quantity	Percentage
1	1998	1	2.2%	9	2016	1	2.2%
2	2005	1	2.2%	10	2017	4	10%
3	2009	1	2.2%	11	2018	5	12.5%
4	2010	1	2.2%	12	2019	2	5%
5	2011	1	2.2%	13	2020	5	12.5%
6	2013	1	2.2%	14	2021	8	20%
7	2014	1	2.2%	15	2022	7	17.5%
8	2015	2	2.2%	16			

3.3 Research methodological approaches

Using QSR NVIVO 10 software, the study conducted the qualitative content analysis procedure by categorising the findings into themes and subthemes.

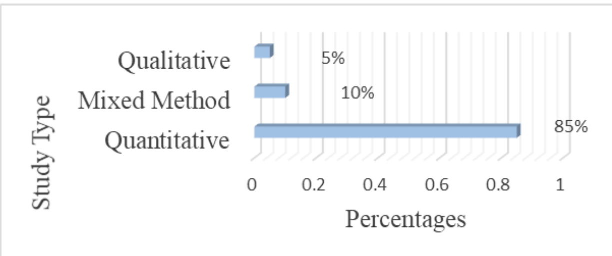

Figure 4: Methodological approaches used by the various articles

The study revealed that most (85%) of the varied articles used quantitative techniques, which include [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], and [49]. [5], [50], [15], [51], [52], and many others also used that. [53], [54], [7], and others used the mixed method-related studies, which formed 10% of the total, whereas the qualitative methods comprised only 5% of the total and consisted of [55] and [56] (**Figure 4**).

3.5 Factors influencing BS in the construction industry

Multi-level factors such as organisational systems, management practices, leadership styles, team dynamics, and individual characteristics shape BS improvement in the construction industry, influencing safety attitudes, behaviours, and outcomes on site. The following display the outcomes of the review based on the foregoing themes.

3.5.1 Organisational factors

Table 3 displays five organisational safety themes, as well as associated aspects. Safety culture and climate is an important issue that determines safety behaviour and norms inside an organisation. Safety climate [49, 57, 58, 59, 60, 50], positive safety culture [56], safety priority [37], social support [37], attachment and psychological ownership [58], and cultural and organisational contexts [42] are all factors that contribute to this theme. These components affect the organisational values, attitudes, and circumstances that influence safety results. Safety Systems and Resources refer to institutional systems and physical resources in place to assure compliance and safety preparedness. This subject includes elements such as PPE programmes [5], safety equipment maintenance and availability [5], safety permits and workplace safety inspections [5]. These systems are critical for ensuring a safe work environment and avoiding accidents. H&S policy and planning entail the creation and execution of policies and task structures to encourage safety and well-being. This subject is influenced by regulations that promote a healthy workplace [58], the practicality of safety standards [61], equipment design [52], and a better sequencing of work activities [61]. Training and knowledge enhancement programmes use organised learning to increase awareness, skills, and a safety mentality. This subject includes variables such as effective H&S training programmes [53], as well as enhancing knowledge, improving workshop atmosphere, and altering staff attitudes [46]. These programmes are critical for providing employees with the information and skills they need to complete their responsibilities safely. Organisational pressure and workload are the stresses and expectations imposed on employees that might influence their safety behaviour. This topic is influenced by production pressure [42] and work pressure [37]. These demands can cause increased stress, weariness, and a lack of adherence to safety measures, jeopardising safety outcomes.

Table 3: Organisational-Level Safety Themes

Theme	Related Factors	Citations	Theme Summary
1. Safety Culture and Climate	- Safety climate - Positive safety culture - Priority of safety - Social support - Attachment, psychological ownership - Cultural and organisational contexts	[49, 57, 58, 59, 60, 50] [56] [37], [37], [58], [42]	Organisational values, beliefs, and environments that influence safety behaviour and norms.
2. Safety Systems and Resources	- PPE programmes - Safety equipment maintenance and availability - Safety permits - Workplace safety inspections	[5]	Institutional systems and physical resources in place to ensure compliance and safety readiness.
3. H&S Policy and Planning	- Policies for promoting a healthy workplace - Practicality of safety rules - Equipment design - Better sequence of work activities	[58] [61] [52], [61]	Development and implementation of policies and task structuring that promote safety and well-being.
4. Training and Knowledge Enhancement	- Strong H&S training programmes - Increasing knowledge, improving workshop climate, and changing employee attitudes	[53] [46]	Programmes aimed at increasing awareness, skill, and safety mindset through structured learning.
5. Organisational Pressure and Workload	- Production pressure - Work pressure	[42] [37]	

3.5.2 Management factors

Table 4 summarises six management-level safety themes, including associated factors. Leadership and commitment are an important subject that shows leadership's role in promoting safety ideals, influencing the atmosphere, and developing effective connections. Management commitment [62], safety leadership [39, 59], leader-member exchange [25], supervisor-worker relationships [63, 64], supervisory management conditions [14], and safety climate [25]. Supervision and oversight relate to the level of managerial control and execution of safety requirements. This theme includes elements like close and strict supervision [65, 48], direct supervision [61], the strictness and frequency of management feedback [66], workplace safety inspections [5], and safety risk tolerance [59]. Safety training and capacity building are key tactics of management for increasing worker safety knowledge and capabilities. Safety training programmes [46, 66, 53], theoretical and practical training programmes [66], industry training courses and standards [52], worker safety and health training [65, 61], regular training in hazard perception and risk comprehension and safety and voice ergonomics training [48]. Communication and knowledge sharing relate to the exchange and quality of information among teams and management groups. This theme includes elements like safety communication [37], frequent communication [61], dense communication networks and frequent supervisor-worker communication [63], safety knowledge sharing [67], safety climate and social-network safety communication patterns [60], and social safety capital [54]. Feedback, motivation, and accountability are management techniques that incentivise safe behaviour and prohibit infractions. This is influenced by factors such as goal-setting and feedback [7], awarding safety role models [61], and enforcing penalties [65]. Worker autonomy and perceived control refer to an employee's sense of control over their job activities, decisions, and surroundings. This theme is assessed using job control ratings [19].

Table 4: Management-Level Safety Themes

Theme	Related Factors	Citations	Theme Summary
1. Leadership and Commitment	- Management commitment - Safety leadership - Leader-member exchange - Supervisor-worker relationships - Management conditions at supervisory level - Safety climate	[62] [39, 59] [25] [63, 64] [14] [25]	Reflects leadership's role in establishing safety values, shaping climate, and building effective relationships.
2. Supervision and Oversight	- Close and strict supervision - Direct supervision - Strictness and frequency of management feedback - Workplace safety inspections - Safety risk tolerance	[65, 48] [61] [64] [5] [59]	Degree of managerial oversight and enforcement of safety standards.
3. Safety Training and Capacity Building	- Safety training programmes - Theoretical and practical training programmes - Industry training courses and standards - H&S training of workers - Regular training in hazard perception and risk comprehension - Increasing knowledge, improving workshop climate through training - Safety and voice ergonomics training	[46, 66, 53] [66] [52] [65, 61] [48] [61]	Training as a core managerial strategy for improving worker safety awareness and competencies.
4. Communication and Knowledge Sharing	- Safety communication - Frequent communication - Dense communication networks and frequent supervisor-worker communication - Safety knowledge sharing - Safety climate and social-network safety communication patterns - Social safety capital	[63] [63] [67] [60] [54]	The flow and richness of information within teams and across management levels.
5. Feedback, Motivation, and Accountability	- Goal-setting and feedback - Rewarding safety role models - Imposing fines	[7] [61] [65].	Managerial practices to incentivise safe behaviour and discourage violations.
6. Worker Autonomy and Perceived Control	- Job control scores	[19]	Employee's perception having control over their work tasks, decisions, and environment.

3.5.3 Leadership factors

Table 5 covers five leadership-level safety themes, as well as associated indicators and citations. Leadership Styles and Approaches examines several leadership styles and how they affect safety culture and employee behaviour. This topic is influenced by transformational leadership [59], supportive leadership [42, 56], safety-specific leadership [39], effective leadership and attitudes, and safety leadership) [39]. Leader-follower relationships refer to the quality of leader-follower relationships and how they affect worker commitment to safety. This theme includes aspects such as leader-member exchange (LMX) [44, 68] and workers' sense of commitment to leaders [59]. Role modelling and impact refer to the impact of visible role models and reinforcement mechanisms on safe behaviour. This topic is influenced by an emphasis on the demonstrative impact of team leaders and technical specialists [47], as well as awarding safety role models [61]. Leadership in risk management refers to leaders' responsibilities for discovering, analysing, and managing project safety hazards. This theme includes aspects like project managers' logical attitude to risk [55] and foremen's involvement in risk perception and risk-taking [55]. Active supervision and training include ongoing, proactive safety engagement and training from supervisors to employees. This theme is monitored by supervisors who provide continuing safety training [42].

Table 5: Leadership-Level Safety Themes

Theme	Related Factors	Citations	Theme Summary
1. Leadership Styles and Approaches	- Transformational leadership - Supportive leadership - Safety-specific leadership - Effective leadership and attitudes - Safety leadership	[59] [42, 56] [39]	Describes distinct leadership styles and how they influence safety culture and employee behaviour.
2. Leader–Follower Relationships	- Leader-member exchange (LMX) - Workers felt obligation to leaders	[44, 68] [59]	Quality of leader–follower relationships and their effect on worker commitment to safety.
3. Role Modeling and Influence	- Focusing on demonstration effect of team leaders and technical specialists - Demonstration effect of team leaders and technical specialists - Rewarding safety role models	[47] [61]	Influence of visible role models and reinforcement mechanisms that guide safe behaviour.
4. Leadership in Risk Management	- Project managers' rational approach to risk - Foremen's role in risk perception and risk-taking	[55]	Leaders' role in identifying, evaluating, and managing safety risks on projects.
5. Active Supervision and Instruction	- Supervisors providing on-going safety instruction	[42]	Continuous, proactive safety engagement and instruction from supervisors to workers

3.5.4 Workgroup factors

Table 6 provides four workgroup-level safety themes, as well as related variables. Group Norms and Social Influence explains how a team's shared ideas and social pressure shape individual safety behaviour. Factors contributing to this subject include social influence [41], workgroup norms [38, 40], guaranteeing safety as a valued group standard, social identity within a group [41], and social consequences on employees. Communication and knowledge sharing are terms used to describe the transmission of information that improves collective safety awareness and responsive behaviour. This theme includes safety communication [63, 37], dense communication networks [63], peer-to-peer exchange [25], safety knowledge sharing [67], and the free exchange of safety information among workers [60]. Team Dynamics and Support refers to the level of interpersonal support, collaboration, and mutual monitoring within teams. This topic is influenced by factors such as collaboration and cooperation [42], social support [42, 56], a supportive atmosphere for coworkers and workers warning each other about harmful activities [42, 61]. Localised safety climate is the impression of safety priority and behaviour within certain teams. This theme is measured using the workgroup safety climate [50], and guarantees that safety is seen as a fundamental group standard, hence increasing collective accountability.

3.5.5 Individual factors

Table 7 provides seven safety themes at the individual level, along with relevant elements. Psychological capital and traits refer to intrinsic psychological qualities that influence safety behaviour, resilience, and well-being. This theme is influenced by factors such as high levels of psychological capital (PsyCap) [69, 44], self-efficacy [43], hope, optimism and resilience) [15]. Motivation and engagement are motivations and rewards that encourage people to adopt and sustain safe behaviours. This subject includes elements such as safety motivation [43, 42, 39, 57], autonomous safety motivation [54], work engagement [67], job satisfaction [67], and safety participation [67]. Knowledge, competence, and skills include cognitive and experiential knowledge, as well as the ability to recognise and respond to risks. This theme is influenced by safety knowledge [69, 42, 51, 39, 44], hazard recognition skill development [60], job competence [70], comprehension of safety signs [48], attitude change through training [46], knowledge sharing [67], and the need for educational and instructional materials [52]. Communication competence is an individual's capacity to communicate efficiently and obtain safety-related information. This topic includes elements, including an elevated degree of communication competence [69, 44] and a high level of psychological capital and communication competence [44]. Personal preferences and behavioural patterns influence how people engage with danger and others. This theme is influenced by several factors, including proactivity, prosociality [25], safety response [50], workers' intuitive attitude to risk and risk perception and risk-taking [55], Cognitive and physical load relate to cognitive or emotional pressures that might impair attentiveness and decision-making ability. This theme is influenced by mental and physical strain [14], as well as occupational stress [25]. Demographics and personal background include individual variables, including education level and age structure [44].

Table 6: Workgroup-Level Safety Themes

Theme	Related Factors	Citations	Theme Summary
1. Group Norms and Social Influence	- Social influence - Workgroup norms - Ensuring safety as a valued group norm - Social identity within a group - Social effects on employees	[41] [38, 40] [41]	How shared beliefs and peer pressure within a team guide individual safety behaviour.
2. Communication and Knowledge Sharing	- Safety communication - Dense communication networks - Peer-peer exchange - Safety knowledge sharing - Free exchange of safety information among workers	[63, 37] [63] [25] [67] [60]	Information exchange that promotes collective safety understanding and responsive behaviour.
3. Team Dynamics and Support	- Teamwork and cooperation - Social support - Co-worker's supportive environment - Workers cautioning each other against unsafe actions	[42] [42, 56] [42, 61]	The quality of interpersonal support, cooperation, and mutual monitoring within teams.
4. Localised Safety Climate	- Workgroup safety climate	[50]	The perception of safety priority and behaviour within specific teams

Table 7: Individual-Level Safety Themes

Theme	Related Factors	Citations	Theme Summary
1. Psychological Capital and Traits	- High level of psychological capital (PsyCap) - Self-efficacy - Hope - Optimism - Resilience	[69, 44] [43] [15]	Internal psychological strengths that contribute to safety behaviour, resilience, and well-being.
2. Motivation and Engagement	- Safety motivation - Autonomous safety motivation - Work engagement - Job satisfaction - Safety participation	[43, 42, 39, 57] [54] [67] [67] [70]	Drives and incentives for individuals to adopt and maintain safe behaviours.

Table 7 continued

Theme	Related Factors	Citations	Theme Summary
3. Knowledge, Competence, and Skills	- (Rich) Safety knowledge - Hazard recognition skill development - Job competence - Comprehension of safety signs - Changing attitude through training - Knowledge sharing - Need for educational and instructional materials	[69, 42, 51, 39, 44] [60] [70] [48] [46] [67] [52]	Cognitive and experiential knowledge and capacity to recognise and respond to hazards.
4. Communication Competence	- High level of communication competence - High level of psychological capital and communication competence	[69, 44] [44]	Individual's ability to effectively express and receive safety-related information.
5. Behaviour and Social Orientation	- Proactivity - Prosociality - Safety response - Worker's intuitive approach to risk, risk perception and risk-taking	[25] [50] [55]	Personal tendencies and behavioural patterns affecting interaction with risk and others.
6. Cognitive and Physical Load	- Mental and physical load - Work stress	[14] [25]	Cognitive or emotional burdens that can reduce alertness and decision-making accuracy.
7. Demographics and Personal Background	- Education level - Age structure	[44]	

3.5 Framework

The framework for improving behavioural safety (BS) in the construction industry (**Figure 5**) defines a multi-level model that encompasses the many aspects affecting safety performance. It consists of six interrelated levels—external, organisational, management, leadership, team, and individual—each aligned with distinct stakeholders and systems influencing safety behaviour. At the core of the paradigm are behavioural safety enhancement strategies**,** which demonstrate that advancement arises not from single acts but from the synergistic and interactive impact of several levels.

At the external level, legislative requirements, industry standards, economic situations, environmental constraints, societal expectations, and technical breakthroughs provide the comprehensive backdrop for construction safety measures. The broad influences mentioned earlier affect the organisational level (**Table 3**), where safety culture, systems, policies, resource allocation, training provision, and workload demands establish the internal foundations for safety performance. The management level operationalises these principles via leadership commitment, supervision, training, capacity development, communication, feedback mechanisms, responsibility sharing, and worker autonomy, ensuring that organisational purpose is reflected in site-level practices.

The leadership level (**Table 5**) emphasises the behavioural and relational aspects of safety; leadership style, leader-member interchange, role modelling, and proactive engagement in risk management directly influence worker attitudes and safety climates. These factors, in turn, affect the team level (**Table 6**), which encompasses workgroup dynamics, communication, cooperation, shared norms, and the development of localised safety cultures that either bolster or detract from behavioural results. At the individual level (**Table 7**), safety conduct is influenced by personal traits such as psychological capital, motivation, competence, communication skills, behaviour, cognitive and physical loads, and demographic variables. These criteria ultimately determine whether workers engage in safe or harmful actions on-site.

Despite their individual presentation, the six layers exhibit extensive interconnection. The arrows in **Figure 5** illustrate direct, indirect, and reciprocal linkages, indicating that actions at one level resonate across others. New legislation requirements (external level) may transform corporate policies, impact management oversight, modify leadership strategies, change team norms, and ultimately direct individual conduct. In contrast, bottom-up processes—such as employee feedback, team learning, or site-level reporting—can enhance management practices, fortify organisational cultures, and perhaps catalyse policy improvements.

This systemic viewpoint underscores that BS improvement is both iterative and multidirectional. Consequently, effective interventions must concurrently address structural, managerial, social, and individual elements. The paradigm has practical application value, since each level may be associated with quantifiable indicators (e.g., safety climate surveys, leadership evaluations, training audits, performance records), facilitating both academic assessment and industrial benchmarking. Significantly, it incorporates cultural and contextual variations, making it suitable for many building situations, including resource-limited or international project contexts.

In conclusion, the framework (**Figure 5**) and its accompanying breakdown (**Tables 3–7**) provide a thorough, evidence-based guide for comprehending and enhancing behavioural safety in construction. By consolidating external systems, organisational frameworks, management methodologies, leadership behaviours, team dynamics, and personal characteristics into a unified model, it elucidates both the origins of safety impacts and the mechanisms via which enduring enhancements might be realised.

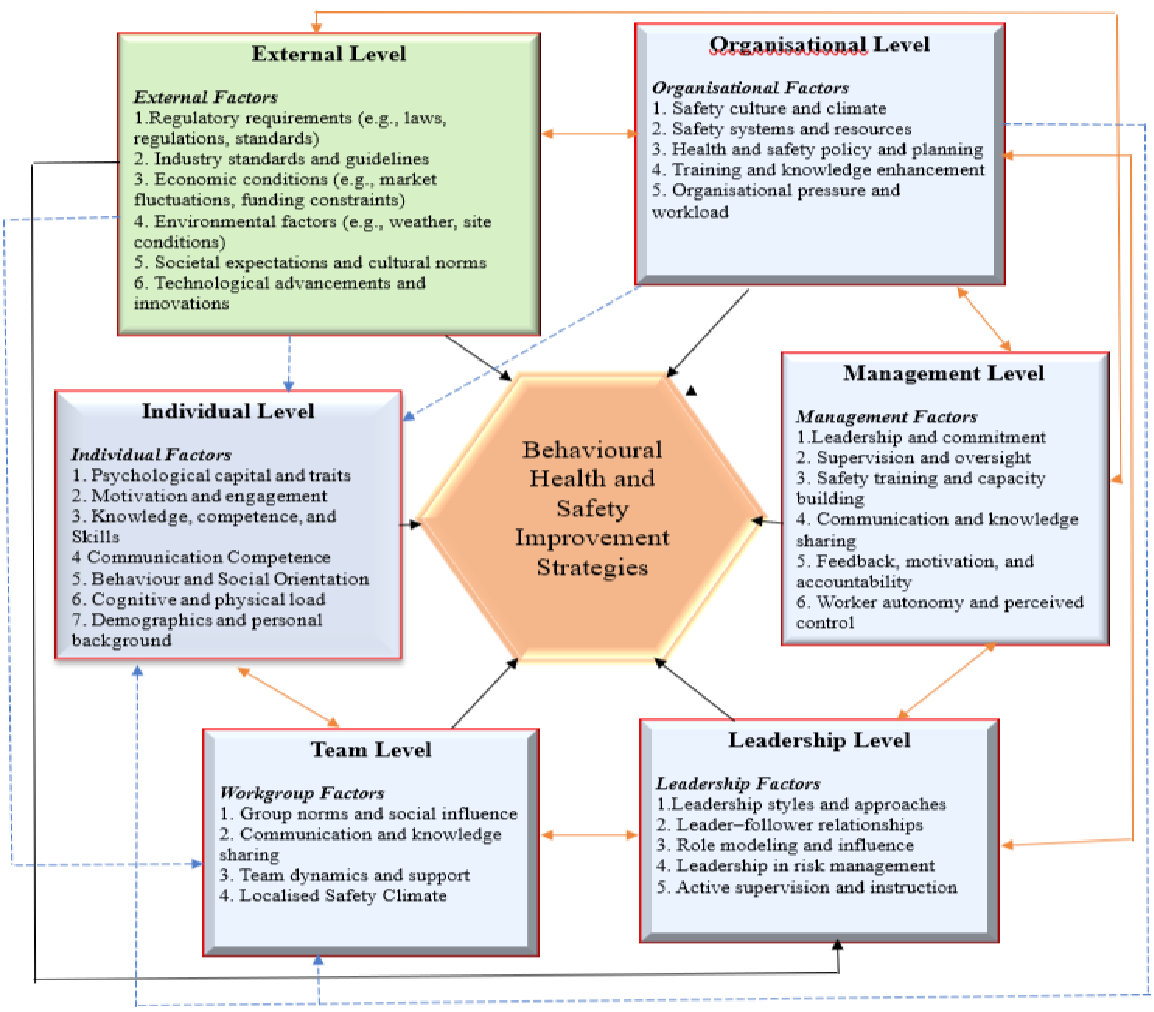

Figure 5: An Integrated framework for behavioural safety improvement strategies for the construction industry

4. Discussion

The framework includes a variety of elements at the external, organisational, management, leadership, team, and individual levels that have a substantial influence on workers' BS in construction (**Figure 5**). The framework's external level consists of numerous variables. Regulatory standards are critical, with frameworks such as ISO 14001:2015[71], ISO 45001[72], and OSHA's Safety and Health Management System offering instructions for increasing worker safety [73]. Industry standards, such as ISO 45001 [72]. provide a systematic approach to risk management and continuous improvement [73]. Economic conditions exert a significant influence, especially on small and medium-sized enterprises (SMEs), which frequently suffer with insufficient financial resources [74]. Economic incentives, such as tax rebates and insurance discounts, can help to promote H&S systems [75]. Environmental elements such as noise and heat stress are crucial to construction safety, and focused interventions such as real-time monitoring can assist in reducing these hazards [76, 77, 78]. Societal expectations and cultural norms influence the construction industry's attitude to safety, with firms prioritising worker safety and aiming for a zero-harm culture. Committed leadership, openness, and accountability are critical in cultivating a safety-first mentality. Nonetheless, cultural differences and linguistic difficulties might be obstacles. Companies must demonstrate that their activities align with society's norms, beliefs, and values [79]. Subsequently, technical improvements such as Building Information Modelling (BIM), internet of things (IoT), artificial intelligence (AI), and virtual reality (VR) can dramatically improve risk awareness, prevention, and training [80, 81]. Nevertheless, the industry continues to face resistance to long-term usage [82]. By addressing these external factors, construction industry may create successful strategies for improving BS and promoting sustainability.

The organisational factors which encompass safety culture and climate, safety systems and resources, H&S policy and planning, training and knowledge enhancement, and organisational pressure and workload, each with associated factors found in this study, emphasise their importance in promoting a safe work environment. Organisational elements were considered in [81]'s review. This included company income, company reputation, company cost, company size, client control, involvement of subcontractors, number of subcontractors, and number of employees or crew size. Organisational variables also included safety management, policy design, safety audit, safety culture, commitment, approach, and safety perception, the implementation strategy, safety compliance, information management, structure and responsibilities, stakeholders' management, resource management, and quality economics [84]. This study's findings are consistent with the findings of [83] and [84], which confirm the importance of organisational structure, resources, and strategic management in promoting a safe construction environment.

This study highlights the importance of managerial influence, oversight, communication, training, and motivational strategies in shaping safety behaviours and outcomes in the construction industry. Hu et al. [85] assert that it is critical for the organisation's top management team to show that they care about safety. When combined with supervisory support, a safety-supportive organisational environment will encourage people to value the role that safety rules and procedures play in their safety performance and, as a result, be more likely to comply with them. This study's findings complement [85], who said that strong leadership commitment and supervisory support are critical in creating a safety-supportive atmosphere that fosters adherence to safety standards and improves safety performance.

This study's finding emphasises how important leadership style, relationship between leaders and followers, role modelling, risk management, and proactive supervision are, in fostering a culture of safety and encouraging safe practices in construction environments. Scholars have found that transactional leadership styles [86], inclusive leadership that promotes employees' taking-charge behaviour [87], and [88] blend of both transformational and transactional leadership styles are helpful in this respect. By demonstrating the beneficial effects of several leadership philosophies, such as transactional, transformational, and inclusive approaches, on promoting safety culture and improving BS management in construction environments, these findings validate and enhance previous research.

This study confirms that group norms, communication, team support, and localised safety climate significantly influence individual safety behaviour and collective commitment in construction teams. The results of this study are supported by [89], who also noted that individual safety violations are strongly impacted by group safety norms, highlighting the crucial role that teams play in influencing BS in construction environments.

This study's identification of psychological capital and traits, motivation and engagement, knowledge, competence and skills, communication competence and social orientation, behaviour, cognitive and physical load, demography, and personal background, indicates the importance of personal attributes, cognitive capacity, and behavioural tendencies in BS performance. Meng et al. [91] identified individual factors influencing construction workers' dangerous behaviours as psychological factors, personality characteristics, subjective attitude consciousness, risk perception, and language and cultural obstacles. Khosravi et al.'s [36] and [90] studies also found society, organisational, work group, site condition, individual factors, contractor, supervision, and project management factors as influencers of unsafe behaviours on construction sites. This study adds depth by thoroughly classifying individual-level safety factors and supports previous research by [63], [36], and [90], highlighting the complex impact of personal psychological and behavioural factors on construction safety.

5. Study Implications

The integrated framework illustrates that behavioural safety in construction is influenced by interrelated external, organisational, managerial, leadership, team, and individual elements, emphasising the need for a systems-orientated rather than a worker-focused approach. This theoretically frames behavioural safety as a resultant consequence of multilevel interactions, enhancing previous models by including organisational environments, leadership impacts, and contextual factors. It connects global knowledge with local realities, providing a transferable but context-specific framework for enhancing safety research and practice.

From a policy perspective, enhancing regulatory frameworks is essential for compliance with international standards such as ISO 14001:2015, ISO 45001:2018, and ILO Convention No. 155 on Occupational Safety and Health. Integrating principles from the U.S. Occupational Safety and Health Administration (OSHA), specifically 29 CFR Part 1926 concerning construction safety, improves compliance and accountability, while adherence to the World Health Organisation's (WHO) Global Plan of Action on Workers' Health fosters comprehensive worker well-being. Policymakers may expedite the adoption of behavioural safety (BS) by providing incentives like tax savings and insurance discounts while instituting comprehensive BS rules to promote safer and more sustainable building practices.

