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Predictive Model Approach to Enhancing Occupational Health Based on Safety Culture and Sustainable Technology in Environmental, Social, and Governance

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ABSTRACT

Introduction: Occupational safety and health (OSH) is a key pillar in creating a productive and sustainable work environment, especially in the high-risk manufacturing sector. As global demands for Environmental, Social, and Governance (ESG) principles increase, the integration of safety culture and sustainable technology is an important strategy to strengthen the protection of workers' health while supporting industrial sustainability.

Method: A quantitative approach was used by distributing questionnaires to 200 workers from various categories of manufacturing industries. The analysis used included correlation tests, multiple linear regression, and scenario simulations of technological improvements and recycling efficiency of personal protective equipment.

Result: The main variables analyzed were discipline in wearing PPE, consistency, reward-punishment, and the application of wearable technology and environmentally friendly PPE. The regression results show that the discipline of using PPE is the most significant factor in shaping occupational safety culture ($p = 0.001$). Although the technology and reward variables are not statistically significant, the simulation shows that increased investment in safety technology can accelerate the growth of safety culture and indirectly strengthen occupational health protection.The implementation of sustainability principles, such as the use of environmentally friendly PPE materials and recycling programs, is also proven to reduce the impact of industrial waste and contribute to the Environmental aspect of ESG.

Conclusion: While lowering the effect of industrial waste, the simulation reveals that higher investment in technology and recycling efficiency might hasten the change of safety culture from reactive to proactive. This study theoretically expands the safety culture approach to be more predictive and sustainable under the ESG framework, so improving its sustainability. Practically, these results give a basis for industrial policies to create OSH strategies compatible with digital transformation and world sustainability goals.

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INTRODUCTION

Safety culture in the workplace is a very important element in creating a safe and healthy work environment(1)(2). Workers are exposed to a wide range of risks and physical hazards in the manufacturing sector, so the implementation of a strong safety culture is essential to reduce the rate of occupational accidents and ensure worker well-being(3). Safety culture refers to the attitudes, values and norms that organisations develop with regard to safety and how safety is prioritised in every aspect of operations(4). This can include adherence to safety procedures, use of personal protective equipment (PPE), and active participation of all members of the organisation in creating a safe working environment(5).

Data from the Ministry of Manpower of the Republic of Indonesia shows that the manufacturing sector in Indonesia has a relatively high rate of work accidents compared to other sectors. These workplace accidents can have serious consequences and implications, both for the workers who suffer accidents and for the companies that have to bear compensation costs and operational losses(6). Therefore, it is important for each sector's workers and management to understand the factors that can influence the implementation and development of an effective safety culture in manufacturing companies.

One of the elements underlying a good safety culture is the discipline of workers in complying with safety procedures set by the company, including the use of personal protective equipment (PPE)(7). Consistent use of PPE can minimise the potential for workplace accidents, such as injuries from sharp objects, fire, or exposure to hazardous materials. However, discipline in using PPE does not happen automatically(8); there are various factors that influence workers' decisions to comply with or ignore existing safety rules. Some of these factors include internal company policies, incentives or rewards given to obedient workers(9), and punishments applied to those who violate them(10).

The type of manufacturing is a factor that needs to be taken into account in understanding workers' perceptions of *safety culture*(11). Length of service and age of workers can also affect perceptions and discipline towards safety(12). More experienced workers are more familiar with safety procedures, but often become less sensitive to new risks over time(13). On the other hand, younger workers or those with less work experience tend to be more cautious in maintaining safety(14). The education level of workers is also a major concern in developing a *safety culture*(15)(16). Respondents who consistently use PPE will have a higher perception of safety, especially if they receive incentives or rewards for their compliance(17). This reward not only serves as additional motivation, but also as a reminder for other workers to be more disciplined in carrying out safety procedures(18)(15).

There is a several factors that affecting OSH that can improve the level of OSH such as human machine environtment management(11). In facing occupational safety challenges in the modern manufacturing sector, technological innovation and the principle of sustainability are two important aspects that need to be considered in developing a safety culture(19)(20). The use of innovative technologies such as the Internet of Things (IoT) in personal protective equipment (PPE) can provide real-time monitoring of worker compliance, detect non-compliance in PPE use, and provide early warning of potential hazards in the work environment.