In practice, leadership commitment is vital to building a safety-first culture. Senior management must exhibit tangible commitment to safety via participative measures that enhance worker involvement. Ongoing training and professional development are essential, while digital advancements like BIM, IoT, AI, and VR provide innovative methods for hazard prediction, risk management, and immersive safety instruction. At the organisational level, complete safety management systems—encompassing policy, audits, cultural evaluations, and resource distributions—guarantee sufficient assistance.

Ultimately, considering individual psychological characteristics, risk perceptions, and social norms facilitates customised responses. These measures together reduce accidents, strengthen positive safety cultures, and enhance sustainability in construction.

6. Conclusion

This analysis examined the deficiency of integrated frameworks for enhancing BS throughout the construction sector. Employing the PRISMA technique, 41 pieces of research were synthesised, uncovering essential determinants of BS across external, organisational, management, leadership, team, and person dimensions. An integrated approach was presented to inform both policy and practice based on these observations. The framework emphasises the significance of enhancing regulations, providing economic incentives, adopting technology, ensuring leadership commitment, implementing organisational safety measures, and facilitating good communication. Implementing these techniques may assist construction companies and policymakers in decreasing accident rates, enhancing behavioural safety standards, and fostering sustainable industry performance.

6.1 Limitations and future research

Several limitations must be acknowledged. The review was restricted to journal publications, excluding theses, conference papers, and other grey literature that may offer additional insights. Exclusion of non-English studies and reliance on published data also raise the risk of publication bias. Moreover, the findings are context-dependent, limiting their generalisability across diverse national and industrial settings. The proposed framework is untested in practice, and its robustness across organisational, leadership, team, and individual levels has yet to be empirically validated.

Future research should broaden geographical coverage by including under-represented regions and employ qualitative or mixed-methods approaches to generate more profound insights into behavioural safety processes. Extending the framework to other high-risk sectors such as mining, manufacturing, and healthcare could reveal transferable strategies. Crucially, implementing and evaluating the framework in real projects will be essential to confirm its effectiveness and refine its applicability.

Author Contributions

KBS was in charge of article selection and inclusion, as well as reviewing and analysing the included papers. He also led the conceptualisation and draughting of the text. NAK participated in the article selection process, read the manuscript, and provided general supervision throughout the project. All writers endorsed the final version and are responsible for the integrity of the work.

Funding

This research received no external funding.

Data availability

The data utilised in this study are peer-reviewed publications which were included in the systematic review. All mentioned sources are publicly available and have been properly cited within the paper.

Declaration of interest

The authors declare no competing interest.

References

[1] Buckley, M., Zendel, A., Biggar, J., Frederiksen, L., Wells, J., 2016. Migrant work and employment in the construction sector. International Labour Organisation. https://www.ilo.org/wcmsp5/groups/public/---ed_protect/---protrav/---migrant/documents/publication/wcms_537174.pdf

[2] Kim, Y. A., Ryoo, B. Y., Kim, Y., Huh, W. C., 2013. Major accident factors for effective safety management of highway construction projects. Journal of Construction Engineering and Management, 139, 628–640. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000640.

[3] Haupt, T.C., Pillay, K., 2016. Investigating the true costs of construction accidents. Journal of

Engineering, Design and Technology, 14 (2), 373-419.

[4] Lee, J., Jeong, J., Soh, J., Jeong, J., 2021. Development of framework for estimating fatality-related losses in the Korean construction industry. International journal of environmental research and public health, 18(16), 8787.

[5] Zaira, M. M., Hadikusumo, B. H. W., 2017. Structural equation model of integrated safety intervention practices affecting the safety behaviour of workers in the construction industry. Safety Science 98,124–135. https://doi.org/10.1016/j.ssci.2017.06.007.

[6] Zhou, Z., Miang, Y., Li, Q., 2015. Overview and analysis of safety management studies in the construction industry. Safety Science 72, 337–350, https://doi.org/10.1016/j.ssci.2014.10.006.

[7] Choudhry, R. M., 2014. Behaviour-based safety on construction sites : A case study. Accident Analysis and Prevention, 70, 14–23. https://doi.org/10.1016/j.aap.2014.03.007.

[8] Cooper, M. D., 2009. Behavioural Safety interventions: a review of process design factors. Professional Safety 54, 36–45. (PDF) Behavioral Safety Interventions A Review of Process Design Factors (researchgate.net)

[9] Talabi, B., Gibb, A., Edum-fotwe, F., n.d.. Behaviour-based safety (BBS): A construction industry's perspective. Loughborough University Institutional Repository. (pdf) behaviour-based safety (bbs): a construction industry's perspective (researchgate.net). Retrieved November, 31, 2022.

[10] Lingard, H., Rowlinson, S., 2010. Behaviour-based safety management in Hong Kong's construction industry: The results of a field study. Construction Management and Economics 16, 481–488. https://doi.org/10.1080/014461998372259.

[11] Wirth, O., Sigurdsson, S. O., 2008. When workplace safety depends on behaviour change : topics for behavioural safety research", Journal of Safety Research 39, 589–598. https://doi.org/10.1016/j.jsr.2008.10.005.

[12] Zhang, P., Li, N., Jiang, Z., Fang, D., Anumba, C. J., 2019. An agent-based modeling approach for understanding the effect of worker- management interactions on construction workers' safety-related behaviours. Automation in Construction 97, 29–43. https://doi.org/10.1016/j.autcon.2018.10.015.

[13] Man, S. S., Chan, A. H. S., Wong, H. M., 2017. Risk-taking behaviours of Hong Kong construction workers: A thematic study. Safety Science 98, 25–36. https://doi.org/10.1016/j.ssci.2017.05.004.

[14] Jiang, Z., Fang, D., Zhang, M., 2015. Understanding the causation of construction workers ' unsafe behaviours based on system dynamics modeling. Journal of Mangement in Engineering 31, 1–14. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000350.

[15] Saleem, M.S., Isha, A.S.N., Yusop, Y.M., Awan, M.I., Naji, G.M.A., 2022. The role of psychological capital and work engagement in enhancing construction workers' safety behaviour. Frontiers in Public Health, 10, 1–19. https://doi.org/10.3389/fpubh.2022.810145.

[16] Beus, J. M., Mccord, M. A., Zohar, D., 2016. Workplace safety : A review and research synthesis, Organisational Psychology Review 6, 1–30. https://doi.org/10.1177/2041386615626243.

[17] Okoye, P.U., Okolie, K.C., 2017. Assessment of human environment interactions on health and safety behaviour of construction workers. International Journal of Neuroscience and Behavioural Science, 5(2), 27-43.

[18] Christian, M. S., Bradley, J. C., Wallace, J. C., Burke, M. J., 2009. Workplace safety : A meta-analysis of the roles of person and situation factors. Journal of Applied Psychology 94, 1103–1127. https://doi.org/10.1037/a0016172.

[19] Stephens, N., Pinion, C., 2020. Job control and safety citizenship : Examining the relationship in two companies based in midwestern United States. Open Journal of Safety Science and

Technology 10, 69–80. https://doi.org/10.4236/ojsst.2020.103006.

[20] Li, M., Zhai, H., Zhang, J., Meng, X., 2020. Research on the relationship between safety leadership, safety attitude and safety citizenship behaviour of railway employees. International Journal of Environmental Research and Public Health 17, 1–17. https://doi.org/doi:10.3390/ijerph17061864.

[21] Kines, P., Andersen, L. P. S., Spangenberg, S., Mikkelsen, K. L., Dyreborg, J., Zohar, D., 2010. Improving construction site safety through leader-based verbal safety communication. Int. Journal of Safety Research 41, 399-406, https://doi.org/10.1016/j.jsr.2010.06.005.

[22] Maliha, M. N., Aisheh, Y. I. A., Tayeh, B. A., Almalki, A., 2021. Safety barriers identification, classification , and ways to improve safety performance in the architecture, engineering, and construction (AEC) industry : Review study. Sustainability 13, 1–24. https://doi.org/https://doi.org/ 10.3390/su13063316.

[23] Xu, J., Cheung, C., Manu, P., Ejohwomu, O., 2021. Safety leading indicators in construction : A systematic review. Safety Science 139, 1–16. https://doi.org/10.1016/j.ssci.2021.105250.

[24] Kalteh, H. O., Mortazavi, S. B., Mohammadi, E., 2021. The relationship between safety culture and safety climate and safety performance : A systematic review 27, 206-216. https://doi.org/10.1080/10803548.2018.1556976.

[25] Meng, Q., Liu, W., Li, Z., Hu, X., 2021. Influencing factors, mechanism and prevention of construction workers' unsafe behaviours: A systematic literature review. International Journal of Environmental Research and Public Health, 18(5), 2644.

[26] Dyreborg, J Törner, M., Rasmussen, K., Bo, K., Hans, F., Gensby, U., Bengtsen, E., Guldenmund, F., Kines, P., 2022. Safety interventions for the prevention of accidents at work : A systematic review. Campbell systematic reviews, 18(2), 1-187. https://doi.org/10.1002/cl2.1234.

[27] Ajayi, S., Adegbenro, O., Alaka, H., Manu, P., Oyegoke, A., 2021. Addressing behavioural safety concerns on Qatari Mega Projects. Journal of Building Engineering. 41, 102398. https://doi.org/10.1016/j.jobe.2021.102398.

[28] Chaher, Z., Kasim, N., Benseghir, H., Kabir, M. N., Ibrahim, A. B., 2018. Developing an effective conceptual framework for safety behaviour in construction industry. E3S Web of Conferences, 65, 03006. https://doi.org/10.1051/e3sconf/20186503006 (ICCEE 2018).

[29] Chen, H., Li, H., Miang, Y., 2021. A review of construction safety climate : Definitions , factors , relationship with safety behaviour and research agenda. Safety Science 142, 1–14. https://doi.org/10.1016/j.ssci.2021.105391.

[30] Jin, R., Zoub, P.X.W., Piroozfarc, P., Woodd, H., Yang, Y. Libo, Y., Hang, Y., 2019. A science mapping approach-based review of construction safety research. Safety Science 113, 285–297. https://doi.org/10.1016/j.ssci.2018.12.006.

[31] Randles, R., Finnegan, A., 2023. Guidelines for writing a systematic review. Nurse Education Today, 125, 105803. https://doi.org/10.1016/j.nedt.2023.105803

[32] Tijani, B., Jin, X., Osei-kyei, R., 2020. A systematic review of mental stressors in the construction industry. International Journal of Building Pathology and Adaptation 39(2), 433-460 https://doi.org/10.1108/IJBPA-02-2020-0011

[33] Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-wilson, E., Mcdonald, S., … Mckenzie, J. E., 2021. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. BMJ 1–36. https://doi.org/10.1136/bmj.n160

[34] Xazaquan, M., Ali, M., Arifin, K., Abas, A., Ahmad, M. A., Khairil, M., Cyio, M. B., Samad, M. A., Lampe, I., Mahfudz, M., Ali, M. N., 2022. Systematic literature review on

indicators use in safety management practices among Utility Industries. International Journal of Environmental Research and Public Health 19, 1–21. https://doi.org/https://doi.org/10.3390/ijerph19106198

[35] Braun, V., Clarke, V., 2006. Qualitative research in psychology using thematic analysis in Psychology. Qual. Res. Psychol. 3, 77–101.

[36] Khosravi, Y., Asilian-Mahabadi, H., Hajizadeh, E., Hassanzadeh-Rangi, N., Bastani, H., Khavanin, A., Mortazavi, S.B., 2014. Modeling the factors affecting unsafe behaviour in the construction industry from safety supervisors' perspective. Journal of Research in Health Sciences 14(1), 29-35.

[37] Alfayez, B., 2021. The social support: A missing link between safety management practices and safety behaviour of foreign construction workers in Saudi Arabia. Open Journal of Business and Management 09, 990–1012. https://doi.org/10.4236/ojbm.2021.93053

[38] Andersen, L. P., Nørdam, L., Joensson, T., Kines, P., Kent, J., 2018. Social identity , safety climate and self-reported accidents among construction workers. Construction Management and Economics, 36, 22–31. https://doi.org/10.1080/01446193.2017.1339360

[39] Basahel, A. M., 2021. Safety leadership , safety attitudes , safety knowledge and motivation toward safety-related behaviours in electrical substation construction projects. International Journal of Environmental Research and Public Health 18, 1–17. https://doi.org/https://doi.org/10.3390/ ijerph18084196.

[40] Choi, B., Lee, S., 2017. Role of social norms and social identifications in safety behaviour of construction workers II: Group analyses for the effects of cultural backgrounds and organisational structures on social influence process. Journal of Construction Engineering and Management 43, 1–11. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001254.

[41] Choi, B., Ahn, S., Lee, S., 2017. Construction workers' group norms and personal standards regarding safety behaviour: Social identity theory perspective. Journal of Management in Engineering, 33(4), 04017001.

[42] Guo, B. H. W., Yiu, T. W., González, V. A., 2016. Predicting safety behaviour in the construction industry : Development and test of an integrative model. Safety Science 84, 1–11. https://doi.org/10.1016/j.ssci.2015.11.020

[43] He, C., Jia, G., Mccabe, B., Chen, Y., Sun, J., 2019. Impact of psychological capital on construction worker safety behaviour : Communication competence as a mediator. Journal of Safety Research 71, 231-241. https://doi.org/10.1016/j.jsr.2019.09.007

[44] He, C., Jia, G., Mccabe, B., Chen, Y., Zhang, P., Sun, J., 2022. Psychological decision-making process of construction worker safety behaviour : An agent- based simulation approach. International Journal of Occupational Safety and Ergonomics 29, 141–153. https://doi.org/10.1080/10803548.2021.2022351

[45] Hess, J. A., Kincl, L., Weeks, D. L., Vaughan, A., Anton, D., 2020. Safety voice for ergonomics (SAVE): evaluation of a masonry apprenticeship training programme. Applied Ergonomics 86, 1–8. https://doi.org/10.1016/j.apergo.2020.103083

[46] Jabarbi, M., Yousefpour, Y., Ghaffari, M., Shokuhian, A., 2021. Evaluation of effectiveness of risk-based comprehensive safety training planning in the gas pipeline construction industry. International Journal of Occupational Safety and Ergonomics 28, 2468-2481. https://doi.org/10.1080/10803548.2021.2002584

[47] Jiang, H., Wang, J., Han, Y., Yin, H., 2018. Structural equation model analysis of factors in the spread of unsafe behaviour among construction workers. Information 9, 1–11. https://doi.org/10.3390/info9020039

[48] Kim, S., Lee, H., Hwang, S., Yi, J., Son, J., 2022. Construction workers ' awareness of safety information depending on physical and mental load. Journal of Asian Architecture and Building Engineering 21, 1067–1077. https://

doi.org/10.1080/13467581.2021.1908899

[49] Panuwatwanich, K., Al-Haadir, S., Stewart, R. A., 2017. Influence of safety motivation and climate on safety behaviour and outcomes : evidence from the Saudi Arabian construction industry. International Journal of Occupational Safety and Ergonomics, 23, 60–75. https://doi.org/10.1080/10803548.2016.1235424

[50] Silva, S., Araújo, A., Costa, D., Meliá, J. L., 2013. Safety climates in construction industry : Understanding the role of construction sites and workgroups. Open Journal of Safety Science and Technology 3, 80–86.https://doi.org/http://dx.doi.org/10.4236/ojsst.2013.34010

[51] Jung, M., Lim, S., Chi, S., 2020. Impact of work environment and occupational stress on safety behaviour of individual construction workers. International Journal of Environmental Research and Public Health 17, 1–21. https://doi.org/doi:10.3390/ijerph17228304.

[52] Bohm, J., Harris, D., Bohm, J., 2010. Risk perception and risk-taking behaviour of construction site dumper drivers. International Journal of Occupational Safety and Ergonomics 16, 55–67. https://doi.org/10.1080/10803548.2010.11076829.

[53] Wilkins, J. R., 2011. Construction workers ' perceptions of health and safety training programmes Construction workers ' perceptions of health and safety training programmes. Construction Management and Economics 29, 1017–1026. https://doi.org/10.1080/01446193.2011.633538.

[54] Zhang, R. P., Lingard, H., Oswald, D., 2020. Impact of supervisory safety communication on safety climate and behaviour in construction workgroups. Journal of Construction Engineering and Management, 146, 1–11. https://doi.org/10.1061/(asce)co.1943-7862.0001881.

[55] Andersen, L. P. S., Grytnes, R., 2021. Different ways of perceiving risk and safety on construction sites and implications for safety cooperation. Construction Management and Economics, 39, 419–431. https://doi.org/10.1080/01446193.2021.1904516

[56] Didla, S., Mearns, K., Flin, R., 2009. Safety citizenship behaviour : A proactive approach to risk management. Journal of Risk Research 12, 475–483. https://doi.org/10.1080/13669870903041433

[57] Zahoor, H., Chan, A. P. C., Utama, W. P., Gao, R., Zafar, I., 2017. Modeling the relationship between safety climate and safety performance in a developing construction industry: a cross-cultural validation study. International Journal of Environmental Research and Public Health 14, 1–19. https://doi.org/10.3390/ijerph14040351

[58] Novieto, D. T., 2021. Safety climate and occupational safety behaviours : the mediating role of psychological ownership among construction professionals. Engineering, Construction and Architectural Management 30, 853-868. https://doi.org/10.1108/ECAM-06-2021-0539

[59] Wu, T., Wang, Y., Ruan, R., Zheng, J., 2022. Divergent effects of transformational leadership on safety compliance : A dual-path moderated mediation model. Plos One 17, 1–17. https://doi.org/10.1371/journal.pone.0262394

[60] Pandit, B., Albert, A., Patil, Y., 2020. Developing construction hazard recognition skill : Leveraging safety climate and social network safety communication patterns. Construction Management and Economics 38, 640–658. https://doi.org/10.1080/01446193.2020.1722316

[61] Liang, H., Lin, K.Y., Zhang, S., Su, Y., 2018. The impact of coworkers' safety violations on an individual worker: A social contagion effect within the construction crew. International journal of environmental research and public health, 15(4), 773.

[62] Moda, H.M., Ofodile, N., Zailani, B.M., Abubakar, M.A., Ibrahim, Y.M., 2023. Management support as a critical success factor (CSF) for changing worker's safety attitude: A case of the Nigerian construction industry. International Journal of Construction Management, 23(15), 2551-2557.

[63] Lingard, H., Zhang, R. P., Oswald, D. (2019). Effect of leadership and communication practices on the safety climate and behaviour of construction workgroups. Engineering, Construction and Architectural Management 26, 886–906. https://doi.org/10.1108/ECAM-01-2018-0015
[64] Choi, B., Lee, S., 2018. An empirically based agent-based model of the sociocognitive process of construction workers' safety behaviour. J. Constr. Eng. Manage 144, 1–16. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001421.
[65] Teo, E. A., L., Ling, F. Y. Y., Ong, D. S. Y., 2005. Fostering safe work behaviour in workers at construction sites. Engineering, Construction and Architectural Management 12, 410–422. https://doi.org/10.1108/09699980510608848.
[66] Fargnoli, M., Lombardi, M., 2019. Preliminary human safety assessment (PHSA) for the improvement of the behavioural aspects of safety climate in the construction industry. Buildings 9, 1–18. https://doi.org/10.3390/buildings9030069.
[67] Ni, G., Zhu, Y., Zhang, Z., Qiao, Y., Li, H., Xu, N., 2020. Influencing mechanism of job satisfaction on safety behaviour of new generation of construction workers based on Chinese context : The mediating roles of work engagement and safety knowledge sharing. International Journal of Environmental Research and Public Health, 17, 1–24. https://doi.org/doi:10.3390/ijerph17228361.
[68] Sun, Y., Yang, H., Qian, C., Jiang, Y., Luo, X., 2022. Voice endorsement and employee safety voice behaviour in construction projects : The mediating role of leader-member exchange. International Journal of Environmental Research and Public Health 19, 1–17. https://doi.org/10.3390/ ijerph19063374.
[69] He, C., McCabe, B., Jia, G., 2021. Effect of leader-member exchange on construction worker safety behaviour: Safety climate and psychological capital as the mediators. Safety Science 142, 1-9. https://doi.org/10.1016/j.ssci.2021.105401.
[70] Wang, J.M., Liao, P.C., Yu, G.B., 2021. The mediating role of job competence between safety participation and behavioural compliance. International journal of environmental research and public health, 18(11), 1–19. https://doi.org/https:// doi.org/10.3390/ijerph18115783
[71] International Organisation for Standardisation. (2015), "Environmental management systems — requirements with guidance for use (ISO 14001:2015)". https://www.iso.org/standard/60857.html.
[72] International Organisation for Standardisation (2015), "ISO 45001: briefing notes occupational health and safety", Geneva, Switzerland: ISO.
[73] Redinger, C., 2019. Occupational health and safety management systems. In T. P. Fuller (Ed.), Global occupational safety and health management handbook (pp. 80–93). CRC Press.
[74] Caldarescu, G., Tanasievici, G. D., Bejinariu, C., Bernevig, M. A., 2021. The influence of economic factors in the management of health and safety specific to SMEs. MATEC Web of Conferences, 342, 01019. https://doi.org/10.1051/matecconf/202134201019.
[75] Podgórski, D., 2006. Factors influencing implementation of occupational safety and health management systems by enterprises in Poland. Human Factors and Ergonomics in Manufacturing & Service Industries, 16(3), pp.255-267.
[76] Chis, T.V., Cioca, L.I., Badea, D.O., Cristea, I., Darabont, D.C., Iordache, R.M., Platon, S.N., Trifu, A., Barsan, V.A., 2025. Integrated noise management strategies in industrial environments: A framework for occupational safety, health, and productivity. Sustainability 17(3), 1181.
[77] Mir, M., Nasirzadeh, F., Lee, S., Cabrera, D., Mills, A., 2022. Construction noise management: A systematic review and di-

rections for future research. Applied Acoustics, 197, 108936. https://doi.org/10.1016/j.apacoust.2022.108936
[78] Rowlinson, S., YunyanJia, A., Li, B., ChuanjingJu, C., 2014. Management of climatic heat stress risk in construction: a review of practices, methodologies, and future research. Accident Analysis & Prevention, 66, 187-198.
[79] Cortés, D., Traxler, A. A., Greiling, D., 2024. Management control practices for the sustainability transformation in the European construction industry. Journal of Accounting & Organisational Change, 20(6), 156-177. https://doi.org/10.1108/JAOC-11-2023-0209.
[80] Haupt, T.C., Akinlolu, M., Raliile, M.T., 2019, November. Applications of digital technologies for health and safety management in construction. In Proceedings of the 8th World Construction Symposium, Colombo, Sri Lanka (pp. 8-10).
[81] Tender, M., Couto, J.P., Gibb, A., Fuller, P., Yeomans, S., 2022. Emerging technologies for health, safety and well-being in construction industry. In: Bolpagni, M., Gavina, R., Ribeiro, D. (eds) Industry 4.0 for the Built Environment. Structural Integrity, vol 20. Springer, Cham. https://doi.org/10.1007/978-3-030-82430-3_16.
[82] Nnaji, C., Karakhan, A. A., 2020. Technologies for safety and health management in construction: Current use, implementation benefits and limitations, and adoption barriers. Journal of Building Engineering, 29, 101212. https://doi.org/10.1016/j.jobe.2020.101212.
[83] Muñoz-La Rivera, F., Mora-Serrano, J., Oñate, E., 2021. Factors influencing safety on construction projects (Fscps): Types and categories. International Journal of Environmental Research and Public Health, 18(20), 10884.
[84] Khalid, U., Amrit Sagoo, A., Benachir M., 2021. Safety management system (SMS) framework development – mitigating the critical safety factors affecting health and safety performance in construction projects. Safety Science 143, 1-16. https://doi.org/10.1016/j.ssci.2021.105402.
[85] Hu, X., Griffin, M.A., Bertuleit M., 2016. Modelling antecedents of safety compliance: incorporating theory from the technological acceptance model. Safety Science 87, 292–298. http://dx.doi.org/10.1016/j.ssci.2015.12.018.
[86] Flin, R., Yule, S., 2004. Leadership for safety: Industrial experience. Qual Saf Health Care 13, 45–51.
doi: 10.1136/qshc.2003.009555.
[87] Zeng, H. Zhao, L., Zhao, Y., 2020. Inclusive leadership and taking-charge behaviour: roles of psychological safety and thriving at work. Front. Psychol. 11, 1-11.
doi: 10.3389/fpsyg.2020.00062.
[88] Clarke, S., 2013. Safety leadership: a meta-analytic review of transformational and transactional leadership styles as antecedents of safety behaviours. Journal of Occupational and Organisational Psychology 86, 22–49.
DOI:10.1111/j.2044-8325.2012. 02064.x
[89] Su, Y., Cong, W., Liang, H., 2019. The impact of supervisor – worker relationship on workers' safety violations : a modified theory of planned behaviour. Journal of Civil Engineering and Management 25, 631–645. https://doi.org/https://doi.org/10.3846/jcem.2019.10439
[90] Zerguine, H., Jalaludin, J., Bahri, S., Tamrin, M., 2016. Review behaviour based safety approach and factors affecting unsafe behaviour in construction sector : A review. Asia Pacific Environmental and Occupational Health Journal 2, 1–12.
[91] Meng, X., Chan, A. H. S., Lui, L. K. H., Fang, Y., 2021. Effects of individual and organisational factors on safety consciousness and safety citizenship behaviour of construction workers : A comparative study between Hong Kong and Mainland China. Safety Science 135, 1–12. https://doi.org/10.1016/j.ssci.2020.105116.

SYNERGY
PUBLISHING PTE. LTD.

Macro Management & Public Policies
https://ojs.s-p.sg/index.php/mmpp

ARTICLE

Research on the Willingness of Elderly People to Participate in Online Live-streaming Shopping

FU Haiming

Northwest Normal University, Lanzhou, Gansu Province 730070

ABSTRACT

With the rapid development of Internet technology, live-streaming shopping has spread rapidly in China and has become an important part of e-commerce. This study aims to explore the current situation and influencing factors of online live-streaming shopping among elderly people in China. Data was collected from 517 elderly people through questionnaires. The results showed that 87.4% of the elderly participated in live-streaming shopping, while 12.6% did not. Among the elderly who participated, there were slightly more men than women, with a high school or technical secondary school education, a monthly income of 3,000 yuan or less, most living with their spouses, and a higher proportion of the elderly living in second - and third-tier cities. Although online shopping has a high level of participation among the elderly in China, there are still some elderly people who do not participate because of the complexity of the operation process, the dislike of the sales pitches of the hosts, and the inability to guarantee the quality. In order to increase the participation of the elderly, this article also provides corresponding improvement suggestions.

Keywords: Online live-streaming shopping; Seniors; Willingness to participate; Influencing factors.

1. Introduction

In recent years, with the rapid development of Internet technology, online live-streaming shopping has become an important e-commerce model, profoundly changing consumers' shopping behavior. Live-streaming shopping, also known as "live-streaming sales", is an e-commerce model in which

*CORRESPONDING AUTHOR:
Fu Haiming (1986-), male, from Qin'an, Gansu Province, is a postgraduate student at the School of Management, Northwest Normal University. Research direction: Operations Management, Email: fuhaiming116@163.com

ARTICLE INFO
Received: 12 March 2025 | Accepted: 20 March 2025 | Published Online: 30 March 2025
DOI: http://doi.org/10.26549/mmpp.v7i1.36168

CITATION
H, F., 2025. Research on the Willingness of Elderly People to Participate in Online Live-streaming Shopping. Macro Management & Public Policies. 7(1): 23–29. DOI: http://doi.org/10.26549/mmpp.v7i1.36168

goods are sold through live video streaming. In this model, merchants or live-streamers interact with viewers through live-streaming platforms such as Douyin, Kuaishou, Taobao Live, etc., showing the features, usage methods and effects of the goods, thereby facilitating purchases. Since 2015, the scale of China's online live-streaming shopping market has expanded rapidly, attracting a large number of consumers to participate. According to the 54th Statistical report on the development of China's Internet released by the National Bureau of Statistics in August 2024①, there are nearly 1.1 billion Internet users in China, and 905 million online shopping users account for 82.3% of all Internet users. The number of Internet users aged 60 and above accounted for 14.3 percent of the total Internet users in China. However, existing research has mostly focused on the younger consumer group, while studies on the willingness of older people to participate in online live-streaming shopping are relatively insufficient (Ding et al., 2023). This study, in the form of a questionnaire survey, mainly explores two aspects: one is the current situation of Chinese seniors' participation in live-streaming shopping, and the other is the influencing factors that affect seniors' participation in live-streaming shopping, with the aim of providing a reference for the development of Chinese seniors' participation in live-streaming shopping.

2. Literature Review

Existing studies have found that online shopping for the elderly has gradually evolved from an emerging consumption pattern to an important part of daily life (Anderson et al., 2017), but the actual use of this behavior among the elderly population is still constrained by multiple factors. Technology acceptance has a significant impact on the engagement of older people with online shopping. Older people's acceptance of technology is influenced not only by their familiarity with smart devices but also by digital literacy and cognitive abilities (Seifert et al., 2021), with significant generational differences compared to younger people (Li et al., 2024), although some older people are willing to try new ways of shopping. Technical complexity and operational barriers remain significant hindrances. Therefore, age-friendly technologies such as simplifying interface design, optimizing user experience, and adding voice control can effectively enhance their willingness to use (McLaughlin et al., 2020), and the mechanisms of action include: Three key paths - payment process simplification (Shin et al., 2024), intergenerational collaboration function embedding (Wang et al., 2024), and multimodal interaction optimization (Lim et al., 2024) - aging-friendly design has become a new dimension for platforms to attract elderly users. In addition, performance expectations and social influence during online shopping drive the willingness of the elderly to participate (Lian et al., 2014), among which the elderly who receive technical guidance from their children have a higher willingness to consume live streaming, and there is a significant synergy between instrumental support and emotional support (Ren et al., 2024; Zeng et al.,2024). At the same time, trust is also an important factor influencing the participation of older people in live-streaming shopping. Older consumers tend to be cautious about the security of online transactions, especially when it comes to personal information protection and payment security (Oliveira et al., 2017). Some scholars have pointed out that enhancing platform transparency, establishing reliable after-sales service mechanisms, and providing third-party payment guarantees are effective strategies for increasing trust (Mou et al., 2017). In addition, a sense of social isolation plays a significant role in online shopping behavior among the elderly. Live-streaming shopping is not just a consumption activity; it also provides a social pathway through interactive functions, which has a positive impact on reducing loneliness and increasing social engagement among the elderly (Chen et al., 2016). Engaging in online communities and live-streaming shopping interactions can

① China Internet Society. Release of the 54th "Statistical Report on the Development of China's Internet" [J]. Media Forum, 2024, 17 (2096-5079):121

significantly enhance the psychological well-being of older people (Seifert et al., 2021). However, the effectiveness of such interaction largely depends on whether the platform is designed to meet the social needs of older people (Chopik et al., 2016). To better promote the participation of seniors in online live-streaming shopping, attention should be paid to how to further improve the quality of life and satisfaction of the senior population by designing age-friendly platforms, enhancing user experience, strengthening data security and social support.

Although existing studies have explored the behavior of elderly people participating in live-streaming shopping and its influencing factors from multiple dimensions and revealed the mechanisms of key elements such as technology acceptance, social impact, trust, and social needs, they have mostly focused on technology acceptance and socio-psychological levels, paying insufficient attention to differences in cultural backgrounds and current situations. This study will build on this and further explore the current situation and influencing factors of elderly people's participation in online live-streaming shopping under the combined influence of factors such as Chinese cultural background and policy support.

3. Questionnaire collection and data analysis

Data collection for this study began in October 2024. The subjects were elderly, defined based on the legal retirement age in China, which is 60 for men and 55 for women. The study collected data on the participation of Chinese seniors in online live-streaming shopping through questionnaires. A total of 600 questionnaires were distributed and 517 valid questionnaires were retrieved. Among them, 452 elderly people participated in online shopping, accounting for 87.4%; There were 65 elderly people who did not participate in live-streaming shopping, accounting for 12.6 percent. This shows that online shopping has a high level of participation among the elderly in China. This phenomenon indicates that online shopping, as an emerging shopping model, has gradually been accepted by the majority of the elderly. However, the data also reveals that some elderly people are still not taking full advantage of this emerging shopping model. Therefore, an in-depth analysis of the factors influencing elderly people's participation in live-streaming shopping is of great significance for further enhancing their engagement.

3.1 Analysis of samples of Elderly People participating in live-streaming shopping

The statistics of elderly people who participated in online shopping are shown in Table 1. The data shows that among the elderly who participated in live-streaming shopping, men accounted for 54.4%, slightly higher than women's 45.6%. The result suggests that in the current online shopping environment, older men may be more willing to try or use this shopping method more frequently. However, the gender difference is not significant, indicating that online shopping is more prevalent among both elderly men and women.

The distribution of educational attainment shows that those with a high school or technical secondary school education account for the highest proportion, at 44.2%, followed by those with a college or bachelor's degree, at 31.4%. It shows that elderly people with a secondary education level are more willing to engage in live-streaming shopping. Educational attainment may influence older people's understanding and acceptance of web technology. Older people with a secondary education level may have certain advantages in technology acceptance and information processing ability, and thus be more willing to try and use online shopping. However, the nearly 20% participation rate among those with lower educational attainment (junior high school and below) indicates that the threshold for live-streaming shopping is not high and it has some appeal to those with lower educational attainment. At the same time, those with a monthly income of 3,000 yuan or less accounted for the highest proportion, reaching 59.5%, indicating that online shopping is more prevalent among low-income elderly people.

This may be because live-streaming shopping offers more price discounts and promotions that attract price-sensitive consumers. At the same time, it also suggests that online shopping may be an effective way for low-income seniors to get the goods they need.

Table 1 Statistical results of the sample of Elderly People participating in online shopping (N=452)

Statistics	Options	Frequency	Proportion
Gender	**male**	**246**	**54.4%**
	female	**206**	**45.6%**
Educational attainment	Junior high school and below	88	19.5%
	High school or technical secondary school	200	44.2%
	College or bachelor's degree	142	31.4%
	Graduate and above	22	4.9%
Monthly income	3,000 yuan or less	269	59.5%
	3001 ~ 6000	109	24.1%
	6001 ~ 9000	56	12.4%
	More than 9,000 yuan	18	4.0%
Living conditions	Live with one's spouse	238	52.7%
	Living with parents	56	12.4%
	Living with children	111	24.6%
	Living alone	25	5.5%
	Living in a nursing home	22	4.9%
City of residence	First-tier cities	95	21.0%
	Second - and third-tier cities	206	45.6%
	Fourth-tier and lower-tier cities	100	22.1%
	Rural areas	51	11.3%
Frequently watch live streaming platform types	E-commerce platforms	277	61.3%
	Short video platforms	332	73.5%
	Social media platforms	132	29.2%
	Live streaming platforms	181	40.0%
	Information Platform	153	33.8%
	Others	38	8.4%

Most elderly people live with their spouses (52.7%), followed by those living with their children (24.6%). This figure reflects that elderly people living with their families can provide them with more opportunities for technical support and information sharing, thereby promoting their engagement in live-streaming shopping. The proportion of elderly people living in second - and third-tier cities is 45.6%, followed by first-tier cities at 21.0%. This may be related to the level of urban development and the popularity of live-streaming shopping. At present, China's second - and third-tier cities have provided better online infrastructure and a more relaxed pace of life, giving older people more opportunities and time to engage in online shopping. However, the proportion of elderly people shopping online in rural areas is relatively low, at only 11.3%, possibly due to insufficient coverage of door-to-door services by logistics delivery, which makes elderly people with mobility issues less enthusiastic about online shopping.

Short-video platforms are the most frequently watched live-streaming platforms by the elderly, accounting for 73.5%, followed by e-commerce platforms, accounting for 61.3%. This suggests that short video platforms are very popular among the elderly, possibly because of their rich content, ease of operation, and strong entertainment and interactivity. The high proportion of e-commerce platforms suggests that older people are more inclined to buy goods directly in online live-streaming shopping, which may be related to the convenience and diversity of goods offered by e-commerce platforms.

3.2 Analysis of samples of Elderly People who did not participate in live-streaming shopping

The statistics of the elderly who did not participate in live-streaming shopping are shown in Table 2, with more than half (52.3%)Older people think the process is too complicated. This finding highlights the significant impact of the technical threshold on the engagement of seniors in live-streaming shopping. Given that older people may have a relatively weaker ability to adapt to new technologies, live-streaming platforms need to develop more user-friendly interfaces, provide simplified operation processes, and be accompanied by easy-to-understand user guides or tutorials. In addition, technical training and support services for the elderly, such as community workshops or online tutorials, may help to lower this threshold.

Table 2 Statistics of Elderly People Who Did Not Participate in Live-streaming Shopping (N=65)

Statistics	Options	Frequency	Proportion
Reasons for not participating in live-streaming shopping	The online shopping process is too complicated	34	52.3%
	The emotional sales pitches of the hosts are annoying	21	32.3%
	It takes too much time to watch live-streaming shopping	20	30.8%
	There are no items I want in the live-streaming room	9	13.8%
	The quality of the products in the live streaming room cannot be guaranteed	24	36.9%
	There are privacy and financial risks in live-streaming shopping	14	21.5%
	There is no guarantee of after-sales service for online shopping	17	26.2%
	The logistics delivery of online shopping is not guaranteed	8	12.3%

In addition, 32.3% of the elderly are repulsed by the emotional sales pitches of live-streaming hosts, which may conflict with their consumption concepts and values. The elderly may prefer rational and stable consumption methods and hold a conservative attitude towards overly emotional or exaggerated sales tactics. As a result, streamers and platforms should consider adjusting their sales strategies and adopting more moderate and rational sales approaches to accommodate the consumption habits and psychological expectations of the elderly. 30.8 percent of older people think that watching online live-streaming shopping takes too much time, indicating that time cost is an important factor affecting their participation in decision-making. Given that older people may be more concerned about time efficiency, platforms could consider providing more precise and efficient shopping recommendations to reduce the time they spend sifting through a vast amount of information. In addition, developing features that allow for quick browsing and comparison of items, or providing personalized shopping suggestions, could also help improve the shopping efficiency of older people. 13.8 percent of seniors said there were no items they wanted in their online live-streaming rooms, revealing problems with product diversity and matching. To attract more elderly people to participate, live-streaming platforms need to diversify their product range, especially those that better meet the needs and preferences of the elderly. At the same time, by analyzing the consumption behavior and preferences of the elderly, the platform can recommend products more precisely and improve the match between products and users' demands.

Quality and trust issues are the main concerns for the elderly who do not participate in online live-streaming shopping. 36.9% and 21.5% of the elderly are respectively worried about the quality of goods, privacy and economic risks. This requires live-streaming platforms to strengthen their control over product quality, increase transparency, and establish reliable after-sales service systems. In addition, strengthening data security and privacy protection measures, as well as providing third-party payment guarantees, can enhance the trust of the elderly and reduce their concerns. 26.2% and 12.3% of the elderly are concerned about after-sales service and logistics delivery issues. This indicates that providing stable and reliable after-sales service and logistics services is crucial for increasing the willingness of older people to participate. Platforms may consider working with reputable logistics companies to ensure that goods are delivered in a timely and safe manner. At the same time, establishing a sound after-sales service system, including a convenient return and exchange process and effective customer service, can further enhance the trust and satisfaction of the elderly.

4. Conclusions

This study conducted an in-depth analysis of the current situation and influencing factors of Chinese seniors' participation in online live-streaming shopping through questionnaires. The findings suggest a high level of participation in online shopping among the elderly in China, but there are still some elderly who do not participate for a variety of reasons. The majority of the elderly (87.4%) participated in live-streaming shopping, indicating that this emerging shopping model has gradually been accepted and used by the elderly. The factors influencing elderly people's participation in live-streaming shopping include gender, education level, monthly income, residence status, city of residence, and type of live-streaming platform, among which education level and monthly income have a significant impact on participation. The elderly who do not participate in live-streaming shopping are mainly due to the complexity of the operation process, the aversion to the sales pitches of the hosts, the time-consuming cost of watching live-streams, the mismatch of goods, the inability to guarantee quality, privacy and economic risks, after-sales service and logistics delivery problems, etc. To increase the participation of the elderly, it is recommended that live-streaming platforms take the following measures: simplify the operation process and optimize the user experience; Strengthen product quality control and increase transparency; Establish a reliable after-sales service system; Provide stable logistics services.

This study provides a new perspective for understanding the behavior of older people participating in online live-streaming shopping and offers valuable references for research and practice in related fields. Future research could further explore the impact of factors such as different cultural backgrounds and policy support on the participation of the elderly in online live-streaming shopping, and how to further improve the quality of life and satisfaction of the elderly population by designing age-friendly platforms, enhancing user experience, strengthening data security and social support.

Project

This research was supported by the following project: The 2025 Gansu Province University Postgraduate "Innovation Star" Project "Research on the Influencing Factors of Elderly People's Willingness to Shop via Live-streaming E-commerce Based on Dual-path Theory" (Project Number: 2025CXZX-LXS013).

References

[1] Anderson M, Perrin A. Tech adoption climbs among older adults[R]. Pew Research Center.2017.

[2] Chen Y R R, Schulz P J. The effect of information communication technology interventions on reducing social isolation in the elderly: a systematic review[J]. Journal of medical Inter-

net research, 2016, 18(1): e4596.

[3] Chopik W J. The benefits of social technology use among older adults are mediated by reduced loneliness [J]. Cyberpsychology, Behavior, and Social Networking, 2016, 19(9): 551-556.

[4] Ding X, Cao C, Li D. Why the Elderly Indulges in Live Shopping: Optimization of Interaction Mechanism Under the Live E-commerce Scenario? [C]//International Conference on Human-Computer Interaction. Cham: Springer International Publishing, 2022: 276-290.

[5] Li Y., Yang Y., Shi S., et al. Seniors' knowledge-based digital marginalization in the era of information technology advancements[J]. Journal of the Knowledge Economy, 2024, 15 (3):12622-12650

[6] Lian J., Yen D. C. Online shopping drivers and barriers for older adults: Age and gender differences[J]. Computers in human behavior, 2014, 37:133-143

[7] Lim C., Chen H., Chen X. A Seamless Technology Integration Framework for Elderly-Centered Interactive Systems: Design, Implementation, and Validation Through the Pillow Fight System[J]. Applied Sciences, 2024, 14 (23):11306

[8] McLaughlin A, Pak R. Designing displays for older adults[M]. CRC press, 2020.

[9] Mou J, Shin D H, Cohen J F. Trust and risk in consumer acceptance of e-services[J]. Electronic Commerce Research, 2017, 17: 255-288.

[10] Oliveira T, Alhinho M, Rita P, et al. Modelling and testing consumer trust dimensions in e-commerce[J]. Computers in Human Behavior, 2017, 71: 153-164.

[11] Ren P., Klausen S. H. Smartphone use, intergenerational support and older adults' wellbeing[J]. Current Psychology, 2024, 43 (1):407-424

[12] Seifert A, Cotten S R, Xie, B. A double burden of exclusion? Digital and social exclusion of older adults in times of COVID-19[J]. The Journals of Gerontology: Series B, 2021, 76(3): e99-e103.

[13] Shin H., Oh C., Kim N. Y., et al. Evaluating and eliciting design requirements for an improved user experience in live-streaming commerce interfaces[J]. Computers in Human Behavior, 2024, 150:107990

[14] Wang Y., Feng Z., Wang H. Multimodal intent understanding and interaction system for elderly-assisted companionship[J]. CCF Transactions on Pervasive Computing and Interaction, 2024, 6 (1):52-67

[15] Zeng Yueliang, Yu Ying, Huang Zhiqi, et al. A Study on the Influencing Factors of Online Shopping Behavior of the Elderly from the Perspective of Social Support: A qualitative Analysis Based on Grounded Theory [J]. Digital Library Forum, 2024, 20 (08):19-28

SYNERGY
PUBLISHING PTE. LTD.

Macro Management & Public Policies

https://ojs.s-p.sg/index.php/mmpp

ARTICLE

Digital footprints of personality: Large-scale analysis reveals quantitative links between MBTI traits and emotional expression on Reddit

LIU Xingcai

Institute of Psychology of the Chinese Academy of Sciences, Beijing, 100000

ABSTRACT

The intersection of personality psychology and computational social science offers unprecedented opportunities to understand human behaviour at scale. However, the precise link between stable personality traits and an individual's online emotional expression remains unquantified across large, naturalistic datasets, with research often bifurcating between complex, "black-box" predictive models and small-scale qualitative studies. Here, we bridge this divide by applying a computationally efficient, lexicon-based framework to a massive dataset of 2,005 Reddit users who publicly self-declared their Myers-Briggs Type Indicator (MBTI) personality type. We analysed the aggregated emotional content of their comment histories, controlling for user activity. We find robust, statistically significant associations between personality dimensions and distinct emotional footprints. The Thinking (T) versus Feeling (F) dimension emerged as the most potent predictor of average sentiment polarity, with 'Thinking' types exhibiting significantly lower average sentiment polarity (β=-0.061, p<1.5e-19). We also find that 'Thinking' types display significantly lower emotional volatility, measured by the standard deviation of their sentiment scores (β=-0.008, p=0.038). Contrary to our initial pro-social hypothesis, Extroversion (E) was not significantly linked to specific'joy'or 'trust' frequencies in the full model, but did correspond to a small but significant increase in overall positive polarity (β=0.016, p=0.032). Furthermore, the Judging (J) dimension unexpectedly emerged as a strong, positive predictor of both overall sentiment (β=0.023, p<0.001) and 'joy' expression (β=0.079, p=0.003). These findings demonstrate that foundational personality traits leave distinct, quantifiable imprints in digital language and that trait-based emotional expression is a multi-dimensional phenomenon where decision-making (T/F) and planning (J/P) traits can be as, or more, influential than social (I/E) traits.

Keywords: MBTI personality traits; Online emotional expression; Digital footprints; Text analysis; Lexicon-based framework.

*CORRESPONDING AUTHOR:
Liu Xingcai, male, born in 1989, holds a Ph.D. and postdoctoral training, specializing in the field of language psychology

ARTICLE INFO
Received: 12 March 2025 | Accepted: 20 March 2025 | Published Online: 30 March 2025
DOI: http://doi.org/10.26549/mmpp.v7i1.36167

CITATION
X, L., 2025. Digital footprints of personality: Large-scale analysis reveals quantitative links between MBTI traits and emotional expression on Reddit. Macro Management & Public Policies. 7(1): 30–. DOI: http://doi.org/10.26549/mmpp.v7i1.36167

INTRODUCTION

The digital platforms of the twenty-first century have become vast, unstructured archives of human cognition and social interaction (Stella et al., 2023). Billions of individuals now use social media to express thoughts, beliefs, and emotions, providing an unprecedented ecological dataset for the social and computational sciences (Musk & K., 2023). Understanding the fundamental drivers of this online behaviour is a central challenge. A classic question in psychology, predating the digital age, is the extent to which stable, internal personality traits govern external behaviour and expression (S et al., 2022b; B et al., 2019). The convergence of these two domains—personality psychology and digital social data—presents a unique opportunity to test foundational psychological theories at a scale previously thought impossible (Schwartz et al., 2013).

The field of Natural Language Processing (NLP) applied to mental health, personality, and emotion is growing rapidly (Musk & K., 2023; S et al., 2022a; B et al., 2019; C et al., 2021). Early research largely focused on coarse sentiment analysis (positive vs. negative), but the field has increasingly shifted towards finer-grained emotion detection (e.g., joy, anger, sadness) to capture a more nuanced view of user expression (H et al., 2021; A et al., 2023). Concurrently, a dominant trend in computational personality research has been prediction: using complex machine learning (ML) and deep learning (DL) models to infer personality traits (typically the Big Five) from a user's text (A et al., 2021; M et al., 2020; N et al., 2021; I et al., 2022; G et al., 2023). Recent studies demonstrate that modern Large Language Models (LLMs) can infer personality from social media posts with moderate, above-chance accuracy (V et al., 2024; H et al., 2023). However, this predictive arms race towards model complexity is often detrimental to interpretability, computational expense, and scalability. These "black-box" models, while powerful, often obscure the specific linguistic mechanisms linking personality and expression (S et al., 2022b; G et al., 2023). Furthermore, their performance against traditional, feature-based methods is not always superior, especially when considering computational trade-offs (V et al., 2024).

A distinct methodological gap thus exists: a lack of large-scale, confirmatory studies that use computationally efficient, interpretable, and transparent methods to validate the linguistic correlates of personality. We are not interested in predicting personality; we leverage a large, self-labeled dataset to explain its linguistic consequences. This study fills this gap by reversing the typical research question. Instead of asking "Can we predict personality from text?", we ask, "Does a known personality trait manifest in text in a predictable way?". We use a computationally efficient, lexicon-based framework (VADER and NRC), which remains robust, highly interpretable, and validated for analysing social media text (S et al., 2022b; C et al., 2019).

Based on our theoretical framework integrating MBTI theory with the Emotion as Social Information (EASI) model (C et al., 2019), we formulated specific hypotheses: (1) Extroversion (E) would correlate with higher mean sentiment (H1a) and elevated frequencies of pro-social emotions like 'joy' (H1b) and 'trust' (H1c) (L et al., 2017; S et al., 2022a); (2) Feeling (F) types would exhibit higher average sentiment, greater affective word expression (H2a), and higher frequencies of interpersonally-focused negative emotions like 'sadness' (H2c) compared to Thinking (T) types; (3) the Thinking (T) dimension would be associated with lower variance in sentiment polarity, indicating greater emotional stability (H3a).

Related Works

The study of human psychology through digital traces is a rapidly expanding field at the intersection of computational linguistics, artificial intelligence, and social science. Social media platforms provide unparalleled resources for analysing mental health (Musk & K., 2023; C et al., 2021), behaviour (W et al., 2021), and personality (B et al., 2019; S et al., 2022a). Research has evolved from broad sentiment analysis to granular emotion detection (H et al., 2021; A et al., 2023) and complex cognitive phenomena (Stella et al., 2023).

A primary focus has been predicting personality traits from user-generated text, with applications in marketing, team-building, and personalized recommendations (B et al., 2019; S et al., 2022a). Early approaches relied on traditional machine learning pipelines with engineered features like TF-IDF (A et al., 2021), emotion lexicons (N et al., 2021), and psycholinguistic dictionaries (S et al., 2022b), using models like SVM, Naive Bayes, or Random Forests (N et al., 2021; C et al., 2021) valued for interpretability and efficiency.

Recent trends shift to deep learning, with hybrid models (e.g., CNN-LSTM) for MBTI classification (M et al., 2020) and Bi-LSTMs for extroversion prediction (A et al., 2021). Pre-trained transformers (e.g., BERT, RoBERTa) and LLMs (e.g., GPT) show strong performance, even in zero-shot settings (H et al., 2023; V et al., 2024). However, these models suffer from an "interpretability gap," obscuring the reasons behind predictions (G et al., 2023; S et al., 2022b), a critical limitation for scientific inquiry focused on explanation. Recent work addresses this by linking LLM embeddings to linguistic markers (V et al., 2024; S et al., 2022b).

A parallel research stream examines emotional expression on social media, including tools (e.g., text, emoticons) (F et al., 2020) and influencing factors like personality. For example, extroversion predicts positive social media posts (L et al., 2017), and the EASI model explains emotional cues as persuasive signals (C et al., 2019).

Our study bridges these fields by using a transparent, lexicon-based methodology for large-scale confirmatory analysis. We validate linguistic manifestations of personality in emotion, responding to calls for psychometrically valid and explainable models (V et al., 2024; S et al., 2022b).

METHODS

Literature Review Methodology

To situate our study, we conducted a systematic literature review of articles published between January 2017 and December 2023 in Google Scholar, PubMed, and ACM Digital Library. Search queries combined keywords from personality (e.g., 'personality', 'MBTI', 'Big Five'), platform ('social media', 'Reddit', 'Twitter'), and method ('NLP', 'text analysis', 'machine learning', 'LLM', 'emotion'), yielding 92 potential articles. Manual screening for relevance to personality prediction or linguistic correlates of personality resulted in 22 core papers. This review identified a gap between high-compute predictive models (e.g., LLMs, DL) (A et al., 2021; M et al., 2020; V et al., 2024; H et al., 2023; I et al., 2022) and small-scale explanatory models (L et al., 2017; S et al., 2022b). Our study addresses this gap with a low-compute, explanatory model applied to a large dataset.

Data Collection and Preprocessing

The dataset was derived from the public Pushshift Reddit comment corpus. Data collection followed two stages: (1) Targeted scanning of personality-focused subreddits (e.g., r/mbti, r/infp, r/intj) identified 5,044 users with self-declared 4-letter MBTI types in their user "flair"; (2) Retrieval of complete comment histories for this cohort, excluding comments from personality subreddits to avoid topical bias. A minimum activity filter (≥20 valid comments) ensured statistical reliability, resulting in a final sample of 2,005 users. Binary dummy variables were created for each MBTI dimension (e.g., 'Is Extrovert' = 1 for E-types, 0 for I-types).

RESULTS

Data Description and Distributions

The final sample of 2,005 users was skewed towards Introversion ('isExtrovert' mean = 0.237), Thinking types ('isThinking' mean = 0.637), and Intuitive types ('isSensing' mean = 0.109), characteristic of online personality communities. User-level average sentiment polarity ('avgSentimentPolarity') was approximately normal (Mean = 0.170, Std. Dev. = 0.146). User activity ('commentCount') followed a long-tail power law (median = 56, mean = 113.15), justifying the 'commentCountScaled' control variable. Full descriptive statistics are presented in Table 1.

Table 1. Descriptive Statistics for Key Analytical Variables (N=2,005)

Variable Class	Variable	Mean	Std. Dev.	Min	25%	50% (Median)	75%	Max
Personality Dims.	isExtrovert	0.237	0.426	0.000	0.000	0.000	0.000	1.000
(Binary)	isSensing	0.109	0.311	0.000	0.000	0.000	0.000	1.000
	isThinking	0.637	0.481	0.000	0.000	1.000	1.000	1.000
	isJudging	0.386	0.487	0.000	0.000	0.000	1.000	1.000
Sentiment Metrics	avgSentimentPolarity	0.170	0.146	-0.263	0.067	0.148	0.256	0.768
	stdSentimentPolarity	0.476	0.080	0.211	0.420	0.474	0.527	0.761
Emotion Metrics	freqJoy	0.711	0.572	0.000	0.362	0.576	0.879	9.250
(NRC Freq.)	freqSadness	0.564	0.430	0.000	0.277	0.444	0.690	12.292
	freqAnger	0.520	0.886	0.000	0.258	0.411	0.650	7.292
	freqTrust	1.059	0.469	0.000	0.533	0.829	1.308	5.865
Control Variable	commentCount	113.15	521.40	20.000	32.000	56.000	112.00	22707.00

Note: Emotion metrics are mean frequencies derived from the NRC lexicon. Statistics are rounded to 3 decimal places.

Baseline Comparative Analysis

Welch's t-tests of 'avgSentimentPolarity' revealed a highly significant difference for the T/F dimension ($p<8.2e-18$), with Feelers (F) (Mean = 0.237, N=727) exhibiting higher average sentiment than Thinkers (T) (Mean = 0.132, N=1278), supporting H2a. The I/E dimension showed a non-significant trend ($p=0.057$), with Extroverts (E) (Mean = 0.179) slightly more positive than Introverts (I) (Mean = 0.166). ANOVA comparing 'freqSadness' across four MBTI types (INFP, INTJ, ESTP, ESFJ) was non-significant ($F(3,149)=0.94$, $p=0.418$), highlighting the need for multivariate regression Multivariate Regression and Ablation Analysis

Correlation analysis and OLS regression models isolated the independent effect of each personality dimension . The ablation study predicting 'avgSentimentPolarity' showed the 'isThinking' coefficient remained stable (-0.060 to -0.061) as predictors and controls were added, demonstrating robustness. The full mode had the highest explanatory power (Adj. $R^2=0.045$).

DISCUSSION

Our large-scale analysis provides quantitative evidence that MBTI personality dimensions correspond to distinct emotional footprints in online language. The dominant role of the T/F dimension confirms its status as a primary driver of sentiment polarity and emotional stability. Thinkers exhibited lower average sentiment and volatility, empirically validating the "logically stable" T-type archetype. This aligns with MBTI theory, as Feelers prioritize harmony and values while Thinkers emphasize logic.

Extroversion's effects were nuanced: a small positive impact on overall sentiment but no link to specific pro-social emotions. This refines prior work (L et al., 2017) by showing bivariate links may not hold when controlling other personality factors, suggesting Extroversion's linguistic marker is generalized positivity.

The unexpected positive role of the J dimension—predicting higher sentiment, joy, and trust—offers a new research avenue. J-types' preference for structure may manifest as more positive, trusting emotional expression, warranting further investigation.

Limitations include self-declared MBTI labels (not clinical diagnoses), self-selection bias, potential NRC lexicon limitations (capturing expressiveness over discrete emotions), and non-representative

Reddit user base. Cross-sectional design limits causal inference. Future work should replicate findings across platforms (Schwartz et al., 2013) and cultures (N et al., 2021), integrating lexicon-based features with LLM embeddings in a confirmatory framework.

In conclusion, our findings demonstrate that personality traits leave quantifiable imprints in digital language, with decision-making (T/F) and planning (J/P) traits as influential as social (I/E) traits. This advances understanding of personality-expression links in naturalistic digital environments.

DATA AVAILABILITY STATEMENT

The aggregated, anonymized user-level sentiment and emotion feature data, and code to reproduce analyses, are deposited in the Zenodo repository:

Repository Name: Digital footprints of personality: Emotional expression and MBTI traits on Reddit (Aggregated Dataset and Code)

Persistent Identifier (DOI): https://doi.org/10.5281/zenodo.17538772

Access Link: https://zenodo.org/records/17538772

Raw comment content from Reddit cannot be shared publicly due to user agreements. Researchers may obtain raw data via the Reddit API (https://www.reddit.com/dev/api/) or Pushshift dataset, complying with terms of service.

REFERENCES

[1] The author declares no conflicts of interest regarding the design, execution, data analysis, and writing of this study.

[2] A, A., et al. (2023). Deep emotion recognition in textual conversations: a survey. Artificial Intelligence Review, 56:11333–11406.

[3] A, B., et al. (2021). Ai knows you: Deep learning model for prediction of extroversion personality trait. IEEE Access, 9:118464–118475.

[4] B, R., et al. (2019). Personality prediction with social behavior by analyzing social media data – a survey. International Journal of Advanced Computer Science and Applications, 10(6):324–332.

[5] C, L., et al. (2019). The persuasive power of emoticons in electronic word-of-mouth communication in social networking. Journal of Business Research, 101:50–65.

[6] C, S., et al. (2021). Big data analytics on social networks for real-time depression detection. Journal of Big Data, 8:111.

[7] H, A. A., et al. (2021). Beyond sentiment analysis: A review of recent trends in text based sentiment analysis and emotion detection. Journal of Big Data, 8:83.

[8] H, L., et al. (2023). Large language models can infer psychological dispositions of social media users. Nature Communications, 14:5678.

[9] I, W. W., et al. (2022). Text based personality prediction from multiple social media data sources using pre-trained language model and model averaging. Journal of Big Data, 9:109.

[10] L, F., et al. (2017). Emotion expression on social networking sites: A study of young persons' use of facebook and twitter in the uk. Journal of Psychological Research and Behaviour Management, 10:247–255.

[11] M, A., et al. (2020). A hybrid deep learning technique for personality trait classification from text. IEEE Access, 8:175960–175971.

[12] Musk, D. R., & K., A. (2023). Mental health analysis in social media posts: A survey. ACM Computing Surveys, 55(1):1–38.

[13] N, A. A., et al. (2021). Big five personality prediction based in indonesian tweets using machine learning methods. PeerJ Computer Science, 7:e521.

SYNERGY PUBLISHING PTE. LTD.

Macro Management & Public Policies

https://ojs.s-p.sg/index.php/mmpp

ARTICLE

Research on Material Procurement Category Strategy and Application in Petrochemical Enterprises

LIU Sheng

Shandong Haikē Chemical Co., Ltd., Dongying, Shandong, 257000

ABSTRACT

This study focuses on procurement category strategies and applications in petrochemical enterprises, aiming to provide theoretical support and practical guidance for optimizing procurement management. The research first analyzes the technical complexity, stringent quality requirements, supply chain risks, and refined management characteristics of material procurement in petrochemical enterprises. Subsequently, differentiated strategies are proposed for different material categories: Strategic materials ensure long-term supply stability through lifecycle cost control and deep supply chain collaboration; Bulk materials achieve cost optimization and risk management via large-scale centralized procurement and dynamic price adjustments; Bottleneck materials establish diversified supply channels and risk hedging mechanisms to ensure supply continuity; General materials enhance procurement efficiency through digital platform-driven operations and supply chain ecosystem development. This categorized procurement management approach effectively improves supply chain resilience, reduces operational costs, and provides crucial support for sustainable industry development.

Keywords: petrochemical enterprises; materials; procurement; categories

1. Introduction

As a cornerstone of the national economy, the petrochemical industry's material procurement management directly impacts production safety, cost control, and supply chain stability. Petrochemical enterprises' material procurement is characterized by high technical barriers,

*CORRESPONDING AUTHOR:
Liu Sheng (b. February 1985), male, native of Heze, Shandong Province, of Han ethnicity, holds a Master's degree and works as an engineer. His research focuses on enterprise supply chain management

ARTICLE INFO
Received: 12 March 2025 | Accepted: 20 March 2025 | Published Online: 30 March 2025
DOI: http://doi.org/10.26549/mmpp.v7i1.36166

CITATION
S, L., 2025. Research on Material Procurement Category Strategy and Application in Petrochemical Enterprises. Macro Management & Public Policies. 7(1): 35–39. DOI: http://doi.org/10.26549/mmpp.v7i1.36166

stringent quality requirements, significant supply chain risks, and complex management. Different material categories exhibit notable variations in supply models, cost structures, and risk profiles. Based on the classification characteristics of petrochemical materials, this paper systematically explores differentiated procurement strategies and key application points for strategic materials, bulk materials, bottleneck materials, and general materials. The aim is to establish a scientific, refined, and flexible procurement management system, providing theoretical support and practical references for enhancing supply chain competitiveness in petrochemical enterprises.

2. Characteristics of Material Procurement in Petrochemical Enterprises

Petrochemical procurement exhibits distinctive industry characteristics, primarily manifested in four aspects: technical complexity, stringent quality requirements, supply chain risks, and refined management. Petrochemical production operates under extreme conditions including high temperatures, high pressures, and strong corrosive environments, demanding highly specialized materials. For instance, special valves must meet large-diameter and high-load standards, while catalysts require high-precision online analysis capabilities. Some equipment involves patented technologies, and the scarcity of qualified suppliers further complicates procurement. Quality control is exceptionally rigorous, with materials undergoing specialized equipment type testing and ISO quality management system certification. Critical equipment often requires third-party supervision and inspection to ensure compliance with safety standards. Supply chain risks are pronounced, as most petrochemical projects are located in remote areas or have multinational operations. Long-distance transportation and extended delivery cycles make them vulnerable to external factors like international politics, exchange rate fluctuations, and import/export policies. Establishing emergency supply mechanisms is essential to address sudden disruptions [1]. Procurement management emphasizes refinement and collaboration, utilizing bundled procurement strategies to achieve economies of scale—such as consolidating bids for similar valves and pipelines to reduce costs. Simultaneously, cross-departmental coordination is strengthened by integrating technical, production, and financial needs to develop differentiated procurement strategies. Electronic procurement systems enable end-to-end digital management, enhancing both efficiency and transparency in the process.

3. Category Strategy and Application Points of Material Procurement in Petrochemical Enterprises

3.1 Strategic Material Procurement Strategy: Full Life Cycle Cost Control and Deep Supply Chain Synergy

In the procurement systems of petrochemical enterprises, strategic materials—including core production equipment, critical process materials, and patented technology licensing supplies—play a decisive role in plant safety, operational efficiency, and long-term competitiveness due to their high value, extended service life, and strong technological dependence. For procuring such materials, it is imperative to abandon the short-sighted logic of “lowest bid wins” and adopt a procurement strategy centered on optimal Life Cycle Cost (LCC), while actively advancing supply chain collaborative innovation [2].

Full lifecycle cost management requires procurement decisions to cover the entire process from equipment selection, procurement, installation, operation and maintenance to decommissioning. During the technical agreement signing phase, the procurement department should collaborate with design institutes, process technology teams, and suppliers to conduct multiple rounds of in-depth technical briefings. This involves precisely defining equipment performance boundaries and material corrosion resistance levels—for example, resistance to H_2S and Cl^- environments—along with interface standards and process compatibility requirements. For instance, specifying intergranular corrosion sensitivity indicators for reactor lining materials can prevent unplanned shutdowns and high replacement costs caused by material failure after commissioning. For patented technology-licensed materials such as specific catalyst formulations or proprietary control systems, long-term framework agreements should be established to lock in supply prices and incorporate technical iteration clauses. These clauses require suppliers to provide version upgrades free of charge or at discounted rates during the contract period, ensuring the facility remains aligned with advanced process requirements throughout its 10-20 year lifecycle and avoiding "technology lock-in" risks [3].

Meanwhile, supply chain collaboration must be extended to the project's source stage by implementing the "Early Supplier Involvement" (ESI) mechanism. During feasibility studies or basic design phases, core equipment manufacturers should be invited to participate in process route discussions. Leveraging their engineering expertise, suppliers can propose optimization suggestions: For instance, while complying with ASME standards, using finite element analysis to optimize high-pressure vessel wall thickness distribution—ensuring safety while saving hundreds of tons of special steel; or recommending modular designs to shorten on-site installation cycles. Furthermore, enterprises and leading suppliers can jointly establish collaborative laboratories to develop customized materials for extreme operating conditions (e.g., ultra-high temperatures, strong corrosion), such as novel nickel-based alloys or nano-coated seals. Such collaborations can resolve "bottleneck" challenges, establish exclusive technical parameters and supply partnerships, thereby creating competitive barriers [4].

3.2 Bulk Material Procurement Strategy: Bulk Procurement and Dynamic Price Regulation

Bulk commodities such as crude oil, coal, natural gas, and basic chemical feedstocks account for over 60% of procurement costs in petrochemical enterprises. These companies must balance economies of scale with market risk management in their procurement strategies. Large-scale centralized procurement can be achieved through regional joint purchasing models, where industry leaders form procurement alliances to consolidate regional demand and leverage bulk advantages. The procurement model adopts a "framework agreement plus dynamic pricing" mechanism. The framework agreement establishes benchmark prices and adjustment formulas, with execution prices regularly adjusted based on international market indices (e.g., Brent crude oil futures, Platts coal index). This approach ensures supply stability while mitigating price volatility risks [5].

In inventory management, bulk material procurement should adopt a dual-tier system combining "strategic reserves" and "commercial reserves". Strategic reserves involve enterprises either constructing their own storage facilities or leasing national warehouses to mitigate extreme supply disruptions. Commercial reserves are implemented through Vendor Managed Inventory (VMI) models, where companies sign inventory-sharing agreements with major suppliers. These agreements allow suppliers to establish forward warehouses in designated areas, with settlements based on actual consumption. This approach not only reduces capital tie-up but also enhances emergency supply capabilities by leveraging suppliers' nationwide storage networks. Additionally, futures hedging tools can be employed to mitigate price risks, with procurement contracts including price protection clauses. If market price fluctuations exceed agreed parameters, both parties will proportionally share cost adjustments.

3.3 Bottleneck Material Procurement Strategy: Diversified Supply Channels and Risk Hedging Mechanism

Bottleneck materials—those with high market concentration, low substitutability, and critical impact on production continuity, such as specialized catalysts, imported instruments, and equipment for extreme operating conditions—require a three-tier procurement framework: primary suppliers, backup suppliers, and contingency plans. When selecting primary suppliers, comprehensive evaluation of their technical expertise, production capacity, and emergency response speed is essential, with supply priority secured through long-term contracts. Backup suppliers must demonstrate seamless product compatibility with primary materials and maintain synchronized upgrades via regular technical collaboration.

In risk hedging strategies, the procurement of bottleneck materials requires a dual safeguard system combining "technological substitution with inventory buffer". The technological substitution approach involves collaborating with research institutions to develop alternative materials or optimizing processes to reduce dependence on specific materials. For instance, for a particular imported catalyst, partnerships with universities could develop domestic catalysts with comparable activity while optimizing reaction conditions to expand their applicability. The inventory buffer strategy entails establishing safety stock levels based on material supply cycles. For imported materials, additional buffers should be allocated by considering shipping timelines, customs clearance periods, and geopolitical risks.

3.4 General Material Procurement Strategy: Digital Platform Driven and Supply Chain Ecosystem Construction

General supplies are characterized by high procurement frequency, low unit value, and a significant proportion of total costs, requiring procurement strategies that prioritize efficiency and cost optimization. The digital procurement platform serves as the core tool, integrating supplier management, demand aggregation, electronic bidding, and contract management to fully digitize the procurement process. The platform must feature intelligent matching capabilities, automatically recommending optimal suppliers and prices based on historical procurement data, while supporting innovative transaction models such as reverse auctions and group purchases to further reduce procurement costs[6].

In the construction of supply chain ecosystems, general material procurement departments should implement tiered supplier management and collaborative innovation. Dynamic evaluations should be conducted based on key metrics including delivery punctuality rates, quality compliance rates, and service response speed. A-level suppliers will receive preferential order allocations and priority payment incentives, while C-level suppliers will face mandatory rectification deadlines or elimination. Concurrently, an innovation incentive mechanism should be established to encourage suppliers to propose cost optimization solutions or process improvement suggestions. Adopted solutions should be rewarded proportionally based on cost savings achieved. For instance, when a supplier reduces transportation damage rates through optimized packaging solutions, the company may return a percentage of the resulting cost savings to the supplier, creating a shared benefit mechanism. Additionally, supply chain financial tools should support supplier development by providing SMEs with accounts receivable financing and order financing services, thereby reducing their capital costs and enhancing supply stability[7].

From an operational perspective, general material procurement must enhance data-driven decision-making capabilities. By leveraging transaction data, supplier profiles, and market price data accumulated through procurement platforms, organizations can develop cost analysis models to identify cost fluctuation patterns and potential savings. For instance, analyzing historical procurement prices of standard components against current raw material market prices enables future price trend forecasting, allowing procurement rhythm adjustments. Furthermore, big data technology can be employed to predict demand, optimize inventory levels and replenishment strategies, and reduce risks of stockpiling and shortages. For example, by forecasting demand for specific spare parts based on production schedules and equipment maintenance cycles, centralized procurement can be utilized to lower unit costs[8].

4 .Conclusion

Research on procurement category strategies for petrochemical enterprises demonstrates that categorized policies are the key to enhancing procurement efficiency. Going forward, these enterprises should continuously refine their category management models, strengthen data-driven decision-making capabilities, and advance procurement management toward intelligent, green, and globalized development, thereby injecting sustained momentum into the industry's high-quality growth.

References:

[1] Xu Xiaoting. A Brief Discussion on the Procurement Mechanism of International Operating Materials of Petroleum and Petrochemical Enterprises [J]. Energy & Chemical Finance and Management, 2025, 4 (03): 67-70.

[2] Yu Chunguang. Exploration on the Management and Supervision of Material Procurement Business of Sino-foreign Joint Venture Petrochemical Enterprises [J]. China Logistics and Procurement, 2025, (08): 109-110.

[3] Tan Yanping, Sun Haibin, Sun Yining. Research on material procurement strategy of petrochemical enterprises from the perspective of supply chain [J]. Market Weekly, 2024, 37 (25): 53-56 82.

[4] Yang Huimei. Analysis of Cost Control Strategies of Material Procurement of Petroleum Enterprises [J]. Modern Industrial Economics and Information Technology, 2024, 14 (05): 228-230.

[5] Zhou Yingmiao. Exploration of measures to improve the accuracy and timeliness of material procurement plans of petroleum and petrochemical enterprises [J]. China Petroleum and Chemical Standards and Quality, 2022, 42 (14): 55-57.

[6] Liu Wenbo. Research on the marketing strategy of Zhejiang Sales Branch of Sinopec Lubricants Co., Ltd.[J].Jilin University, 2014.

[7] Wu Peng. Strengthen the procurement and management of materials in petrochemical enterprises to reduce the cost of production process[J].Petroleum and Petrochemical Material Procurement, 2025(9):7-9.

[8] Li Jingyu. Measures to improve the accuracy and timeliness of material procurement plans of petroleum and petrochemical enterprises[J]. China Chemical Trade, 2024(3).

Macro Management & Public Policies
https://ojs.s-p.sg/index.php/mmpp

ARTICLE

Marketing Model Innovation and Consumer Behavior Analysis in the Digital Age

lIANG wuchang

Shandong Vocational and Technical University of Engineering, Jinan City, Shandong Province, 250000

ABSTRACT

Against the backdrop of the global digital transformation of the economy, enterprises' marketing models are evolving in depth from traditional approaches to digital and intelligent ones. The integrated application of technologies such as big data, artificial intelligence and blockchain enables enterprises to reach consumers, build brands and guide demand in a more precise manner. Consumer behavior in the digital environment exhibits the characteristics of diversification, instantaneity and personalization, with its decision-making models and value perceptions undergoing remarkable changes. Starting from the interactive relationship between digital marketing innovation and the evolution of consumer behavior, this paper explores the reconstruction of marketing concepts, channel structures and brand communication mechanisms driven by digital technologies. The study points out that the core of digital marketing lies in the reshaping of user value under data-driven approaches, and the changes in consumer behavior have propelled the marketing system to shift from one-way communication to intelligent interaction, providing a new path for enterprises to achieve precision marketing and sustainable growth.

Keywords: digital era; marketing innovation; consumer behavior; data-driven; intelligent marketing

The digital economy has become a pivotal force driving the transformation of the global commercial system. With the steady rise in internet penetration and the popularization of smart terminals, the relationship between enterprises and consumers has extended beyond transactional interactions

*CORRESPONDING AUTHOR:
Name: Liang WuchangEthnicity: HanGender: MaleDate of Birth: May 24, 1983Professional Title: Intermediate Professional TitleAffiliation: Shandong Vocational and Technical University of Engineering Research Direction: Business Administration Educational Background: Postgraduate Postal Code: 250000Native Place: Zaozhuang, Shandong Province

ARTICLE INFO
Received: 12 March 2025 | Accepted: 22March 2025 | Published Online: 30 March 2025
DOI: http://doi.org/10.26549/mmpp.v7i1.36165

CITATION
W, L., 2025. Marketing Model Innovation and Consumer Behavior Analysis in the Digital Age. Macro Management & Public Policies. 7(1): 40–45. DOI: http://doi.org/10.26549/mmpp.v7i1.36165

in physical spaces to social networks, content platforms and virtual ecosystems. Traditional marketing models, which rely on empirical judgment and offline promotion, are increasingly showing limitations in terms of precision, interactivity and data feedback. Based on data and driven by technology, digital marketing achieves in-depth insight into consumer psychology and behavioral guidance through algorithms, recommendation mechanisms and situational experiences. At the same time, consumers' decision-making logic has become increasingly complex in an environment of information overload and media fragmentation, presenting new characteristics such as multi-channel comparison, emotional identification and social participation. This paper aims to analyze the innovative trends of marketing models in the digital era and the interactive mechanism between such trends and the evolution of consumer behavior, and explore how enterprises can realize value co-creation and marketing optimization through digital technologies to build a sustainable competitive business advantage.

The Transformation of Marketing Against the Background of Digital-Transformation

1.1 Reshaping of the Marketing Ecosystem Driven by the Digital Economy

The rapid rise of the digital economy has endowed corporate marketing activities with the characteristics of digitalization, intellectualization and networking. The marketing ecosystem has transformed from an enterprise-centric linear system into a consumer-centric dynamic network. Supported by digital technologies, information flow, capital flow and logistics have achieved a high degree of integration, enabling marketing activities to break through the constraints of time and space. Data has become a new factor of production; through data collection and analysis, enterprises can accurately identify consumer demands and realize the full-process optimization of product R&D, promotion and services. Taking e-commerce platforms as an example, recommendation systems based on user portraits have become a mainstream marketing mechanism, realizing the shift from "products seeking customers" to "customers seeking products". This ecological reshaping has expanded corporate marketing beyond mere product sales to relationship management and value co-creation, forging a new marketing paradigm for the digital era.

1.2 Technological Innovation Leading the Evolution of Marketing Models

The in-depth integration of big data, artificial intelligence (AI) and cloud computing has driven the transformation of marketing models from information dissemination to intelligent decision-making. The application of AI algorithms enables enterprises to extract valuable insights from massive volumes of data and identify consumer preferences and behavioral patterns. For example, intelligent recommendation systems deliver personalized content by analyzing users' search and purchase history; affective computing technology can recognize consumers' emotional responses, facilitating the design of more emotionally resonant content for brand communication. Blockchain technology, by enhancing data security and transaction transparency, has also boosted consumers' trust and brand loyalty. Empowered by technology, marketing activities have shifted from an experience-oriented approach to scientific decision-making, thereby achieving a dual improvement in marketing efficiency and precision.

1.3 A New Pattern of Digital Communication and Brand Interaction

The diversification of digital media has transformed the pathways of information dissemination. Enterprises shape their brand images in a multi-dimensional way through emerging channels such as short videos, live streaming, social media and virtual communities. Brand communication has evolved from one-way output into a co-creation process with user participation, where interactive marketing, storytelling narration and situational experience have become key strategies to enhance user stickiness. For instance, enterprises leverage Artificial Intelligence Generated Content (AIGC) for virtual character marketing, endowing brand images with greater affinity and expandability. The essence of digital communication lies in content-centric emotional connection: it realizes real-time optimization of communication effects through data feedback, forming a closed-loop system of content generation - user resonance - behavioral conversion.

2. Innovation Paths of Digital Marketing Models

2.1 Construction of a Data-Driven Precision Marketing System

The core feature of the digital era lies in the widespread application of data and the deepening of intelligent decision-making. As the core goal of the digital marketing system, precision marketing essentially relies on data analysis to achieve efficient matching between consumer demands and enterprise resources through scientific algorithms. By leveraging big data collection, machine learning and artificial intelligence algorithms, enterprises can identify consumer behavioral characteristics and potential preferences from complex information, thereby realizing market segmentation and personalized strategy design. For example, retail enterprises formulate differentiated promotion and product combination strategies by analyzing purchase frequency, category preferences and seasonal trends in different regions. In-depth mining of social media data enables enterprises to accurately capture user emotions and interest tags, and further form dynamic user portraits to achieve precise multi-touchpoint reach. Data-driven marketing not only improves the efficiency and conversion rate of information dissemination, but also promotes enterprises to shift from the traditional "sales-oriented" model to a "user value-oriented" one, making marketing an important support for value creation and strategic decision-making.

2.2 Integrated Development of Social and Content-Oriented Marketing

In an era marked by the high fragmentation of digital communication, content has become the core link connecting brands and consumers. The integration of social and content-oriented marketing has shifted the communication model from media-dominated to user-dominated, where consumers participate in brand building through interactive behaviors and drive the reproduction of social influence. Social platforms leverage algorithmic recommendation mechanisms to distribute content precisely based on users' interests and behavioral preferences, and enterprises can boost user engagement through short videos, interactive topics, creative challenges and other formats. For instance, brands create scenario-based consumption through storytelling and life-oriented content on platforms such as Douyin and Bilibili, enabling users to form brand cognition in a state of emotional resonance. The essence of content marketing lies not in information indoctrination, but in emotional stimulation and cultural communication. Through the continuous output of high-quality content and community operation, enterprises not only achieve brand exposure and word-of-mouth accumulation, but also build a multi-level social fission effect through user self-propagation, facilitating the dual growth of brand value and commercial returns

2.3 Technological Empowerment of Experiential and Immersive Marketing

With the development of virtual reality (VR), augmented reality (AR) and metaverse technologies, experiential and immersive marketing have become important directions for digital innovation. By virtue of immersive technologies, enterprises can reconstruct brand scenarios in virtual spaces, enabling consumers to participate in brand experiences at both sensory and emotional levels. For example, automobile enterprises use VR test-drive systems to allow users to experience driving performance and brand culture in a virtual environment, while clothing enterprises realize personalized matching and instant purchase decisions through AR virtual fitting mirrors. The application of technologies has transformed consumers fr om audiences into participants, fostering in-depth experiences and emotional connections during interactions. The core value of experiential marketing lies in enhancing consumers' cognitive memory and cultural identification of brands, and realizing the transformation from information display to perceptual resonance through technical means. This marketing model centered on immersive experience not only elevates the innovative expressiveness of brands, but also drives the evolution of traditional advertising communication toward emotion-driven and perceptual value transmission, providing new technical support for enterprises to build sustainable competitive advantages.

3. Digital Shift of Consumer Behavior and Its Psychological Mechanisms

3.1 Changes in Decision-Making Paths Under Omnichannel Integration

In the digital environment, consumers' purchase decisions no longer follow the traditional linear path of cognition - interest - purchase, but evolve into a complex, cross-cutting network across multiple channels. Consumers frequently switch between different platforms, acquiring information through diverse channels such as search engines, social media, short-video platforms and online forums, and conducting multi-dimensional comparisons and verifications. Brand reputation, peer reviews and social interaction have become important variables influencing decision-making. Consumers have greater autonomy throughout the purchase journey: they leverage data and algorithmic recommendations for personalized screening, thus seizing the initiative in information acquisition. Against this backdrop, enterprises need to track omnichannel data to identify consumers' behavioral and psychological changes at different touchpoints, integrate online and offline resources, and deliver a consistent, seamless user experience. The core of multi-channel decision-making lies in the improvement of consumers' information control capability, which requires enterprises to establish a real-time response mechanism based on data insights, and realize precise communication and contextual marketing to maintain a competitive edge in an environment of information overload.

3.2 Emotional and Symbolic Trends in Consumer Psychology

Consumer behavior in the digital economy era is becoming increasingly emotional and symbolic; purchasing is no longer merely the satisfaction of functional needs, but also an embodiment of individual expression and social identity. Brands have gradually evolved into emotional symbols and cultural icons, and consumers convey their identity, aesthetic tastes and value positions through brand selection. The popularization of social media has reinforced this trend: in behaviors such as posting content, checking in and leaving reviews, users participate in social interaction by virtue of brand narratives, achieving emotional resonance and self-shaping. In marketing practices, enterprises should focus on constructing cultural contexts and symbolic systems, shaping brand personalities through storytelling, visual aesthetics and value expression to arouse consumers' emotional resonance. Emotion-driven purchase decisions have transformed marketing from one-way communication to relational connection; brands are no longer just product providers, but platforms for emotional experience and cultural participation. The essence of emotional marketing is to enable consumers to see their own reflections in brands, thereby fostering in-depth psychological identification and brand loyalty.

3.3 Enhanced Consumer Autonomy in the Era of Data Awareness

With the advancement of digitalization, consumers' role in the data ecosystem has undergone a fundamental shift, transforming from passive information recipients into active data subjects. The rising awareness of privacy protection has made consumers pay greater attention to the transparency and compliance of enterprises in the process of data collection, analysis and utilization. The application of new technologies such as blockchain, encryption algorithms and distributed storage has provided technical guarantees for data traceability and personal authorization, further strengthening consumers' sense of control over their own data rights and interests. On this basis, consumers have begun to act as important collaborators in the digital marketing ecosystem through means such as selective authorization and participation in data co-creation. If enterprises can establish an open and transparent data trust mechanism, they can not only enhance user stickiness, but also boost brand credibility. Consumers' active participation has turned the marketing relationship from one-way indoctrination to value co-creation. While respecting users' data sovereignty, enterprises should take ethical governance and social responsibility as the guide, build a new digital consumption ecosystem centered on trust, and realize a development pattern of long-term win-win cooperation.

4. Interactive Mechanisms Between Digital Marketing and Consumer Behavior

4.1 The Shift from Information Dissemination to Value Co-Creation

The advent of the digital era has transformed the logic of marketing from information-dominated to value co-creation. Traditional marketing is enterprise-centric, conveying brand information through one-way communication with consumers in a passive receptive position. By contrast, digital marketing enables the co-construction of information and value through social media, community platforms and interactive content. In the consumption process, users become co-narrators of brand stories through the integration of UGC (User-Generated Content) and PGC (Professionally-Generated Content). For example, on social platforms, consumers participate in brand building by posting content, creating short videos and engaging in topic interactions, turning the enterprise's brand voice from a single tone into a multi-dimensional chorus. Through an open marketing ecosystem, enterprises absorb users' creativity and emotional feedback, forming a dynamic cycle of enterprise empowerment - user creation - brand resonance. This value co-creation mechanism enhances consumers' sense of participation and belonging, and also drives market competition to shift from a mere contest of product attributes to that of experience and emotional identification, further reshaping the interactive relationship between brands and consumers.

4.2 Algorithmic-Driven Behavioral Prediction and Relationship Maintenance

Algorithmic driving has become a pivotal mechanism for improving precision and efficiency in digital marketing. Through the combination of generative algorithms and machine learning models, enterprises can real-time track consumers' behavioral trajectories, capture emotional changes and potential demands, and achieve accurate prediction and dynamic response. For instance, intelligent retail platforms use data analysis to track users' browsing, collection and purchase paths, and then automatically adjust recommended content and pricing strategies, forming a closed-loop system of prediction - feedback - optimization. This algorithmic-driven marketing model not only improves the efficiency of consumer reach, but also reshapes the paradigm of customer relationship management. Enterprises can intervene in advance before consumers' demands become explicit, and strengthen brand presence through personalized push notifications, membership benefits and interactive content, thus achieving sustained relationship maintenance. Data-driven behavioral prediction enables enterprises to shift from passive response to active guidance, moving relationship maintenance forward from the post-purchase phase to the front end of consumption decision-making, which significantly enhances customer stickiness and the capability of customer lifetime value management.

4.3 Brand Identification Shaping in the Digital Trust System

In a highly virtualized and information-fragmented business environment, trust has become the core link between brands and consumers. The transparency and authenticity of digital marketing directly affect consumers' sense of psychological security and brand loyalty. Enterprises need to establish a systematic digital trust system through compliant data management, information security assurance and authentic content development. The application of blockchain technology provides traceable technical support for brand credibility, ensuring the immutability of transactions and data records, thereby enhancing brand authority. At the same time, the formation of brand identification relies not only on product performance, but also on enterprises' fulfillment of social responsibilities and expression of cultural positions. When brands take a proactive stance on public welfare, environmental protection and social issues, consumers will establish in-depth identification at the value level. The digital trust system enables consumers to gain a sense of psychological security and emotional belonging in the virtual consumption environment, thus forming long-term preferences and loyalty in brand selection. This trust-based brand identification shaping is becoming a pivotal path for enterprises to build enduring competitive advantages in the era of digital competition.

5. Conclusion

The digital era has brought unprecedented opportunities and challenges to marketing. Technological advancements have driven the transformation of marketing models from experience-oriented to intelligent decision-making, while changes in consumer behavior have further forced enterprises to innovate their marketing concepts and communication pathways. Future marketing will no longer rely solely on data analysis and algorithmic recommendations, but will center on value co-creation and emotional connection to achieve the harmonious coexistence of humans and technology. Enterprises should strike a balance between technological innovation and ethical governance, and realize the dual growth of commercial value and social value by building an open, intelligent and trusted marketing ecosystem. The innovative direction of digital marketing should focus on the optimization of user experience and the integration of social responsibility, enabling marketing to truly become a bridge connecting enterprises with consumers, and technology with culture.

References

[1] Sun, Z. H. (2025). Discussion on the countermeasures of enterprise marketing and supply chain management in the digital era. Business Culture, (13), 174-176.

[2] Deng, M. (2022). Reflections on the innovation of marketing models under the digital background. Modern Marketing, (22), 155-157.

[3] Lu, Y. X. (2025). Innovation and practice of marketing strategies in the digital era. Market Modernization, (13), 62-64.

[4] Li, P. P. (2024). Research on the innovation of marketing strategies under the background of the digital era. Marketing World, (22), 92-94.

[5] Jiang, H. (2024). Research on the innovation and practice of marketing strategies in the digital era. Investment and Cooperation, (08), 178-180.

SYNERGY
PUBLISHING PTE. LTD.

Macro Management & Public Policies

https://ojs.s-p.sg/index.php/mmpp

ARTICLE

Synergizing Precision Agriculture with Microbial Ecosystem Engineering

WANG Fei [1] ***WANG Jian*** [1] ***WANG Jia*** [2] ***LI Fangfang*** [2] ***ZhANG Hongrui*** [3] ***WANG Yuqian*** [3]

[1.] *Yongfeng Biological Fertilizer Co., LTD. Zhengzhou，450001*

[2.] *Zhengzhou Zhituo Biotechnology Co., LTD. Zhengzhou，450001*

[3.] *Hainan Tianhu Application Technology Co., LTD. 570100*

ABSTRACT

The integration of Precision Agriculture (PA) and Microbial Ecosystem Engineering (MEE) offers a promising approach to enhancing agricultural productivity, sustainability, and resilience. PA uses modern technologies, remote sensing, IoT sensors, and data analytics to optimize the use of resources, whereas MEE is concerned with the manipulation of soil microbiomes to enhance the health of soils, the recycling of nutrients and resistance to diseases. This review examines the synergies of these two disciplines, and how the real-time information provided by PA can be used to inform the targeted use of useful microbes and microbial consortia. This integrated methodology would enhance the fertility of soil, minimize the environmental impact, and increase the crop production through the integration of the accuracy of PA and the biological potential of MEE. Although this is a huge potential, issues like data integration, scalability, regulatory issues and knowledge deficiency must be encountered. The most important way of breaking these barriers and achieving the full potential of this integrated solution to sustainable agriculture will be through future research and interdisciplinary collaboration.

Keywords: Precision Agriculture, Microbial Ecosystem Engineering, Soil Microbiomes, Sustainable Agriculture, Data Integration.

Introduction

The world is experiencing a paradigm shift concerning the global agricultural sector due to the twin realities of the rise in population and economic

*CORRESPONDING AUTHOR:
Wang Fei (born December 1971), male, Han ethnicity, native of Nanbu County, Sichuan Province, holds a Master's degree and is a Senior Economist. His primary research focuses on biotechnology, intelligent technology, and modern agricultural development

ARTICLE INFO
Received: |
DOI: http://doi.org/10.26549/mmpp.v7i1.36164

CITATION
F, W., J, W., J, W., F, L., H, Z., Y, W., 2025. Synergizing Precision Agriculture with Microbial Ecosystem Engineering. Macro Management & Public Policies. 7(1): 46–66. DOI: http://doi.org/10.26549/mmpp.v7i1.36164

sustainability of the environment. As the world is expected to have almost 10 billion population by the year 2050, the food production is expected to grow by about 70% to satisfy the growing demand. Simultaneously, the problem of climate change, land degradation, and natural resources reduction is a serious challenge to agricultural systems. The traditional agricultural practices that heavily depend on high input of water, fertile, pesticides and energy are no longer viable in the midst of these strains. More than ever, there is a strong need to develop agricultural systems which are not only efficient but also resilient, sustainable and able to improve soil health [1, 2].

A new technology, known as precision agriculture (PA), an information-driven method that uses the latest technologies, including satellite images, drones, Internet of Things (IoT) sensors, and artificial intelligence (AI), is developed to solve these problems. Using real-time data to optimize agriculture practices enables applicable use of inputs, efficient utilization of water, and less environmental impact as a result of PA. PA helps to maximize efficiency and productivity and reduce waste and environmental harm by using technologies like variable rate fertilization, autonomous tractors, and yield prediction models. Although these innovations are very promising as they aim to enhance the productivity and sustainability of farming, they are more concerned with the control of the physical resources including land, water and fertilizers without considering the intricate biological systems that support soil health and plant development [3, 4].

Simultaneously with the increase in PA, microbial ecosystem engineering (MEE) has become an effective the aide to improve soil health, crop production, and environmental sustainability. Microbiome in the soil is a complex assemblage of bacteria, fungi, archaea, and other microorganisms which are of significant importance in the nutrient cycling, disease suppression, and plant growth promotion. These microorganisms despite their microscopic nature are the basis of the health and productivity of agricultural systems. Examples of soil bacteria and fungi include those that help in the decomposition of organic matter, the release of nutrients into the soil by plants, and others enter into symbiotic associations with the roots of plants, increasing their ability to uptake water and other essential nutrients like nitrogen, phosphorus, etc. Notably, a number of these microorganisms can assist plants to withstand pests, diseases as well as environmental stresses. Nevertheless, microbiome potential in the soil is not fully utilized because of poor knowledge of its complexity and the difficulty in controlling the population of the microbes [5].

The goal of microbial ecosystem engineering is to utilize this potential by exploiting and controlling soil microbial communities to achieve particular agricultural outcomes. It can include the inoculation of soils with desirable microbes, the creation of synthetic microbial consortia (SynComs) that can be able to execute a given functionality, or even genetic modification of microbes to increase their functionality. These engineering solutions, in turn, may contribute greatly to soil fertility, plant growth, and the reduction of the necessity to use chemical fertilizers and pesticides. MEE offers more holistic, nature-based approach to agriculture, which is in line with the objectives of sustainability, by creating a healthy and diverse microbiome [6, 7].

Although the contributions of both precision agriculture and microbial ecosystem engineering can be viewed as very promising on their own, their combination can provide even more potential to bring revolution in the current agriculture. A synthesis of the two disciplines has the potential to produce a more holistic, data-driven methodology of farming that works to optimize physical inputs, but also improves the biological complexity of agricultural ecosystems. An example of this is that real-time data of PA technologies can be utilized to monitor microbial populations more accurately and, therefore, allow more specific interventions on microbes. On the other hand, MEE can also educate the creation of more effective PA strategies, by increasing soil health and resilience, and thereby, raising the overall effectiveness of farming systems. This synergy can be not only helpful in enhancing crop production but also creating a more environmentally sustainable production system, fewer chemical inputs needed, and healthier soils that can be used in the future. Precision agriculture combined with microbial ecosystem engineering is an emerging yet fast growing border of agricultural science. Although both areas have experienced a high level of progress, there is still a research gap in the systematic combination of these technologies and methods. This review article aims to fill this gap, by giving an inclusive view of the synergies between precision agriculture and microbial ecosystem engineering, and how the two ways of engineering agriculture have the potential of making it a more sustainable, resilient, and productive system. Describing the most recent developments, issues, and prospects in both disciplines, this article is expected to serve as a roadmap to the researchers, agronomists, and policymakers that are interested in adopting an integrated and technology-based solution to sustainable agriculture [8-11].

Moreover, the review can be used to encourage interdisciplinary cooperation among the disciplines of agricultural technology, microbiology, and environmental science. Integration of PA and MEE should not just be based on the technical expertise but also a further insight into the soil biology, ecosystem dynamics and data analytics. The article can lead to the development of research and innovation in the agricultural industry by uniting the knowledge gained through these various fields. Finally, we hope to facilitate future research, promote the use of integrated agriculture, and help to bring about a more sustainable future of agriculture, which can achieve food security needs of the future without compromising the health of our planet.

2. Precision Agriculture: Technological Foundations and Applications

3. Precision Agriculture (PA) has transformed the practice of farming by adding the latest technologies and data analytics to control agricultural activities more cost-effectively and sustainably. With the increasing population around the world, the agricultural systems have to produce more food out of less resources and hence the increased dependency on the high-technology advancements. PA is a conceptualization of the problem of productivity enhancement and environmental reduction damage as it offers the means to achieve more specific and precise interventions into the field. The real-time data and automated systems allow PA to optimize the use of resources, increase productivity, decrease waste, and be a better environmental steward. This section will discuss the technological aspects behind Precision Agriculture, investigate the uses of this technology in agriculture, and discuss the advantages and issues associated with the implementation of PA systems [12-14].

Precision Agriculture revolves around a set of technologies that help farmers to collect, process, and take action on large volumes of data collected on their farms. The technologies provide information which is used to maximize crop production, cut waste, and improve efficiency of agricultural operations.

3.1 Remote Sensing Technologies

Remote sensing refers to the process of gathering information at a distance with the help of different instruments, which are usually located on satellites, drones, or airplanes to observe the state of crops and the soil. These technologies are very important in Precision Agriculture which gives detailed information over a wide farming area with high resolution.

Multispectral imaging allows satellite systems, e.g. the Landsat series at NASA or the Sentinel satellites at the European Space Agency, to collect wavelengths spanning the surface of the Earth. The images will help the farmers to track different activities of their farms such as the health of their crops, the level of moisture on their soil, and changes in temperature. Considering the example of satellite imagery, one can detect the areas that are either under stress in the field, e.g., water or nutrient deficiency, and make a corrective action. Data on satellites are especially applicable in large scale farms or landscapes in which traditional monitoring cannot be done [15].

The drones with high-resolution cameras and multispectral and thermal sensors bring even more detailed information on the field. Drone operation in contrast to satellites enables the close-up images of the crops and lower altitudes in which the precise areas of particular crop may be monitored. Sensors such as thermal sensors are used to detect the changes in temperature of plants, which may either be water stress or signs of an ailment. An effective scenario where drones are utilized in PA is in vineyards where the drones can be used to monitor crops things like mildew can be detected and thus dealt with before it spreads to a large scale.

These sensors directly measure the soil or on the surface in order to observe important soil parameters in real time. These sensors can be used to continuously monitor soil moisture, temperature, pH and nutrient levels. Installation of networks of ground sensors over a field will give farmers access to granular data, which is used to make decisions about irrigation schedules, fertilization, and soil health. As an example, intelligent soil sensors may automatically regulate the flow of irrigation systems according to the moisture level on the ground in real-time to minimize water wastage, and to make crops as hydrated as possible [16].

2.2 Global Positioning System (GPS)

Precision Agriculture is impossible without GPS. This technology enables the navigation of equipment accurately all over the field so that every area of the field is dealt with accordingly. GPS sensors are mounted in machines like the tractor, combine harvesters, and sprayers allowing them to work within pinpoint precision.

Among the most important uses of GPS in PA is in the auto-steering technology of tractors and other machines, in which the technology is used to direct the machines in straight lines with minimum overlaps. This accuracy lowers the fuel consumption and labor expenses and also gives the standard measure of application inputs such as fertilizers, pesticides, and seeds. GPS controlled tractors can be used in large fields to maximize their field cover, requiring less passes to get a job done and make sure the inputs are used effectively.

VRT is based on GPS which enables the accurate application of fertilizers, seeds and pesticides in various areas of a field. This method employs GPS positioning together with sensor information to implement inputs within various rates, which depend on the requirements of each area. In an instance, a field that has zones of fertile soils might not need a lot of fertilizer whereas the parts with poor soils may demand high rate of application. Using the personalized application, VRT will reduce the waste of resources, lower the environmental effects, and improve the productivity of crops [17, 18].

2.3 Geographic Information Systems (GIS)

Precision Agriculture involves the use of GIS which is a necessary software to visualize, analyze and interpret spatial data. GIS enables farmers to make finer maps which integrate data of various sources such as remote sensing images, GPS-based data, and sensor readings on the ground. These maps assist farmers in keeping track of the situation in the field, measuring the growth of crops, and deciding on interventions according to the conditions of the soils, weather, and performance statistics.

GIS develops the spatial maps that reflect variability in the soil conditions and crop production along with pest pressures. With these maps, the farmer is able to determine, the areas of the field that need extra attention e.g. areas with high or low nutrient concentrations or areas likely to be eroded. An example is where a field map can show an area with low yields which is associated with the existence of high acidity in the soil, where it may be corrected through specific soil amendments.

When using GIS, the farmers will be able to apply site-specific management practices, which means that interventions applied to various areas in a field will be adapted to the specifics of each zone.

This is because it enhances the productivity of crops with the least input and reduction on environmental degradation. As an illustration, variable-rate irrigation (VRI) systems may be adopted by superimposing the data in the field maps on the soil moisture data in a way that water is applied effectively to regions that have different moisture levels [19, 20].

2.4 Internet of Things (IoT)

Precision Agriculture is being revolutionized by the Internet of Things (IoT) that links sensors, devices and machines to the internet, allowing it to monitor and be controlled remotely. IoT-related systems allow the communication of farm equipment, sensors, and cloud-based systems, which inform farmers about real-time information about the field conditions, crop health, and equipment status.

IoT-based irrigation systems have sensors to monitor the moisture content of the soil and adjust the amount of water used in relation to it. Through real-time data, these systems are also able to avoid over-irrigation and also lower the amount of water used especially in areas that have limited water. To illustrate, in the almond orchards in California, the IoT-based irrigation systems have enabled farmers to utilize less water by 30% and still produce quality yields. Another application of IoT is to keep track of the performance of farm machinery, including harvesters and tractors. Sensors have the capability of detecting such hiccups as engine malfunctions, fuel efficiency, and wear and tear on their parts and inform farmers of maintenance requirements that might lead to expensive repairs or idles [21].

2.5 Artificial Intelligence (AI) and Machine Learning (ML)

Precision Agriculture is depriving of AI and machine learning (ML) as tools especially in the analysis of high volumes of data and making predictive decisions. AI and ML models can identify trends and information that cannot be easily identified by human beings through the analysis of historical and real-time data.

Drones, satellites, and sensors can be analyzed using AI-powered systems to identify the existence of early diseases, pests, or nutrient deficiencies in crops. To illustrate, multispectral images of drones can be processed with the help of AI algorithms to reveal the initial signs of stress in crops due to the lack of water or caused by pests, which can be subjected to specific actions to reduce the use of pesticides or fertilizers. The analysis of data on weather patterns, soil conditions and plant growth levels can be used to predict crop yields using machine learning models with high accuracy. The predictions enable farmers to make sound judgments on when to harvest, store, and also on labor needs. An example is in wheat farming where machine learning models have been applied to forecast yields in response to temperature, rainfall, and soil conditions to enable farmers to optimize harvesting [22].

2.6 Automated Machinery and Robotics

Precision Agriculture has changed the physical nature of farming through automation and robotics. Robot systems, harvesters, and autonomous tractors avoid human involvement, promote efficiency, and guarantee the accuracy of inputs use. These GPS-controlled tractor can work autonomously doing such tasks as tilling, planting, and fertilizing. They are highly efficient and they save on labor costs with minimal human intervention. Self-driven tractors with real time sensors are able to calibrate their speed and action according to the soil making them to prepare the fields in the best possible manner.

Robotic harvesters are being utilized in crops that are sensitive or need accuracy. These are machines that are meant to harvest fruits or vegetables without harming the plants. The robotic strawberry harvesters are an example, where the AI and vision system is used to detect ripe fruits, harvest them without harming the plants and surrounding fruits, which is of particular concern to the delicate crops [23].

2.7 Applications of Precision Agriculture

The central aim of Precision Agriculture is to adapt the farming process to the unique conditions of each field so that farmers will be able to optimize what they input and as a result produce the maximum outcomes. Some of the most significant applications of PA that evidence its transformative potential is provided below.

Among the most important advantages of PA is the possibility to implement the fertilizers of variable rates within a field, depending on the requirements of particular zones of soil. Conventional methods of fertilizer application put the same level of fertilizer in all parts of the field and this has resulted to inefficiencies and over use of fertilizers. VRF enables the use to be both precise and site-specific which saves on the costs of fertilizers and prevents further pollution of the environment and also enhances crop yield. An example of the application of VRF in corn farming is applying nitrogen according to the level of nutrients found in soil, thereby leading to an increase in yields and reduction in the amount of nitrogen released into waterways [24].

There is a limit in water resource, and effective irrigation is essential in saving this resource and at the same time maintaining crop well being. PA technologies will ensure that farmers use water where and when it is required. Through sensors that check the levels of soil moisture, farmers will be able to vary the irrigation rates to prevent excessive watering or water shortage, achieving maximum growth of plants with minimal water consumption. Precision irrigation is also found in arid areas such as California and has been shown to save up to 30 percent of water usage without reducing crop yield since pests and disease can be detected before they cause extensive damage to the crop.PA technology, including drones and remote sensing, can ensure that pests and diseases are detected early enough to avoid causing large-scale destruction. At the level of plant health, farmers can implement pest control interventions only when needed, which will lead to the minimization of the use of pesticides and the preservation of useful insects. Drones with the infrared sensors are also applied in vineyards to observe the health of grapevines and signs of fungus so that they can be treated specifically, which will not require the use of pesticides as often, as well as they can save the environment [25].

Table 1: Key Technologies in Precision Agriculture (PA) and Their Applications

Technology	Description	Applications in Agriculture	Benefits
Remote Sensing (Satellites, UAVs)	Use of satellites or drones to collect high-resolution imagery	Crop monitoring, pest detection, yield prediction	Early disease detection, efficient resource management, field mapping
GPS and Auto-steering Systems	Precision navigation for farm machinery	Precision planting, variable rate fertilization, autonomous equipment	Reduced input waste, higher precision in field operations
IoT and Soil Sensors	Sensors embedded in soil to measure moisture, temperature, and nutrients	Precision irrigation, soil health monitoring	Real-time soil data, optimized water and fertilizer use
GIS (Geographic Information System)	Software that integrates spatial data for analysis and decision-making	Field mapping, zone-specific crop management	Data-driven decision-making, enhanced yield predictions
Artificial Intelligence (AI)	Machine learning algorithms analyzing vast datasets	Yield prediction, pest and disease modeling, precision farming management	Improved accuracy of predictions, automation of data analysis

With the help of the sophisticated data analytics, farmers are able to make more accurate predictions regarding crop yields. Predicting yield models are AI-driven and machine learning models that consider multiple variables like weather conditions, soil condition, and the stage of crop growth to be more accurate. This is useful in allowing farmers to schedule their harvests, maximize storage space, and better supply chains.

Precision Agriculture is changing the approach to farming practices as it provides answers to some of the most burning issues in the modern agriculture. Through a combination of innovative technologies, such as remote sensing, GPS, GIS, IoT, AI, and automation, PA allows farmers to control their fields more precisely than they have ever controlled them. These technologies can make a significant contribution to the rise of crop growth, reducing the cost of inputs, resource conservation, and decreasing the environmental impact. Nevertheless, the implementation of PA technologies is accompanied by such problems as the cost of initial investment is high, and the use of such technologies requires specialized knowledge. However, the advantages of PA are way more than these challenges, and with the further evolution of the technologies, PA is bound to contribute significantly to the future of sustainable agriculture. A summary of the major technologies that are applied within Precision Agriculture as well as their applications and advantages are presented in Table 1. It will enable one to swiftly understand the technological support that facilitates PA [26].

4. Microbial Ecosystem Engineering: Enhancing Soil Health and Plant Performance

Microbial ecosystem engineering (MEE) is a novel method of controlling the microbial communities in agricultural soils to increase crop output, better soil wellbeing, and environmental sustainability. The microbiome of the soil, the different community of bacteria, fungi, archaea, viruses and other microorganisms inhabiting soil, is the most important in shaping the most important agricultural processes as nutrient recycling, stimulation of plant growth, disease control and maintenance of soil structure. Although historically, the agricultural practices have in most cases ignored the role played by the microbiome, the recent developments have been keen to point out its relevance in ensuring the sustainability of farming habits. These microorganisms can be manipulated through MEE to enhance agricultural performance including improving the growth of plants, enriching nutrients etc. [27].

3.1 Soil Microbiome Dynamics

The soil is a dynamic ecosystem, which hosts millions of microorganisms, which create complex networks. These communities of microbes live in relationship with one another as well as with plants in a manner that significantly influences the soil health, plant growth and the whole agroecosystem. The soil microbiome is a source of not only necessary nutrients to the plants but also affects soil physical characteristics, tolerance to stress, and resistance to pests by plants. It is essential to know about the role of these microorganisms in order to exploit the potential of microbial ecosystem engineering [28].

3.1.1 Nutrient Cycling and Soil Fertility

The soil microbiome contributes to the nutrient cycling as one of the major functions. Microorganisms decompose organic matter and thus turn it into a form that can be absorbed by plants thus keeping soil fertile. Sulfur cycling Nitrogen fixation, phosphorus solubilization, and sulfur cycling are all types of nutrient cycling, which is important to the growth and productivity of plants. Nonetheless, the majority of plants are not able to use nitrogen directly in the atmosphere, so, nitrogen fixation is one of the most significant processes in the sustainable agriculture. Some of the symbiotic bacteria like Rhizobium and Frankia establish collaborations with legume roots by fixing nitrogen in the atmosphere to ammonia at a form easily accessible by plants. Nitrogen fixing non-symbiotic bacteria, such as Azotobacter and Clostridium, also add to the levels of soil nitrogen. This process has the potential of reducing use of synthetic fertilizers of nitrogen which requires a lot of energy to be made and which pollute the environment [29].

Phosphorus is a limiting nutrient that is mostly found in soils, but plays a vital role in the transfer of energy to plants, photosynthesis as well as root development. Numerous microorganisms such as some species of bacteria and fungi are able to solubilize compounds of inorganic phosphorus, which is then able to be taken by the plants. Mycorrhizal fungi (symbiosis with the roots of plants) mobilize phosphorus and other nutrients, including potassium, in the soil and carry it directly to plant roots, thereby increasing the growth of plants, particularly in nutrient-depleted soils.

Microorganisms also take part in the decomposition of organic materials in the ground turning them into humus that enriches the soil and enhances the soil structure. This not only restores the vital nutrients but it also enhances the soil aeration, water holding ability as well as soil porosity and this forms a habitat that supports the healthy growth of the root of the plants [30].

3.1.2 Disease Suppression

The health of soil microbiome and its diversity are important in averting plant diseases. Crop yields may be severely affected by soil-borne pathogens, e.g. fungi, bacteria, and nematodes. Nonetheless, desirable microorganisms are capable of outcompeting these pathogens in a number of ways. Most soil microorganisms synthesize antimicrobial products which suppress other pathogen growth. Indicatively, Bacillus and Pseudomonas species manufacture antibiotics and volatile substances that avert the increased development of deleterious fungi and bacteria.

The useful microbes also compete with pathogenic microorganisms in space and nutrients available in soil. These good microorganisms make the pathogenic organisms unable to find a place to settle on the roots of plants or the rhizosphere by outcompeting the pathogens. Some of the useful microbes are able to activate the natural defense of the plant and increase its resistance to diseases. Such microorganisms have the potential of triggering the immune of the plant, rendering it more immune to pathogens. Such biocontrol minimizes the use of synthetic chemical pesticides and hence is a more sustainable solution to conventional pest control [31, 32].

3.1.3 Plant Growth Promotion

Microorganisms play a direct role in plant growth, including through increased nutrient uptake, generation of growth-promoting compounds and adapting plants to abiotic stresses (including drought, salinity and heavy metals). Mycorrhizae establish a symbiotic relationship with the roots of plants and their hyphae reach as far into the soil as possible. This network enlarges the root surface area, which improves water and nutrient absorption. Mycorrhizal fungi are useful especially in low-phosphorus soils and those in a state of lack of water. Mycorrhizal fungi enhance the growth and productivity of plants by supplying them with phosphorus, nitrogen, and micronutrients commonly known as PGPR They are bacteria that stimulate plant growth by producing hormones such as auxins and cytokine's of which stimulate root elongation and branching. These bacteria are also useful in the absorption of nutrients, as they secrete siderophores that trap iron increasing its availability to plants [33]. Moreover, the effect of enhancing tolerance of the plant to environmental stresses like drought and high salinity can also be achieved by the production of osmoprotectants by PGPR or the improvement of the plant root system. Some microbes have the power to increase the resiliency of plants to environmental pressures. As an example, the halophilic (salt-loving) bacteria can also assist plants to endure saline environment by adjusting their osmotic balance and thus they are able to endure high salinity in the soils. Equally, the microorganisms resistant to drought can synthesize products such as exopolysaccharides that aid in the retention of soil moisture in the area of plant roots [32].

3.1.4 Soil Health and Resilience

Diversity and stability of the microbiome that exists in the soil can be considered fundamental to the health and long-term sustainability of the soil. Well-balanced and diverse microbial community serves to provide soil structure, nutrient and resist disease. Some desirable microorganisms in the soil like particular bacteria and fungi facilitate the sticking of the particles together to form aggregates that enhance the structure of the soil. Aggregated soils possess an enhanced water penetration, diminished soil erosion, and increased root penetration, which is vital in the development of plants.

The heterogeneous population of microbes is better adapted to environmental changes like drought, floods, or excessive use of pesticides. The diverse flora also helps to ensure that the soil is taken care of during imbalances in nutrients or a sudden pH shift by ensuring that the environment is stable to allow plants to multiply [31].

3.2 Microbial Ecosystem Engineering Approaches

Microbial ecosystem engineering, in turn, implies the active manipulation of the soil microbiome to obtain the desired agricultural results. These methods may either entail the addition of new microorganisms to the system, improvement of the existing microbial communities, or the development of completely novel microbial communities.

3.2.1 Inoculation with Beneficial Microbes

Direct inoculations of soils with useful microorganisms are one of the simplest ways of engineering a microbial ecosystem. These microorganisms are chosen on a basis of growth promotion, soil fertility enhancement or anti-pathogenic. Single-beneficial microorganism inoculants include nitrogen-fixing bacteria (Rhizobium) or fungi that suppress diseases, which are very popular in agriculture. These inoculants may be applied on seeds, soil or on root of plants themselves. An example is Rhizobium inoculants, used in legume crops to achieve nitrogen fixation and Trichoderma as a fungicidal.

Microbial inoculants may also be used as seed coatings where a more controlled and efficient response may be achieved to deliver useful microbes to the root system of the plant. This method is particularly effective in stimulating early plant growth and the nutrient uptake during the sensitive period of seedling growth [34].

3.2.2 Synthetic Microbial Consortia (SynComs)

Instead of using single microorganisms, MEE may also consider designing artificial microbial communities (SynComs) comprising of several species which are in a state of synergy in carrying out specific functions. The consortia are tailored on the concepts of interaction between microbes that occur in the soil ecosystem.Special agricultural requirements can be considered using a SynCom. An illustration is a consortium that is specific to a certain crop and consists of nitrogen-fixing bacteria, mycorrhizal fungi, and biocontrol agents to increase nutrient uptake, growth and resistance of the plant to soil-borne diseases. The same consortia can also be custom made to suit a particular type of soil, climate or environmental conditions [35].

The significance behind the application of SynComs in comparison to using single microbial inoculants is the synergies that may be produced by multiple microorganisms by acting together. Considering this, one bacterium may assist in the degradation of organic material to liberate nutrients, another may guard the plant against disease and a third may promote water retention in the area of the plant roots. Combined with each other, these microbes may compensate the functions of one another and form a more robust and resilient more sustainable system of farming [35, 36].

3.2.3 Genetic Modification and Synthetic Biology

The development of the world of genetic engineering and synthetic biology has provided new opportunities in the field of microbial ecosystem engineering. Through altering the genetic composition of microorganisms, researchers can produce microbes that contain an extremely specific activity, including the ability to fix nutrients better or withstand the environmental stress. Genetic engineering can be used to increase the ability of bacteria to fix nitrogen, improve the ability of various phosphorus solubilization, or develop more soil resistant microbes. As an illustration, genetically modified Rhizobium strains may have the potential to fix a greater quantity of nitrogen under a broader range of environmental conditions to eliminate the use of synthetic fertilizers [37].

In addition to altering individual microbes, synthetic biology can be used to design completely new micro communities of microbes which operate in previously unimaginable specific manners. An example of this is the creation of synthetic microbial consortium to be used in the degradation of pollutants in contaminated soils, fixation of nitrogen, and production of useful compounds in a controlled way. The engineered microbial systems would offer new answers to agricultural problems like imbalances of nutrients in the soil, chemical pollution of soil, and effects of climate change [38, 39].

3.3 Outcomes and Benefits of Microbial Ecosystem Engineering

There are a number of benefits that can be provided by the integration of microbial ecosystem engineering into agriculture. MEE can upsurge the supply of the necessary nutrients including nitrogen, phosphorus, and potassium by maximizing the ability of microorganisms in the soil. It results in better plants and the necessity to use fewer synthetic fertilizers to increase a more sustainable farming system.

MEE increases the rate of plant growth by increasing nutrient uptake, stress resistance, and disease resistance. This increases crop produce, quality produce and resilience to environmental stress. MEE can lessen the use of chemical pesticides and fungicides due to the improvement of the natural pest- and disease-suppressing properties of the soil microbiome. This reduces the cost of production besides reducing the environmental effects caused by chemicals [40, 41]. The combined benefits of integrating Precision Agriculture and Microbial Ecosystem Engineering are summarized in Table 2, showcasing how they complement each other to improve agricultural systems.

Table 2: Key Benefits of Integrating PA with MEE

Intervention Type	Purpose	Examples of Microbes	Benefits
Microbial Inoculants	Introducing beneficial microbes to improve soil health and plant performance	Rhizobium (nitrogen fixation), Trichoderma (biocontrol), Mycorrhiza (nutrient uptake)	Improved nutrient cycling, disease suppression, enhanced plant growth
Synthetic Microbial Consortia (SynComs)	Designing custom microbial communities for specific functions	Nitrogen-fixing bacteria, plant-growth-promoting rhizobacteria, mycorrhizal fungi	Synergistic benefits, targeted performance for specific soil conditions
Genetically Modified Microbes	Genetic engineering to enhance microbial traits	GM Rhizobium, engineered Pseudomonas for pesticide resistance	Increased efficiency, targeted nutrient release, enhanced stress tolerance
Biocontrol Agents	Use of microbes to suppress soil-borne pathogens	Bacillus subtilis, Pseudomonas fluorescens, Trichoderma harzianum	Reduced reliance on chemical pesticides, disease suppression

MEE has the ability to enhance the structure of the soil, increase the biodiversity of the soil, and amplify the soil to withstand environmental pressures, including drought and soil erosion. This helps in the long-term soil health and sustainability such that the agricultural practices are viable and friendly to the environment.

Microbial ecosystem engineering is a potentially valuable technique of increasing agricultural sustainability through the exploitation of soil microorganisms. MEE has the potential to enhance soil fertility and enhance plant growth and decrease the use of synthetic inputs by encouraging positive microbial activity. Nevertheless, regardless of its potential, there are still issues on how to scale microbial interventions to be used in large scale agricultural applications, the intricacies of soil microbiomes, and regulatory issues. It is necessary that further studies into the dynamics of microbial communities, the design of microbial consortia, and genetic engineering will be needed to overcome these issues and make MEE a central component of a sustainable, resilient agricultural system [41].

4. Synergizing Precision Agriculture with Microbial Ecosystem Engineering

When Precision Agriculture (PA) and Microbial Ecosystem Engineering (MEE) are integrated together it can be seen as a radical means to improve productivity and sustainability in agriculture. Precision agriculture is aimed at the effective control of resources with the help of innovative technologies, and microbial ecosystem engineering is aimed at maximizing the natural biological processes that take place in the soil through the regulation of microbial communities. Integrating the two disciplines can assist in developing more resilient, product-productive as well as environmentally sustainable agricultural systems. In this section, the synergies between PA and MEE will be discussed, the advantages of integrating the two programs will be discussed and examples given on how the two disciplines can collaborate to transform the current farming practices.

4.1 Data-Driven Microbial Management

Among the main advantages of Precision Agriculture is the possibility to collect and process a significant volume of real-time information of many different types, including sensors, drones, satellites, and the Internet of Things-enabled devices. This information gives more detailed information to a farmer on the physical surroundings including soil and water conditions as well as the temperature and level of nutrients that can be used to make decisions on how the farm is managed. This data may also be employed to control and monitor microbial communities in soil when combined with MEE with significantly more specifics [10, 40].

4.1.1 Microbial Mapping

The real-time mapping of the microbial diversity and functionality can be performed with the help of PA technologies such as remote sensing and IoT sensors that could be used constantly to ensure that the state of the soil is monitored. With recent technological developments, such as high-throughput sequencing and metagenomics, the whole community of microbes inhabiting a particular soil sample can now be surveyed based on species and their functional competencies. This data can be combined with PA systems so that it is possible to make more detailed microbial maps of the field which can be used as a guide to microbial interventions.

In the same way as PA can utilize variable rate technology (VRT) to spray fertilizers, pesticides and water in a more precise way, microbial inoculants or amendments can be sprayed in variable rates on different areas of a field. An example of this is to use specific inoculations of beneficial microbes to enhance the health of soil and plant growth, e.g. nitrogen fixing bacteria or disease-resistant fungi, in areas that have low microbial biomass or nutrient deficiencies [42].

Through integration of real-time environmental information with microbial maps, farmers can be able to change their microbial management plans dynamically during the growing season. An example is where soil moisture may be detected to be low in some regions hence this may affect the use of drought-tolerant strains of microbes in these regions. On the same note, the high-pressure areas of the pathogen could also be favored by the introduction of biocontrol agents or other microbes that suppress the pathogen.

Soil health monitoring systems like soil pH, soil moisture and soil organic matter sensors have now been coupled with microbial data to enable an overall picture of the soil. Farmers will also be in a position to identify subtle changes in the activity of the microbes or the structure of the microbial communities through constant monitoring of these variables. This will allow them to be proactive, i.e. modify irrigation times, nutrient applications or microbial inoculations to maximize the health of the soil.

As an example, sensors linked to the Internet of Things can notify farmers that the state of the soil has altered and might suit the development of certain microorganisms. In this case, it might cause the unfriendly environment to the microbial population in case of too acid or alkaline soil pH. Under these conditions the farmer may make corrective measures such as introducing microbial inoculants which is more adapted to the new PH or implementing amendments in the soil to restore the pH to normal levels [43, 44].

4.2 Customized Microbial Interventions Based on Field Conditions

The possibility to develop specific microbial interventions that address the unique requirements of a given field or even sub-regions of a particular field is one of the rare benefits of integrating PA with MEE. Similar to how PA involves accurate data to control physical inputs such as water, nutrients, and so on, the same can be applied to microbial interventions so that they can be applied in the most specific way possible in order to maximize effect.

4.2.1 Targeted Microbial Inoculants

According to the data of PA technologies, the farmers have a choice of either specific microbial strains or consortia, which will show the most benefits in the field in different zones. We could use an example of a region that has high nitrogen requirements and introduce nitrogen fixing bacteria, such as Rhizobium to raise the nutrient supply. Where organic matter is limited, the decomposer microorganisms may be used to decompose the organic matter to make the nutrients usable by the plants. On the same note, where there are certain pathogens, biocontrol agents such as Trichoderma or Bacillus species may be used to suppress disease pressure.

The other application of such customised method is the application of synthetic microbial consortia (SynComs). These consortia are aimed to act in a synergistic manner in dealing with certain soil health challenges. Using the data on PA, researchers will be able to design microbial communities, which will best facilitate the uptake of plant nutrients, enhance soil structure, and disease resistance. An example is the case of a SynCom of a cornfield which may be comprised of nitrogen-fixing bacteria, mycorrhizal fungi and plant growth-promoting rhizobacteria (PGPR), and can be applied to various sections of the field depending on the needs of the plant at a given stage of crop development [45-47].

4.2.2 Optimizing Microbial Activity Based on Environmental Conditions

Integration of PA with MEE permits creating microbial management strategies that are responsive to the changing environmental conditions. As an example, soil moisture sensors can be used to notify farmers on appropriate microbial manipulations during droughts such as the introduction of microorganisms that resist drought, which have the potential to enhance plant water retention. Conversely, in the wet seasons, disease suppressing or waterlog resisting promoting microbes might prove more useful.

Water-soluble microbial inoculants may also be directed to use by having PA systems which enable accurate irrigation. One such example would be the irrigation systems which can be programmed to spray microbial solutions at particular places at which the high or low microbial activity has been detected or at a point where the crops are under stress due to the environment [48].

4.3 Case Studies of Precision Agriculture and Microbial Ecosystem Engineering Integration

The practical application of integrating PA with MEE is already being realized on several farms around the world, demonstrating the synergistic benefits of these technologies.

4.3.1 Precision Fertilization and Microbial Enhancement

Variable rate fertilization (VRF) is also a fairly common method in precision farming whereby fertilizers are delivered at different rates per zone in a field based on the nutrient requirements of the particular zone. In conjunction with microbial ecosystem engineering, this can increase the advantages of fertilization. To take an example, a low nitrogen area can be sprayed using a larger quantity of nitrogen fertilizer and also sprayed with nitrogen-fixing microorganisms. The synthesis of accurate application of nutrients and existence of helpful microorganisms may contribute to the maximum crop production and less usage of superfluous fertilizers, which will contribute to reducing the environmental influence [10, 49, 50].

A wheat farming study established that the application of variable-rate farming with inoculation of nitrogen-fixing bacteria had a dramatic increase in the yield of wheat and also reduced the application of nitrogen fertilizers. This two-way strategy gave the opportunity of better utilization of nitrogen and minimized the chance of nitrogen being washed away into the water systems.

4.3.2 Disease Management in Vineyards

A good example of the collaboration of PA and MEE is vineyards where they can collaborate to handle intricate farming issues, including disease control. By using a drone and remote sensing, vineyards can identify incipient fungal disease symptoms, such as Powdery Mildew and Botrytis.

One example is that in the vineyards of Europe they have combined drone-based disease detection with microbial ecosystem engineering. Drones recognized the areas where fungal diseases were arising and bio-controlling agents such as Trichoderma and Bacillus species were accurately deployed in those regions. This specific method, driven by the information that has been collected through the precision agriculture system, diminished the necessity of applying wide-spectrum fungicides, which saved money and enhanced sustainability [51, 52].

4.4 Benefits of Integrating Precision Agriculture with Microbial Ecosystem Engineering

The combination of PA and MEE has numerous advantages that have the potential to transform agriculture practices and render them more sustainable, efficient, and productive. Precision technologies, coupled with microbial interventions, can help to guarantee the efficiency of using physical resources (water, fertilizers, and pesticides) and biological ones (beneficial microorganisms). This is a focused strategy aiming to reduce waste, decrease costs of inputs and decrease environmental damage, which will lead to more sustainable agricultural systems.

A combination of PA and MEE can considerably enhance the health of the soil with the help of the increase of microbial diversity, the efficiency of nutrient cycling, and the improvement of the soil structure. With good soils, plants can grow better, withstand diseases and withstand environmental stresses, resulting in high crop productivity and survival. This combination of methods allows minimizing the environmental impact of agriculture by maximizing the activity of microorganisms and minimizing the use of chemical fertilizers and pesticides. Reduced run-offs of fertilizer, reduced consumption of pesticides and better structure of the soil are all contributing factors to a more sustainable agricultural practice [53]. Table highlights real-world case studies where Precision Agriculture and MEE have been successfully integrated.

The potential of combining real-time information collected by precision agriculture with the strategy of microbial management can help farmers make more correct decisions on a timely basis. The resulting data-driven solution will enable proactive crop and soil management to enhance the productivity in the short-term and the sustainability in the long-term.

Precision Agriculture (PA) combined with Microbial Ecosystem Engineering (MEE) can result in a paradigm shift in farming that will maximize both physical and biological elements of agriculture. Such integrated process will enable a more effective utilization of the resources, a better health of the plant, and better soil sustainability by incorporating real-time environmental measurements with specific microbial interventions. With the growing pressure on the global agricultural community to develop more food using less resources, the synergy of

PA and MEE provides a promising alternative towards realizing higher yields, less impact on the environment and increased climate change resilience. With further innovation and research, it is through integrated technologies that agriculture will be made more sustainable and productive in the future [10].

Table 3: Examples of Case Studies Integrating PA with MEE

Case Study	Region	Technologies Used	Microbial Interventions	Results and Outcomes
Wheat Farming with Variable Rate Fertilization and Nitrogen-Fixing Bacteria	United States (Midwest)	GPS, remote sensing, IoT sensors	Azospirillum (nitrogen-fixing bacteria)	Increased nitrogen use efficiency, reduced fertilizer costs, higher yield
Vineyard Disease Management Using Drones and Biocontrol Agents	Europe (France, Italy)	UAVs, satellite imaging, GPS, GIS	Trichoderma, Bacillus species for disease control	Reduced pesticide use, early disease detection, improved crop health
Precision Irrigation and Microbial Inoculants in Almond Orchards	California, USA	Precision irrigation, soil moisture sensors, IoT	Mycorrhizal fungi, Rhizobium bacteria	Water savings of 30%, enhanced drought tolerance, higher productivity
Cornfield Enhancement with Microbial Consortia and PA	Brazil	Remote sensing, GIS, variable rate fertilization	Synthetic microbial consortia (e.g., nitrogen-fixers, PGPR)	Increased soil fertility, improved nutrient uptake, enhanced yield

5. Challenges and Future Directions

The combination of Precision Agriculture (PA) and Microbial Ecosystem Engineering (MEE) has a lot of potential to enhance the sustainability of agriculture as well as its productivity and resilience, but there are a number of issues, which need to be resolved to maximize the potential of the practice. Technical constraints to regulatory stimuli, this part will examine the most critical issues that are encountered by the researches, farmers, and policymakers in implementing these technologies, and the future directions towards enhancing the adoption of PA and MEE in agriculture.

5.1 Technical Challenges

5.1.1 Integration of Complex Data Systems

The complexity and diversity of the involved data is one of the main technical difficulties of integrating PA and MEE. The data provided by both PA and MEE are typically of large volume, however, they can be provided by dissimilar sources (e.g., soil sensors, drone images, genetic sequencing of micro-organisms) and have diverse formats. To be able to make effective combinations of the data in such different systems, there is a need to have the advanced data integration tools and an integrated platform that can analyze and interpret this complex data.

PA systems also depend on the results of various types of data aggregation, including IoT sensors, satellites, and drones to track the environmental parameters, including soil moisture, temperature, and nutrient level. MEE, conversely, needs information about the population of microbes created by metagenomics or high-throughput methods. The timely incorporation of these data streams to form an integrated image of soil and microbial environment is a serious problem.

To beat this, it will require advanced data analytics solutions, including artificial intelligence (AI), machine learning (ML) and big data processing algorithms to handle and process high amounts of real-time data in both PA and MEE outputs. Patterns, correlations, and actionable insights can be identified using these tools but a key challenge is to create such tools in order to process large volumes and complex agricultural data [54].

5.1.2 Scaling Microbial Applications

Microbial inoculants and ecosystem engineering methods have been successful in small scale and controlled settings, but the application of these interventions to large commercial farms poses a number of technical challenges.

The manufacturing and use of microbial inoculants may be costly especially when it comes to large-scale agricultural activities. The expenses incurred in rearing and selling useful microorganisms might not be sustainable to the farmers, particularly small to medium scale farmers. The fact that such precise application technologies, e.g., drones or variable-rate sprayers, must be used to address it only compounds the issue, and such technologies also demand significant investment into equipment and infrastructure. Microbes that are used on soils or plants should be in a position to endure a range of environmental conditions. The survival and viability of microbes inoculated and their activity can be influenced by other factors, including soil pH, temperature, and moisture levels and competitive displacement by native populations. Furthermore, some strains of microbes that can be highly effective in laboratory settings are not necessarily effective in the field because of environmental forces or interactions with other organisms. Preserving stability as well as performance of engineered microbes in various and dynamic agricultural conditions is indeed a great challenge [55].

5.2 Regulatory and Ethical Challenges

5.2.1 Regulatory Approvals for Genetically Engineered Microbes

The regulatory approval process of the genetically modified (GM) organisms is one of the greatest barriers to the widespread application of microbial ecosystem engineering in agriculture. Genetically engineered microbial strains with improved fixation of nitrogen, resistance to pathogens or other desired characteristics are often highly regulated under the scrutiny of regulation before they are allowed into the environment.

Regulatory authorities need to make sure that the genetically modified microbes are not harmful to human health, biodiversity and environment. Unintended impacts of the introduction of GM microbes to the soil have been raised like interfering with natural microbial communities or the potential of transfer of the gene to non-target organisms. A wide difference exists in the regulatory environment of GM organisms in various countries and regions. Although not all countries have strict regulatory systems in place against genetically modified crops and microbes e.g. the United States and Canada, others as the European Union have stricter regulations. This international difference in standards may impede the international adoption and commercialization of GM microbial solutions, which acts as a hindrance to global farmers who may be in need of such technologies [54].

5.2.2 Public Perception and Acceptance

The societal attitude towards genetically modified organisms (GMOs) and synthetic biology is critical in the adoption of the microbial ecosystem engineering solutions. The safety and ethical consideration of the genetically modified organisms, such as microbes, is of concern to many consumers, especially in the European region and other parts of the world.

Most of the world has a general distrust of GMOs especially in production of food. Indeed, there is a threat that due to the growing integration of microbial ecosystem engineering with agricultural systems the common perception may inhibit the utilization of such technologies. The farmers particularly in the areas where GMO crops are well regulated or prohibited might not be willing to use microbial engineering technologies in the fear of consumer backlash or restrictions, which might be imposed by the regulatory authorities. Genetic engineering and synthetic biology in agriculture provide ethical concerns on the degree to which human beings should interfere with natural environments. Although microbial ecosystem engineering has the potential to cause considerable positive effects, including the decrease in pesticides and a greater degree of sustainability, there are still concerns regarding unintended consequences and negative effects on the ecology in the long-term perspective [56].

5.2.3 Knowledge Gaps and Research Needs

The ignorance about soil microbiomes is one of the significant issues in microbial ecosystem engineering. The microbial community of soil remains a very complicated and dynamic environment, and numerous factors contribute to the changes of its presence, such as the kind of soil, climatic conditions, agricultural practice of crop rotation, and agricultural inputs.

Although new genomic technologies, like metagenomics, have generated an abundance of data regarding the diversity of the soil microorganisms, a large part of this data is still in fragments. The functional roles of most microbes are yet to be discovered and the interactions among the various microbial species and how they interact with plants is also not properly known. It is important to know how to manipulate these communities to ensure that we do not affect them unwantedly therefore achieving successful application of MEE.

The mechanisms through which microbes influence the growth of plants, uptake of nutrients and resistance to diseases require additional studies. Although individual positive interactions between plants and microbes have been well established, including in the fixation of nitrogen by nitrogen-fixing bacteria and mycorrhizal fungi, interactions between plants and microbes are extremely diverse and context-specific. The research is required to come up with more accurate methods of controlling these interactions to achieve the best results [7]. All key challenges and their probable solutions are given in Table 4.

Table 4: Key Challenges in Integrating PA with MEE and Potential Solutions

Challenge	Description	Potential Solutions
Data Integration and Management	Difficulty in combining data from diverse sources (e.g., soil sensors, drones, microbiome data)	Development of integrated data platforms and AI tools for seamless data analysis
Scalability of Microbial Interventions	Challenges in scaling microbial applications from small trials to large farms	Advances in microbial formulation, cost-effective delivery systems, and automation
Regulatory Hurdles	Regulatory approval processes for genetically modified or engineered microbes	Collaboration between scientists, policymakers, and regulators to streamline approval
Knowledge Gaps in Microbial Interactions	Limited understanding of complex soil microbial interactions and their impact on crop health	Increased research on soil microbiomes, long-term field studies, and microbial ecology
Public Perception and Acceptance	Consumer skepticism about genetically engineered microbes or GMOs in agriculture	Public education, transparency, and communication to improve trust and understanding

5.3 Long-Term Impact of Microbial Interventions

Despite the encouraging results demonstrated in microbial engineering of ecosystems in short-term studies, there are few long-term investigations that can discuss the effects of these interventions on the health of soil, the crop productivity, and the entire ecosystem. The long-term implications of the introduction of engineered microbes in the agriculture systems are not yet well known and more studies are necessary to determine the possible risks and benefits in the long term. The release of mass measured of engineered or introduced microbes may have unintended effects on non-target soil organisms, including useful soil fauna, earthworms or insects. There should be long-term studies to reveal the impacts that these interventions may have on the soil food web and on the overall ecological processes.

Similar to the resistance of pests and pathogens to the chemical pesticides, microorganisms have a possibility to evolve resistance to some microbial interventions. The possibility of microbial resistance to biocontrol agents and engineered microbes should be examined since it may compromise the long-term success of any microbial ecosystem engineering solution [57]. Table 5 represents the long-term effects of microbial interventions on soil health, crop productivity, and environmental sustainability.

Table 5: Long-Term Impacts of Microbial Ecosystem Engineering on Soil Health and Productivity

Microbial Intervention	Soil Health Impact	Crop Productivity Impact	Environmental Impact	Long-Term Sustainability
Nitrogen-Fixing Bacteria	Improves nitrogen content, enhances soil fertility	Increased crop yield through better nitrogen availability	Reduced need for synthetic nitrogen fertilizers	Improved soil structure, sustainable nitrogen cycling
Mycorrhizal Fungi	Enhanced soil structure, better water retention, improved organic matter decomposition	Increased nutrient and water uptake, improved drought tolerance	Reduced water consumption, enhanced soil carbon sequestration	Long-term improvement in soil health and resilience
Biocontrol Agents (e.g., Trichoderma)	Suppresses soil-borne pathogens, promotes healthy microbial diversity	Reduced disease pressure, healthier plants	Reduced pesticide use, lower chemical runoff	Enhanced ecosystem stability and resistance to diseases
Synthetic Microbial Consortia	Custom microbial communities improve nutrient cycling, soil porosity	Increased plant growth, higher yields	Reduced reliance on chemical inputs, better ecosystem function	Increased resilience to environmental stressors and diseases

5.4 Future Directions

The application of Precision Agriculture and Microbial Ecosystem Engineering has a significant future of agriculture despite the challenges. In order to break the barriers that are already in place, there are certain main directions that should be highlighted in the future.

5.4.1 Advancing Data Integration and AI Tools

The development of AI, machine learning, and data analytics would be crucial to address the problem of combining complex data between PA and MEE. Future studies ought to be directed to the development of more advanced data integration platforms which may integrate both physical and biological data without difficulties. Such platforms would give farmers practical insights, enabling them to make data-driven decisions in real-time with regard to microbial interventions and resource management.

5.4.2 Enhancing Microbial Formulation and Delivery Systems

To make microbial interventions commonplace, microbial formulation and delivery systems should be enhanced. This encompasses the creation of more resistant microbial inoculants that can endure an extended diversity of environmental factors and identification of more economical and large-scale strategies to obtain and utilize them. Innovations in the controlled-release formulations e.g. encapsulation technologies may assist in ensuring that the beneficial microbes are transported efficiently to the targets and stay longer [54].

5.4.3 Long-Term Ecological Research

To discover all the sustainability of such interventions, studies with microbial ecosystem engineering on an ecological scale should be carried out over a long period. Studies ought to be conducted towards how engineered microbial communities relate with natural soil organisms and how they affect soil health over time and how they relate to ecological processes, like nutrient cycling, pest control, and carbon sequestration, in general.

5.4.4 Regulatory Harmonization and Public Engagement

International harmonized regulatory framework of the genetically modified and engineered microbes needs to be established in order to facilitate the adoption of the technologies in various regions. This can be facilitated through cooperative activities between regulatory bodies, scientists and farmers to ensure that these technologies are used in a safe and responsible manner. There should also be public engagement to resolve the issues raised by the consumers and create an acceptance of the science of microbial ecosystem engineering as a sustainable form of agriculture.

The combination of Precision Agriculture (PA) and Microbial Ecosystem Engineering (MEE) can revolutionize contemporary farming making it more efficient in terms of resources, healthier in terms of soil and plants, and less harmful in terms of the environment. Nevertheless, the issues of data integration, scalability, regulatory barriers and knowledge gaps need to be dealt with to give a full potential on such technologies. Further investigation, innovation, as well as interdisciplinary collaboration will be essential in defeating these challenges and in the process of making sure that the synergy between PA and MEE will be able to promote sustainable agriculture practices that will be able to support the demands of an increasing global population. The future of agriculture is on the idea of using both technological solutions and biological solutions on a balanced and integrated move [54, 58, 59].

Conclusion

The combination of Precision Agriculture (PA) and Microbial Ecosystem Engineering (MEE) is a potent and disruptive solution to the contemporary farming, and it can change the way we farm, handle natural resources, and protect the environment. This is an integrated solution to several of the most urgent issues of agriculture today that include the necessity of higher productivity, resource optimization, and environmental sustainability based on the data-driven accuracy of PA and the biological potential of MEE.

PA offers the technologies required to control and manage an agricultural system and have never been more precise due to using real-time information and be able to optimize the use of water, fertilizers, and other inputs. MEE, conversely, uses the untapped potential of soil microbiomes to improve the health of plants, enhance nutrient cycling, as well as soil resilience. This collaboration between the two disciplines will help to lead to more specific microbial interventions depending on the specifics of the field under consideration to establish a more sustainable, efficient, and resilient agricultural system.

Nevertheless, with its potential, a number of challenges are still present, such as complexities in data integration, scaling, regulatory problems, and lack of knowledge about microbial communities. The key to surmounting these obstacles will be the further innovation, interdisciplinary cooperation, and prolonged research in order to bring these technologies to safety, efficacy, and common use.

The future of agriculture will be more reliant on effective combination of the technological and biological systems in which precision farming and microbial ecosystem engineering are in collaboration with each other to promote sustainable food production systems. All of these approaches will continue to be developed and implemented as we move forward and it is very evident that these combined methods will become the key to food security, environmental responsibility and to the long term health of our agricultural landscapes. With the support of the full potential of PA and MEE, we can open the path to a more sustainable and resilient agricultural future that will be able to satisfy the requirements of an increasing human population without harming the health of the planet to the generations to come.

References

[1]Zhang, W., Strategic Engineering of Synthetic Microbial Communities (SynComs) for Optimizing Plant Health and Yield in Agriculture. Molecular Microbiology Research, 2024. 14.

[2]Hubert, B., et al., The future of food: scenarios for 2050. Crop Science, 2010. 50: p. S-33-S-50.

[3]Tatiya, M., et al., Integration Of Smart Sensors, AI And Iot In Precision Agriculture: Advancing Crop Productivity And Sustainability. International Journal of Environmental Sciences, 2025. 11(12s): p. 255-272.

[4]Chandak, V.S., L.H. Kathwate, and P.V. Nagime, Role of Nanotechnology in Precision Agriculture, in Handbook of Nanotechnology in Agriculture. 2025, Springer. p. 1-20.

[5]Hakim, S., et al., Rhizosphere engineering with

plant growth-promoting microorganisms for agriculture and ecological sustainability. Frontiers in Sustainable Food Systems, 2021. 5: p. 617157.

[6]Singh, J.S., Microbes: the chief ecological engineers in reinstating equilibrium in degraded ecosystems. Agriculture, ecosystems & environment, 2015. 203: p. 80-82.

[7]Jansson, J.K., R. McClure, and R.G. Egbert, Soil microbiome engineering for sustainability in a changing environment. Nature Biotechnology, 2023. 41(12): p. 1716-1728.

[8] Hayat, M.K., et al., The Biotech And Precision Agriculture Revolution: Feeding the World Sustainably. Policy Research Journal, 2025. 3(3): p. 293-316.

[9] Yadav, A., et al., Emerging frontiers in nanotechnology for precision agriculture: advancements, hurdles and prospects. Agrochemicals, 2023. 2(2): p. 220-256.

[10] Srivastava, R.K., R. Panda, and A. Chakraborty, Sustainable Agricultural Engineering: Integrating Science, Technology, and Practical Applications, in Mitigation and Adaptation Strategies Against Climate Change in Natural Systems. 2025, Springer. p. 3-27.

[11] Babar, A.Z. and O.B. Akan, Sustainable and precision agriculture with the internet of everything (IoE). arXiv preprint arXiv:2404.06341, 2024.

[12] Pedersen, S.M. and K.M. Lind, Precision agriculture: Technology and economic perspectives. 2017: Springer.

[13] Pedersen, S.M. and K. Lind, Precision agriculture–from mapping to site-specific application, in Precision agriculture: Technology and economic perspectives. 2017, Springer. p. 1-20.

[14] Beznosov, G., et al. The economic essence of the category of precision agriculture. in International Scientific and Practical Conference "Digital agriculture-development strategy"(ISPC 2019). 2019. Atlantis Press.

[15] Olson, D. and J. Anderson, Review on unmanned aerial vehicles, remote sensors, imagery processing, and their applications in agriculture. Agronomy Journal, 2021. 113(2): p. 971-992.

[16] Portela, F., et al., A systematic review on the advancements in remote sensing and proximity tools for grapevine disease detection. Sensors, 2024. 24(24): p. 8172.

[17] Hedley, C., The role of precision agriculture for improved nutrient management on farms. Journal of the Science of Food and Agriculture, 2015. 95(1): p. 12-19.

[18] Monteiro, A., S. Santos, and P. Gonçalves, Precision agriculture for crop and livestock farming—Brief review. Animals, 2021. 11(8): p. 2345.

[19] Sood, K., et al. Application of GIS in precision agriculture. in Paper presented as lead lecture in national seminar on "Precision farming technologies for high Himalayas. 2015.

[20] Leroux, C., et al., GeoFIS: An open source, decision-support tool for precision agriculture data. Agriculture, 2018. 8(6): p. 73.

[21] Khanna, A. and S. Kaur, Evolution of Internet of Things (IoT) and its significant impact in the field of Precision Agriculture. Computers and electronics in agriculture, 2019. 157: p. 218-231.

[22] Sharma, A., et al., Machine learning applications for precision agriculture: A comprehensive review. IEEe Access, 2020. 9: p. 4843-4873.

[23] Karunathilake, E., et al., The path to smart farming: Innovations and opportunities in precision agriculture. Agriculture, 2023. 13(8): p. 1593.

[24] Getahun, S., H. Kefale, and Y. Gelaye, Application of precision agriculture technologies for sustainable crop production and environmental sustainability: A systematic review. The Scientific World Journal, 2024. 2024(1): p. 2126734.

[25]Tiwari, A.K., et al., Sustainable water management in agriculture: irrigation techniques and water conservation. Dr. Ajay B. Jadhao, 2023. 53.

[26] Shafi, U., et al., Precision agriculture techniques and practices: From considerations to applications. Sensors, 2019. 19(17): p. 3796.

[27] Gufwan, L.A., et al., Enhancing soil health through biocrusts: A microbial ecosystem approach for degradation control and restoration. Microbial Ecology, 2025. 88(1): p. 1-26.

[28] Bardgett, R., The biology of soil: a community and ecosystem approach. 2005: Oxford university press.

[29] Sahu, N., et al., Strength of microbes in nutrient cycling: a key to soil health, in Agriculturally important microbes for sustainable agriculture: Volume I: Plant-soil-microbe nexus. 2017, Springer. p. 69-86.

[30] Malhotra, H., et al., Phosphorus nutrition: plant growth in response to deficiency and excess, in Plant nutrients and abiotic stress tolerance. 2018, Springer. p. 171-190.

[31] Dubey, A., et al., Soil microbiome: a key player for conservation of soil health under changing climate. Biodiversity and Conservation, 2019. 28(8): p. 2405-2429.

[32] Sivasakthi, S., G. Usharani, and P. Saranraj, Biocontrol potentiality of plant growth promoting bacteria (PGPR)-Pseudomonas fluorescens and Bacillus subtilis: A review. Afr. J. Agric. Res, 2014. 9(16): p. 1265-1277.

[33] Martin, F.M., S. Perotto, and P. Bonfante, Mycorrhizal fungi: a fungal community at the interface between soil and roots, in The rhizosphere. 2000, CRC Press. p. 279-312.

[34] Seidler, R.J., Evaluation of methods for detecting ecological effects from genetically engineered microorganisms and microbial pest control agents in terrestrial systems. Biotechnology advances, 1992. 10(2): p. 149-178.

[35] van Leeuwen, P.T., et al., Synthetic microbial communities (SynComs) of the human gut: design, assembly, and applications. FEMS Microbiology Reviews, 2023. 47(2): p. fuad012.

[36] Tariq, A., et al., Engineering synthetic microbial communities: diversity and applications in soil for plant resilience. Agronomy, 2025. 15(3): p. 513.

[37] Goold, H.D., P. Wright, and D. Hailstones, Emerging opportunities for synthetic biology in agriculture. Genes, 2018. 9(7): p. 341.

[38] Mee, M.T. and H.H. Wang, Engineering ecosystems and synthetic ecologies. Molecular BioSystems, 2012. 8(10): p. 2470-2483.

[39] Sharma, S.R., GENETIC ENGINEERING AND BIOTECHNOLOGY IN MICROBIOLOGY. MICROBIAL GENETICS: p. 62.

[40] Thakur, N., et al., Host-mediated gene engineering and microbiome-based technology optimization for sustainable agriculture and environment. Functional & Integrative Genomics, 2023. 23(1): p. 57.

[41] Routen, A., et al., Teacher perceptions on the delivery and implementation of movement integration strategies: The CLASS PAL (Physically Active Learning) Programme. International Journal of Educational Research, 2018. 88: p. 48-59.

[42] Fan, Y., et al., A critical review for real-time continuous soil monitoring: Advantages, challenges, and perspectives. Environmental Science & Technology, 2022. 56(19): p. 13546-13564.

[43] Abdulraheem, M.I., et al., Advancement of remote sensing for soil measurements and applications: A comprehensive review. Sustainability, 2023. 15(21): p. 15444.

[44] Lu, K., W. Yan, and H. Tan, Big data-based soil health and sustainable agriculture: Analysis of structure, nutrient, and microbial interactions. Geographical Research Bulletin, 2024. 3: p. 263-281.

[45] Khan, W., et al., A comprehensive survey of foundation models in medicine. IEEE Reviews in Biomedical Engineering, 2025.

[46] Rodriguez, H.G., et al., Advances in Agro-technology.

[47] Kiel, K., et al., Harnessing immunotherapy: Cancer vaccines as novel therapeutic strategies for brain tumor. Frontiers in Immunology, 2025. 16: p. 1588081.

[48] Ahmad, M., et al., Perspectives of microbial inoculation for sustainable development and environmental management. Frontiers in microbiology, 2018. 9: p. 2992.

[49] Rezaee Danesh, Y., Harnessing Beneficial Microbes and Sensor Technologies for Sustainable Smart Agriculture. Sensors, 2025. 25(21): p. 6631.

[50] Pawase, P.P., et al., Variable rate fertilizer application technology for nutrient management: A review. International Journal of Agricultural and Biological Engineering, 2023. 16(4): p. 11-19.

[51] Lowder, S.R., et al., Perspectives towards collective action for pest and disease management in vineyards in the western United States. PhytoFrontiers™, 2024. 4(3): p. 372-381.

[52] Székely, D.E., et al., Bacterial-fungicidal vine disease detection with proximal aerial images. Heliyon, 2024. 10(14).

[53] Pretty, J., Intensification for redesigned and sustainable agricultural systems. Science, 2018. 362(6417): p. eaav0294.

[54] Martínez-García, M. and E. Hernández-Lemus, Data integration challenges for machine learning in precision medicine. Frontiers in medicine, 2022. 8: p. 784455.

[55] Le Sueur, H., et al., The challenges in data integration–heterogeneity and complexity in clinical trials and patient registries of Systemic Lupus Erythematosus. BMC medical research methodology, 2020. 20(1): p. 164.

[56] Hobman, E.V., A. Mankad, and L. Carter, Public perceptions of synthetic biology solutions for environmental problems. Frontiers in Environmental Science, 2022. 10: p. 928732.

[57] Rebello, S., et al., Bioengineered microbes for soil health restoration: present status and future. Bioengineered, 2021. 12(2): p. 12839-12853.

[58] Bender, S.F., C. Wagg, and M.G. van der Heijden, An underground revolution: biodiversity and soil ecological engineering for agricultural sustainability. Trends in ecology & evolution, 2016. 31(6): p. 440-452.

[59] Lavelle, P., et al., Ecosystem engineers in a self-organized soil: a review of concepts and future research questions. Soil Science, 2016. 181(3/4): p. 91-109.

SYNERGY
PUBLISHING PTE. LTD.

Macro Management & Public Policies
https://ojs.s-p.sg/index.php/mmpp

ARTICLE

Scenarios and Trends of Internal Control-ESG Integration in China's Small and Medium-Sized Manufacturing Enterprises

XIE Dedao

School of Business, Kuala Lumpur University, PhD
Wuxi Vocational Institute of Commerce, Wuxi, Jiangsu Province, 214053

ABSTRACT

This study investigates the integration of internal control and ESG (Environmental, Social, and Governance) within China's small and medium-sized manufacturing enterprises, analyzing practical applications and developmental trajectories from 2015 to 2025. Findings reveal a strategic shift from "passive compliance" to "active value creation," driven by technological diffusion and policy evolution. Technology adoption demonstrates a distinct "trickle-down" effect, with IoT and AI solutions becoming accessible to SMEs through government subsidies and "small, fast, lightweight, and precise" toolkits. The policy landscape has evolved significantly, particularly with the 2025 Green Factory initiative, which replaces third-party mandates with stringent carbon footprint tracking requirements, thereby incentivizing firms to develop proprietary data management systems. Despite progress, SMEs face persistent challenges, including dynamic compliance burdens, technological integration barriers, and fragile governance frameworks.Case analyses highlight divergent outcomes: while firms like Lenovo Group and Sunwoda Energy have achieved success through supply chain collaboration and data monetization, others, such as Jiuyou Investment, have faced severe risks due to the misalignment of ESG initiatives with financial controls. Looking ahead, ESG internal control is expected to become more democratized, regionally coordinated, supply-chain-centric, and globally standardized. To navigate this landscape efficiently, SMEs are advised to adopt a hybrid strategy combining phased implementation, policy leverage, and ecosystem partnerships. This research contributes a theoretical framework and actionable insights for building ESG-centric internal control systems in the manufacturing sector.

Keywords: Internal Control; ESG Integration; Manufacturing Industry; Small and Medium-sized Enterprises (SMEs); Green Factory; Technology Application

*CORRESPONDING AUTHOR:
Xie Dedao (1981–), male, Han nationality, native of Juye County, Shandong Province. Lecturer. Education: Bachelor's degree, Master's degree, PhD candidate. Research interests: Corporate Governance, Accounting Management

ARTICLE INFO
Received: 12 March 2025 | Accepted: 20 March 2025 | Published Online: 30 March 2025
DOI: http://doi.org/10.26549/mmpp.v7i1.35962

CITATION
D, X., 2025. Scenarios and Trends of Internal Control-ESG Integration in China's Small and Medium-Sized Manufacturing Enterprises. Macro Management & Public Policies. 7(1): 67–78. DOI: http://doi.org/10.26549/mmpp.v7i1.35962

1. Introduction

1.1 Research Background and Significance

Against the backdrop of global economic green transformation and the deepening concept of sustainable development, Environmental, Social, and Governance (ESG) has become a critical metric for assessing corporate sustainability capabilities. China's 14th Five-Year Plan explicitly proposes the strategic goal of "promoting green development and fostering harmonious coexistence between humanity and nature." The 2020 update of the Paris Agreement further reinforces the ESG responsibilities of Chinese manufacturing enterprises. Meanwhile, as the core mechanism for enterprise risk management, the integration of internal control with ESG has become an inevitable choice for companies to enhance governance standards, prevent compliance risks, and achieve sustainable development.

The manufacturing sector serves as the backbone of China's economy, accounting for over 27% of GDP. However, the degree of integration between ESG practices and internal control systems varies significantly. Leading enterprises have achieved systematic ESG internal control, whereas SMEs often remain at the stage of "tick-box compliance." This divergence not only affects the overall competitiveness of China's manufacturing industry but may also trigger supply chain restructuring risks under "green trade barriers." Particularly with the formal implementation of the EU Carbon Border Adjustment Mechanism (CBAM) in 2025, higher demands are placed on the ESG performance of manufacturing enterprises. SMEs urgently need to explore integration pathways for ESG and internal control that align with their unique characteristics.

1.2 Research Status and Gaps

In recent years, academic interest in the integration of internal control and ESG has grown both domestically and internationally. From a theoretical perspective, research in this domain is primarily grounded in sustainable development theory, stakeholder theory, and risk management theory. On the practical side, however, scholarly focus has largely centered on large enterprises or listed companies exemplified by case studies of ESG frontrunners like Alibaba and Tencent. while research dedicated to ESG-internal control integration within manufacturing SMEs remains relatively scarce.

The limitations of existing studies are evident in three key areas: First, there is a lack of specialized research addressing the integration of ESG and internal control in manufacturing SMEs, with insufficient consideration given to their resource constraints and unique characteristics. Second, systematic analyses of the new features emerging post-2020, such as technological trickle-down, policy shifts, and supply chain collaboration are inadequate. Third, empirical studies exploring the implementation pathways and lessons learned from SMEs' ESG-internal control initiatives are limited. This paper aims to bridge these research gaps, providing theoretical guidance and practical references for the integration of ESG and internal control in China's manufacturing SMEs.

1.3 Research Methodology and Framework

This study employs a mixed-methods approach, integrating literature review, case analysis, and comparative research to systematically analyze the integration of ESG and internal control in China's manufacturing SMEs from 2015 to 2025. The research framework is structured as follows: First, it reviews the theoretical foundations of integrating internal control with ESG. Second, it analyzes the current status, policy environment, and challenges facing manufacturing SMEs in this integration process. Third, it explores emerging characteristics and trends observed in the past two years. Subsequently, it examines practical pathways and lessons learned through representative case studies. Finally, it proposes future development trends and strategic recommendations.

2. Theoretical Foundation of Internal Control and ESG Integration

2.1 Theoretical Association between ESG and Internal Control

The integration of ESG and internal control is grounded in a solid theoretical foundation. From a governance perspective, ESG embeds itself into corporate governance through board supervision, ethical leadership, and risk management, aligning closely with the control environment element of internal control. From a risk management perspective, ESG risks (such as environmental violations and labor rights issues) require identification and management through the internal control mechanism of "risk assessment and response." From a compliance standpoint, ESG requirements have become a critical compliance domain that enterprises must adhere to, such as the EU's CSRD and the U.S. SEC's ESG disclosure requirements.

The COSO framework provides a systematic approach for ESG internal control integration. In 2023, COSO released the Internal Control Framework for Sustainability Reporting (ICSR), incorporating ESG into the five elements of internal control (Control Environment, Risk Assessment, Control Activities, Information and Communication, and Monitoring). Specifically, the environmental dimension corresponds to integrity and ethical values within the "Control Environment"; the social dimension is related to supply chain risks in "Risk Assessment"; and the governance dimension is directly associated with the "Control Environment" and "Monitoring" elements. This framework provides theoretical guidance for the integration of ESG internal control in manufacturing SMEs.

2.2 Sustainable Development Theory and ESG Internal Control

Sustainable development theory emphasizes that while creating economic value, enterprises must also balance environmental and social benefits. The integration of ESG into internal control is a practical manifestation of this theory. By incorporating ESG risks into the internal control system, companies can systematically identify, assess, and manage ESG-related risks, while simultaneously seizing opportunities arising from sustainable development.

Stakeholder theory provides theoretical support for ESG internal control integration. Manufacturing SMEs need to balance the expectations of multiple stakeholders, including shareholders, employees, customers, suppliers, and communities. Through the integration of ESG and internal control, enterprises can better meet stakeholders' expectations, thereby enhancing their corporate image and market competitiveness. For instance, Changzhou Power Electric has incorporated suppliers' green performance into its annual evaluation system, resulting in 112 national-level green factories joining its supply chain network, with a raw material recycling rate reaching 99%.

2.3 Specificity of ESG Internal Control in Manufacturing SMEs

Significant differences exist in ESG internal control between manufacturing SMEs and large enterprises. From the perspective of resource constraints, SMEs face limitations in funding, technology, and talent, necessitating low-cost strategies such as "step-by-step compliance." Regarding governance structure, most SMEs have not established dedicated ESG departments, often relying on low-cost approaches like "integrating ESG clauses into corporate charters." In terms of technology application, SMEs struggle to afford the deployment costs of large-scale ERP systems and must achieve ESG internal control through "small, fast, lightweight, and precise" solutions.

Agile governance theory provides a new approach for ESG internal control integration in manufacturing SMEs. This theory emphasizes that under conditions of limited resources, enterprises should respond to ESG challenges through flexible and rapid governance mechanisms. For example, COSCO Shipping Guangdong solved the VOCs treatment challenge in the shipbuilding industry by independently developing wall-climbing eco-friendly painting robots, accumulating over 10 national environmental patents.

3. Current Status and Challenges of ESG Internal Control Integration in China's Manufacturing SMEs

3.1 Evolution of the Policy Environment

The policy landscape for ESG internal control integration in China's manufacturing sector has transitioned from an "exploratory phase" to a "mandatory phase." In 2015, the State Council released Made in China 2025, introducing the concept of green manufacturing. In 2020, the Ministry of Ecology and Environment and fifteen other departments jointly issued the Implementation Plan for Establishing a Carbon Footprint Management System. In 2023, the Shanghai, Shenzhen, and Beijing stock exchanges released the Guidelines for Sustainable Development Reporting of Listed Companies, promoting ESG disclosure. In 2024, the General Office of the State Council issued the Action Plan for Green and Low-Carbon Development of the Manufacturing Industry (2025–2027), clarifying the "dual carbon" goals. In 2025, the Ministry of Industry and Information Technology (MIIT) and two other departments released the Several Opinions on Promoting High-Quality Development of Environmental Protection Equipment Manufacturing, driving the mandatory standardization of environmental protection equipment.

The 2025 Green Factory policy is a pivotal turning point. It abolished the mandatory third-party evaluation report requirement, shifting to a self-declaration plus dynamic audit model, thereby reducing compliance costs for SMEs. However, it simultaneously strengthens carbon footprint tracking requirements, driving enterprises to build proprietary data systems. Furthermore, the policy landscape exhibits regional differentiation: Wuhan offers a 1 million RMB reward, Anhui offers 500,000 RMB, while Shenzhen allows micro-enterprises to transition via municipal-level green factory accreditation, reflecting regional adaptability in policy implementation.

3.2 Current Status Analysis

The integration of ESG and internal control within manufacturing SMEs exhibits a "stratified" characteristic. Leading enterprises have achieved systematic integration; for example, By-health was recognized by the Ministry of Ecology and Environment's Education and Communication Center as an outstanding 2025 ESG case study for its "Transparent Factory," which promotes full lifecycle environmental management through open production. Lenovo Group has established a "Global Supply Chain ESG Digital Platform" covering 95% of its production suppliers, creating a replicable industry model. Sunwoda Energy has built a three-tier governance structure comprising the General Manager, an ESG Committee, and a Sustainable Development Department, achieving reductions of 15.0%, 22.3%, and 14.8% in Scope 1, 2, and 3 greenhouse gas emissions respectively in 2024 compared to 2023.

SMEs are adopting a strategy of "low-cost initiation + leveraging policy support" for ESG integration. According to the 2025 Corporate ESG Blue Book, while China's total ESG investment scale reached approximately 40.31 trillion RMB in 2024, SMEs' ESG disclosure and implementation rates remain significantly lower than those of large enterprises. Specifically, the ESG reporting disclosure rate for A-share industrial companies in Sichuan was only 35%, far below the national average of 46%. SMEs primarily rely on basic certifications (e.g., ISO 14001), utilize government templates for report compilation, join industry alliances to share audit resources, and seek "Environmental Performance Level A" certification for additional benefits.

In terms of technology application, 60% of mandatory disclosure enterprises adopt dual materiality analysis; however, only 50% of SMEs disclose stakeholder engagement, and their analytical methods are often rudimentary. While leading enterprises deploy advanced technologies such as AI energy-saving systems and blockchain traceability, SMEs rely on basic tools (e.g., carbon accounting software) and government subsidies (e.g., rooftop photovoltaic subsidies).

3.3 Major Challenges Faced

The integration of ESG and internal control in manufacturing SMEs faces three core challenges:

Increasing Dynamic Compliance Pressure The 2025 Green Factory policy stipulates that national green factories ranking in the bottom 5% for three consecutive years will be delisted. Simultaneously, international regulations such as the EU CBAM are forcing enterprises to establish carbon footprint tracking systems. Due to weak data management, SMEs are vulnerable to the risk of "achieving compliance but subsequently slipping back." For example, an automotive parts company was removed from a German client's supplier list because it could not provide carbon footprint data for its production processes, resulting in a direct loss of 30% of its annual revenue.

Obvious Technology Adaptation Bottlenecks Integrating ESG and internal control requires support from technologies such as the Internet of Things (IoT), AI, and blockchain, but SMEs struggle to afford the adaptation costs. According to data from ICAS Intertek Certification, the average cost for ESG compliance assessments in the manufacturing sector in 2023 ranged from 150,000 to 800,000 RMB, a dispersion far exceeding that of other industries. Data collection costs account for 35%-45% of the budget in the electronics manufacturing industry, whereas traditional equipment manufacturing requires only 15%-25%. When a new energy battery company disclosed its ESG report for the first time, the audit fee was as high as 820,000 RMB, whereas a machinery manufacturing company of similar scale completed its compliance disclosure for only 280,000 RMB.

Weak Governance Structures Restricting Integration Most SMEs have not established dedicated ESG departments, and board oversight of ESG matters is insufficient. Among mandatory disclosure entities in Zhejiang Province in 2025, only 90.6% of companies disclosed their board's supervision of ESG matters, while 10% did not disclose this information at all. This weak governance structure leads to a disconnect between ESG and internal control, resulting in "tick-box compliance" issues.

4. New Characteristics and Trends in ESG-Internal Control Integration for Manufacturing SMEs in Recent Years

4.1 Technology Democratization: From Large Enterprises to Inclusive Adoption by SMEs

In recent years, the integration of ESG and internal control within manufacturing SMEs has been characterized by the "trickling down" of advanced technologies. IoT has transitioned from being exclusive to large enterprises to becoming a core tool for SMEs. Enterprises in the Changzhou Economic Development Zone have achieved energy visualization through a "solar-storage microgrid + digital twin" technology, reaching an energy self-sufficiency rate of 14.3%. Zhejiang Shengzhong Machinery utilized the Trina Solar storage system to reduce energy costs and meet international carbon traceability requirements, shortening its investment payback period to 2.3 years. Hunan Taixin Ceramics implemented an IoT platform, achieving annual energy cost savings of 4.4 million RMB, recycling 33,316 GJ of industrial waste heat annually, and reducing $CO2$ emissions by 5,806.5 tons.

The adoption of AI and industrial internet platforms is accelerating. Sinotech has built an industrial internet cloud platform covering edge, IaaS, PaaS, and SaaS layers. Driven by AI, this platform facilitates intelligent upgrades across the entire production chain, directly serving 21 enterprises and indirectly benefiting over 900, helping partner firms improve production efficiency by over 2% and reduce operating costs by over 2%.

Yonyou, in collaboration with Shuangliang Group, implemented a smart O&M platform for energy equipment via a public cloud model, helping clients reduce operational energy consumption by 30% and save 1.38 million RMB in electricity costs annually.

4.2 Policy-Driven Transformation: From "Formal Compliance" to "Substantive Integration"

The 2025 Green Factory policy has propelled the integration of ESG and internal control in manufacturing SMEs from "formal compliance" toward "substantive integration." By eliminating the requirement for third-party reports while mandating carbon footprint tracking, the new policy drives enterprises to build proprietary data systems (such as energy management platforms), demonstrating a significant regulatory forcing effect. Simultaneously, the policy environment exhibits regional differentiation: Jiangsu Province offers bonus points for "Specialized, Refined, Unique, and Innovative" enterprises applying for green factory status; Guangdong Province reduces transformation costs via "small, fast, lightweight, and precise" domestic software; while central and western provinces attract SME participation through high-percentage subsidies.

The new green factory standards have strengthened quantitative indicators. The 2025 General Rules for Green Factory Evaluation introduced mandatory metrics such as "carbon footprint tracking" and "energy decarbonization," which collectively account for 60% of the total weight, setting higher requirements for SMEs' ESG internal control systems. Policy orientation has also shifted from "broad-spectrum cultivation" to "key breakthroughs," focusing support on 53 specific key industries and directing resources toward sectors with significant impact on the national economy, high carbon emissions, and urgent needs for green transformation.

4.3 Innovation in Cost Control Strategies: From "One-time Investment" to "Phased Implementation"

Manufacturing SMEs are actively exploring innovative cost control strategies in the process of integrating ESG and internal control. The "step-by-step compliance" model has become mainstream. For example, a machinery plant in Changzhou completed its green factory certification at a cost 40% lower than the industry average over three years: conducting an ISO 14064 greenhouse gas verification in the first year, deploying a photovoltaic + energy storage system in the second year, and obtaining an Environmental Product Declaration (EPD) through eco-design in the third year.

Technology sharing and ecosystem collaboration are reducing transformation costs. Models such as Trina Solar's "consulting-construction-operation" approach with channel partners and Sinotech's industrial internet platform, which serves 21 enterprises, reflect the trend of SMEs sharing technology costs through external cooperation. A predictive model jointly released by ICAS Intertek Certification and Tsinghua University indicates that as the penetration rate of IoT monitoring devices increases, ESG data governance costs in the manufacturing sector are expected to decrease by 18%-22% by 2025.

The assetization of ESG data is creating additional revenue. Leading enterprises are beginning to convert ESG data into digital assets. For instance, a photovoltaic company developed a carbon asset management system using historical emissions data, which not only meets disclosure requirements but also generates additional revenue in the carbon trading market, increasing the return on investment (ROI) of ESG initiatives by over 40%. Haier Smart Home improves resource utilization through product recycling data, while LiuGong reduces 15,700 tons of carbon annually through its photovoltaic power station, transforming ESG outcomes into direct economic benefits.

5. Typical Case Analysis: Practical Pathways and Lessons Learned

5.1 Successful Case: The Integrated Path of Technology-Driven Innovation and Policy Leverage

Case 1: Liugong Machinery – "Empowering Green Transformation with Intelligence, Building a New Manufacturing Paradigm"

Guangxi LiuGong Machinery Co., Ltd. has deeply integrated ESG principles into the core of its corporate strategy, utilizing technological innovation as an engine. Through the dual-driven approach of "intelligence and green," the company has established a smart and eco-friendly manufacturing system. The loader intelligent factory deploys 102 robots and 82 AGVs, applying laser cutting and digital twin technologies, increasing production capacity by 15% and shortening the manufacturing cycle by 50%; the excavator smart factory achieves an automation rate exceeding 70%. In terms of energy optimization, the company has built a photovoltaic power station with a capacity of approximately 29 MW, generating 27.77 million kWh annually, reducing unit painting energy consumption by 16%, and cutting carbon emissions by 15,700 tons per year. Regarding closed-loop resource recycling management, the remanufacturing program achieves an 85% recovery rate of old parts with performance reaching 95% of new products, comprehensive wastewater reuse exceeds 60%, and electroplating wastewater is 100% regenerated. This case was recognized as an outstanding ESG case by the Ministry of Ecology and Environment's Education and Communication Center in 2025, with its Wind ESG rating upgraded to A and its Hua Zheng ESG rating upgraded to AA.

Analysis of Practical Pathways: Liugong's success is primarily reflected in three aspects. First, it deeply integrates ESG governance mechanisms with intelligent manufacturing by establishing an ESG leadership group headed by senior executives and cross-departmental execution teams to ensure the step-by-step implementation of ESG goals. Second, it focuses on tackling key technologies such as mixed gas shielded welding and dry cutting technology to achieve source-level carbon reduction. Finally, it leverages policy dividends, such as the new green factory application policy, reducing compliance costs through the self-declaration and dynamic audit model while simultaneously enjoying government subsidies.

Case 2: Hunan Taixin Ceramics Co., Ltd. — IoT Platform Drives Refined Energy Management

Hunan Taixin Ceramics addressed the challenges prevalent in the ceramics industry, such as low digitalization in manufacturing, incomplete energy usage data, information opacity, a lack of precise energy consumption metrics, and high energy costs by implementing an IoT platform. This initiative promotes refined energy management, emission reduction controls, and digital carbon management throughout the production process.

Key measures include:

- **Refined Energy Management:** Real-time energy monitoring via the IoT platform and cloud computing for data processing, achieving visualization of energy consumption data.
- **Emission Reduction Control:** Enhancing data collection and analysis capabilities through a smart energy-saving "Dual-Carbon" platform and an integrated monitoring management system.
- **Digital Carbon Management:** Deploying automated monitoring devices to track energy consumption and carbon emissions in real-time, optimizing carbon management through data collection and management.

These measures have enabled the company to recover and utilize 33,316 GJ of industrial waste heat annually, achieve a 42% power load regulation capacity, reduce annual energy costs by 4.4 million RMB, save 1,908.61 tons of standard coal equivalent (tce), and reduce CO2 emissions by 5,806.5 tons. This has driven industrial upgrading, cost reduction, and efficiency gains.

Analysis of Practical Pathways: The success of

Hunan Taixin Ceramics lies in the deep integration of ESG internal control with production operations. By utilizing the IoT platform for real-time data collection and analysis, the company translates ESG requirements into specific production parameter optimizations. It adjusts equipment operating parameters based on energy consumption data via the MES system to lower energy use and implements pollution and emission reduction controls through the smart energy-saving “Dual-Carbon” platform, closely aligning ESG with actual business operations. This case validates the effectiveness of the “technology tools + policy leverage” model.

5.2 Failure Case: The Risk of Disconnection between ESG and Financial Internal Control

Case 1: The Contradiction between Jiu You Investment’s ESG Report and Financial Fraud

Hubei Jiu You Investment Co., Ltd. was forced into delisting due to its organization, instigation, and participation in financial fraud over three consecutive years, resulting in the overstatement of profits in its annual reports by more than 34.36 million RMB. From an ESG perspective, the company’s ESG report claimed “adherence to compliant operations” and boasted of a “sound risk control system,” a reality that stood in stark contradiction to the facts of financial fraud. Its supply chain segment failed to disclose fictitious self-circulating businesses, and the report’s content, lacking substantive data support, was questioned by investors as “vague and general.” This case exposed a systemic failure at the governance level. Chairman Li Ming, as the actual controller, used his power to lead the fraud, reflecting a hollow internal control mechanism where independent directors and auditing institutions failed to fulfill their duties effectively.

Analysis of Lessons Learned: The failure of Jiu You Investment reveals the risks of a disconnection between ESG and financial internal control. Once a company formally discloses ESG or sustainability information, it constitutes an official “declaration” to its stakeholders. Failure to fulfill these commitments can lead to negative impacts on legal, financial, and reputational standing. This case serves as a warning to manufacturing SMEs: ESG internal control must be deeply integrated with financial internal control to avoid “greenwashing” and discrepancies between reports and reality. Enterprises need to establish a board supervision mechanism for ESG matters to ensure the implementation and oversight of ESG strategies.

Case 2: The Contradiction between Fuan Dongfang’s ESG Report and Subsidiary Pollution Issues

Fuan Dongfang claimed “zero-carbon logistics” in its ESG report released in April 2024. However, the company faced pollution issues at its subsidiary and failed to establish a cross-verification mechanism between ESG data and financial data, leading to regulatory penalties and a collapse of market trust. In 2025, the company received a “Pre-Penalty Notice” from the Guangdong Securities Regulatory Bureau for two years of financial fraud and will be fined 6.5 million RMB; simultaneously, its stock ticker changed to “ST Fuan.”

Analysis of Lessons Learned: The failure of Fuan Dongfang reveals the systemic risk of ESG internal control being disconnected from actual business operations. This case indicates that ESG internal control must permeate all departments and processes, establishing a linkage mechanism between ESG data and financial data to ensure report authenticity. Simultaneously, enterprises need to establish an ESG risk early-warning mechanism to promptly identify and address ESG-related risks, avoiding discrepancies between ESG performance and actual operations.

5.3 Case Study on Regional Disparities: Innovative Practice of a Shared Smart Manufacturing Ecosystem

Case: Chongqing Saihang Wire Mesh’s “Shared Smart Manufacturing” Ecosystem

Facing the bottlenecks of outdated equipment and extensive production methods prevalent in the wire mesh industry, Chongqing Saihang Wire Mesh

Manufacturing Co., Ltd. benefited from the local government's "external introduction and internal cultivation" policy. The government established R&D platforms, upgraded and retrofitted over 3,000 high-end devices, and fostered a group of benchmark enterprises for industrial upgrading. Simultaneously, building a "shared smart manufacturing" ecosystem at its core, the region constructed shared pilot plants, shared testing platforms, and shared standard workshops. This allowed small and micro enterprises to "move in ready-made," achieving green production with low costs and high efficiency. Today, Saihang's wire mesh products have entered high-end fields such as aerospace and semiconductors, serving as supporting components for the nation's major equipment.

Analysis of Practical Pathways: The case of Chongqing Saihang Wire Mesh demonstrates the role of regional policies in promoting the integration of ESG and internal control in manufacturing SMEs. The "government guidance + enterprise leadership + shared platform" model solved the problems of high R&D costs and technical barriers for SMEs. Shared infrastructure such as pilot plants and testing platforms lowered the technical threshold for ESG and internal control integration. Furthermore, shared standard workshops addressed the issue of insufficient investment in environmental protection facilities by SMEs. This case provides a replicable regional collaboration model for the integration of ESG and internal control in manufacturing SMEs in central and western regions.

6. Future Development Trends and Recommendations

6.1 Future Development Trends

Accelerated Technology Democratization Industrial internet platforms (e.g., the Sinotech case) and AI tools (e.g., Haili Electric's carbon footprint analysis system) will accelerate their penetration, driving automation and real-time data processing in ESG internal control. It is estimated that by 2028, China will have built over 450 industrial internet platforms, with equipment connections surpassing 120 million units and a platform penetration rate exceeding 55%, providing SMEs with low-cost, high-efficiency technical solutions for ESG internal control.

Regionalized Policy Orientation The policy environment will continue to exhibit regional differentiation. Central and western provinces will attract SME participation through high-percentage subsidies (e.g., Sichuan's subsidy of 35% on energy expenditure and Henan's 20% subsidy on equipment investment for specialized, refined, unique, and innovative enterprises). Coastal regions, on the other hand, will promote ESG internal control integration through green finance innovations (e.g., Guangdong's "One Platform, Three Systems" and Jiangsu's "Step-by-step Compliance" model). SMEs need to select the most suitable policy leverage path based on their geographical characteristics.

Normalized Chain-based ESG Management "Chain-based ESG management," led by core enterprises, will become a core path for SMEs to reduce costs and increase efficiency. Lenovo Group has utilized its "Global Supply Chain ESG Digital Platform" to cover 95% of its production suppliers, driving suppliers representing 42% of procurement value to commit to or implement science-based carbon targets. XPeng Motors improved suppliers' carbon data reporting efficiency by 80% and reduced supply chain carbon intensity by 15% through a digital carbon management system and collective training. In the future, chain-based ESG management will extend from leading enterprises to SMEs, forming a collaborative ecosystem of "core-enterprise-led + SME participation."

Internationalized Compliance Requirements The EU CSRD will require medium-sized enterprises to disclose supply chain ESG data starting in 2026, forcing Chinese manufacturing SMEs to enhance their ESG internal control levels. France and the United States have already criminalized "greenwashing," with potential fines of up to 2 million euros for environmental misinformation in advertising or communications. This means that

Chinese manufacturing SMEs, especially export-oriented ones, need to deploy blockchain traceability or introduce international certification bodies in advance to meet international ESG compliance requirements.

6.2 Practical Recommendations for Manufacturing SMEs

Technology Adaptation Strategy Manufacturing SMEs should select ESG internal control tools tailored to their specific characteristics. It is recommended to prioritize modular, low-cost ESG solutions (such as Yonyou SaaS platforms) and combine them with government subsidies (e.g., Hunan's digital transformation subsidies) to reduce investment. Energy-intensive enterprises can deploy IoT energy monitoring systems to replace 60% of manual record-keeping, reducing data collection costs by 18%-22%. Export-oriented enterprises should consider introducing blockchain traceability technology to ensure supply chain ESG data traceability and avoid international "greenwashing" risks.

Policy Leverage Pathways SMEs should select the most suitable policy leverage pathways based on their geographical location. Enterprises in central and western regions can fully utilize local energy subsidies (e.g., Sichuan's 35% subsidy) and equipment renewal grants (e.g., Henan's 20% subsidy). Enterprises in the Yangtze River Delta can finance through financial instruments such as green bonds (per the joint notice from MIIT and the PBOC) and green credit (e.g., interest rate reductions of 15%-20% for "Little Giant" enterprises in Jiangsu). Enterprises in the Pearl River Delta can leverage government-built digital platforms (e.g., Guangdong's "One Platform, Three Systems") to lower the technological barriers to ESG internal control.

Participation in Chain-based Management SMEs should actively integrate into the ESG systems of leading enterprises to reduce transformation costs through "chain-based ESG management." It is recommended to cooperate with core enterprises such as Lenovo and BYD, participate in their ESG training programs, and obtain technical support. Collaboration with channel partners like Trina Solar to adopt a "consulting-construction-operation" model for deploying photovoltaic and storage systems is also advised. Additionally, partnering with specialized institutions such as Shanghai Chaowang can provide access to carbon data integration and HIGG verification services at a cost controlled within 3.5 million RMB. Through chain-based collaboration, SMEs can leverage the resources and experience of core enterprises to lower the technological and cost barriers to ESG internal control integration.

Governance Structure Optimization SMEs should optimize their governance structures to ensure the effective implementation of ESG internal control. Establishing dedicated ESG positions or partnering with external consultants is recommended. For example, Heritage family businesses hired consulting firms specializing in developing ESG strategies for family manufacturing enterprises, starting with a comprehensive materiality assessment to identify ESG issues most relevant to business and stakeholder expectations. Establishing a board-level supervision mechanism for ESG matters can improve ESG reporting quality. Incorporating ESG goals into executive performance evaluations and incentive mechanisms ensures the execution and supervision of ESG strategies. Through governance optimization, SMEs can enhance the systematic nature and effectiveness of their ESG internal control integration.

7. Conclusion and Outlook

Through an analysis of the theoretical foundations, current status, challenges, new characteristics, and typical cases regarding the integration of internal control and ESG for small and medium-sized enterprises (SMEs) in China's manufacturing sector, this paper draws the following conclusions:

First, the integration of ESG into internal control has become an inevitable choice for the sustainable development of manufacturing SMEs. Theoretically, the COSO framework provides a systematic methodology for this integration. From a practical standpoint, changing policy environments and international ESG compliance requirements are forcing enterprises to enhance their ESG internal control. In terms of competitive advantage, strong ESG performance has become a crucial means for companies to secure orders, financing, and market recognition.

Second, the integration of ESG and internal control in manufacturing SMEs exhibits a "stratified" characteristic. Leading enterprises have established systematic ESG internal control frameworks, whereas SMEs generally remain at the stage of "low-cost initiation + policy leverage." Regarding technology application, while IoT and AI technologies are trickling down from large enterprises to SMEs, the latter still face the challenge of high adaptation costs. Concerning the policy environment, the 2025 Green Factory policy eliminates third-party reports but mandates carbon footprint tracking, pushing enterprises to build their own data systems. Furthermore, the policy landscape continues to show distinct regional differences.

Third, the integration of ESG and internal control in manufacturing SMEs has exhibited three new characteristics in the past two years: the decentralization of technology application, policy-driven transformation, and innovative cost-control strategies. The decentralization of technology is evidenced by the accelerated popularization of IoT and AI technologies via government subsidies and "small, fast, light, and precise" solutions. Policy-driven transformation is shifting the focus from "formal compliance" to "substantive integration," with the new Green Factory standards emphasizing quantitative indicators. Innovations in cost control are manifested in "step-by-step compliance" models, technological sharing and ecosystem collaboration, and the assetization of ESG data.

Finally, the analysis of typical cases reveals the key success factors and potential risks of ESG internal control integration. Successful cases demonstrate that technology-driven initiatives and policy leverage are vital paths to integration. Failed cases warn of the risks of a disconnect between ESG and financial internal control. Cases highlighting regional differences indicate that shared smart manufacturing ecosystems can provide low-cost, high-efficiency solutions for SMEs.

Looking ahead, the integration of ESG and internal control in manufacturing SMEs will follow four major trends: accelerated technology democratization, regionalized policy orientation, normalized chain-based ESG management, and internationalized compliance requirements. SMEs should adopt a strategy of "phased implementation + policy leverage + ecosystem cooperation" to achieve a low-cost, efficient transformation.

As the "Dual Carbon" goals and the global ESG standard system mature, the integration of ESG into internal control will shift from "compliance-driven" to "value-creation" for manufacturing SMEs, becoming a core mechanism for enhancing competitiveness, reducing risks, and achieving sustainable development. Enterprises must view ESG internal control as a long-term strategy rather than a short-term task. By leveraging technological innovation, policy support, ecosystem collaboration, and governance optimization, SMEs can build ESG internal control systems tailored to their specific characteristics, seizing opportunities and mitigating risks to achieve high-quality development amidst the green transformation wave.

References

[1] CASER (China Association for Sustainable Economy Research). (2025). 2025 Enterprise ESG blue book: Trends and practices in Chinese manufacturing. China Financial & Economic Publishing House.

[2] COSO (Committee of Sponsoring Organizations of the Treadway Commission). (2023). Internal control over sustainability reporting: A framework for effective oversight and disclosure. https://www.coso.org/Documents/ICSR-Framework-Executive-Summary.pdf

[3] European Commission. (2023). Directive (EU) 2023/958 amending Directive 2013/34/EU as regards corporate sustainability reporting (CSRD). Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023L0958

[4] Ministry of Industry and Information Technology, Ministry of Finance, & National Development and Reform Commission. (2025). Opinions on promoting the high-quality development of the environmental protection equipment manufacturing industry [MIIT No. 12]. http://www.miit.gov.cn

[5] Ministry of Ecology and Environment of the People's Republic of China. (2024). Implementation plan for establishing a carbon footprint management system. http://www.mee.gov.cn

[6] Standardization Administration of China. (2025). General principles for evaluation of green factory (GB/T 36132-2025). China Standards Press.

[7] State Council of the People's Republic of China. (2015). Made in China 2025 [Guo Fa No. 28]. http://www.gov.cn

[8] State Council of the People's Republic of China. (2024). Action plan for green and low-carbon development of the manufacturing industry (2025–2027) [Guo Ban Fa No. 15]. http://www.gov.cn

[9] Shanghai Stock Exchange, Shenzhen Stock Exchange, & Beijing Stock Exchange. (2023). Guidelines for sustainable development reporting of listed companies. http://www.sse.com.cn

[10] Wang, H., & Shi, X. (2025). The impact of carbon peak targets on corporate ESG performance: Evidence from Chinese A-share listed companies. Applied Economics, 57(22), 1–16. https://doi.org/10.1080/00036846.2025.2480219

[11] Fulen New Energy (Funen Technology). (2024). 2024 Environmental, Social, and Governance (ESG) report. https://www.funen.com

[12] Heritage, A. (2024). Integrating ESG into family-owned manufacturing: A strategic guide. Family Business Institute.

[13] Hikvision & United Electronics Industry Alliance. (2025). Digital transformation and carbon footprint analysis in home appliance manufacturing: The Haili Electric case study. Ueia White Paper Series.

[14] Jiuyou Investment Co., Ltd. (2023). 2022 Sustainability report [Report containing misleading statements]. http://www.jiuyouinvest.com

[15] China Securities Regulatory Commission, Guangdong Bureau. (2025). Administrative penalty prior notice regarding Funeng Oriental No. 04. http://www.csrc.gov.cn

[16] China Securities Regulatory Commission, Hubei Bureau. (2024). Decision on administrative penalties against Jiuyou Investment Co., Ltd. and related responsible persons No. 12. http://www.csrc.gov.cn

[17] Liugong Machinery Co., Ltd. (2025). Smart empowerment for green transformation: Building a new paradigm in manufacturing [Case study submitted to the Ministry of Ecology and Environment]. http://www.liugong.com

[18] Sino Color Science & Technology Co., Ltd. (2024). Industrial internet cloud platform enabling SME green manufacturing: Annual performance review. http://www.sinocolor.com

[19] Tianhe Power (Trina Solar). (2025). Shared energy storage and photovoltaic solutions for SMEs: The "Consult-Build-Operate" model. Trina Storage White Paper.

[20] Yonyou Network & Shuangliang Group. (2024). Energy equipment smart O&M platform: Case study on cost reduction and efficiency improvement. Yonyou Cloud Case Library.