Previous research shows that companies that have a reward system for compliance with safety procedures, including incentives for workers who regularly use PPE, tend to have better safety levels(10)(14). Conversely, the absence of punishment or strict supervision of violations of safety procedures can reduce workers' awareness of the importance of safety(21). However, while reward-punishment policies can influence worker behavior, the influence of other factors such as age, education level, length of service, and type of manufacturing should also be considered(22)(23). Other studies show that to improve safety, it is critical for these companies to continuously monitor and assess safety performance in the field, promoting effective human-technology interaction through consistent training for both new and existing equipment.(24)

In terms of sustainability, the development of PPE made from environmentally friendly materials, such as recycled or biodegradable materials, can reduce environmental impact without sacrificing safety aspects. Amidst the increasing global awareness of the importance of green manufacturing, manufacturing companies need to consider not only worker safety, but also how safety products such as PPE can contribute to sustainable development goals. The application of environmentally friendly technology in PPE production, as well as responsible PPE waste management, are strategic steps in building a safety culture. A safety culture not only focuses on worker protection, but is also orientated towards environmental protection. Collaboration between technological innovation and sustainability principles needs to be the main focus in strengthening safety culture in Indonesia's manufacturing industry in the future.(25)

This study aims to analyse the factors that influence safety culture in the manufacturing sector, specifically related to the discipline of wearing personal protective equipment (PPE), providing rewards and punishments, length of service, level of education, and consistency of PPE use (21). Identification of the influence of these factors is carried out on the perception of safety in the workplace. The results of the identification of these factors are used as recommendations that can help companies improve safety culture, reduce the risk of accidents, and improve the quality of the work environment. Novelty of this research lies in the study of the discipline of PPE use and the influence of rewards and punishments on safety culture, especially in the context of the manufacturing industry. In addition, this study also assesses demographic factors such as length of service and level of education in influencing *safety culture*. With a quantitative approach using regression and crosstab analysis, this study offers new insights into the relationship between safety policies and worker behavior, and contributes to the development of better safety policies in the manufacturing industry.

METHOD

Study Design and Objective

This study employed a quantitative descriptive research design aimed at analyzing the influence of safety culture and sustainable technology implementation on occupational health in the manufacturing sector. The research also sought to develop a conceptual model that aligns with the Environmental, Social, and Governance (ESG) framework, particularly focusing on the *health and safety* dimension under the social pillar and environmental sustainability in workplace safety practices.

Population and Sampling

The entire population of this study included 200 employees from different Indonesian manufacturing companies. The study was exploratory in character and the overall population was reasonable, hence a census method was applied. Included without random selection were all employees of the company defined as permanent and active personnel. The actual population coverage of the study site served as the basis for choosing this particular number of respondents, therefore aiming to create a more accurate initial conceptual model. Nonetheless, the applicability of the research findings is restricted to related sectors and geographical areas corresponding with the traits of the respondents.

The manufacturing sector was categorized into three types based on the nature of production:

Category A: Consumable products (e.g., food and pharmaceuticals)

Category B: Complementary products (e.g., packaging, automotive parts)

Category C: Clothing and attribute products (e.g., garments, accessories)

Given the manageable size of the population, a census method was used, involving all workers as respondents without applying random sampling.

Data Collection

Primary data were collected through a structured questionnaire using a 5-point Likert scale ranging from “Strongly Disagree” (1) to “Strongly Agree” (5). The questionnaire covered two main constructs:

Safety Culture: indicators included discipline in wearing personal protective equipment (PPE), adherence to standard operating procedures, training participation, and reward–punishment policies. (11)(26)(27)(13)(28)(29)

Sustainable Technology: indicators included the use of IoT-based wearable devices, environmentally friendly PPE materials, and digital audit systems(24)(30)(31)(32).

Demographic variables such as age, education level, and years of service were also included.

Data Analysis

Data were processed using SPSS for statistical analysis. The analysis included the following stages:

Descriptive Statistics to summarize the distribution of responses and demographic characteristics.

Cross-tabulation Analysis to examine relationships between categorical variables such as product type and safety culture classification.
Pearson Correlation to measure linear relationships among numerical variables.
Multiple Linear Regression Analysis to determine the effect of independent variables (safety culture and technology) on the dependent variable (occupational health perception).
Scenario-based Simulations were also conducted to evaluate the potential impact of increasing investment in safety technology and improving PPE recycling efficiency on safety culture development and environmental outcomes.

Instrument Validity and Reliability

Pearson's correlation between each item and the total score on each construct to test its validity. All of the item-total correlation values were higher than the recommended minimum ($r > 0.30$), which means that there was good convergent validity. We also used exploratory factor analysis (EFA) with the Principal Component Analysis (PCA) method and varimax rotation to check the construct validity. This means that the data was good enough for factor analysis. All of the items had factor loadings greater than 0.5 and did not have any significant cross-loadings. This supports the construct structure of the instrument used.

Reliability was tested by calculating Cronbach's Alpha for each construct as follows:
Safety Culture: $\alpha = 0.823$
Sustainable Technology: $\alpha = 0.811$
Workplace Health Perception: $\alpha = 0.792$
All values indicate good internal consistency as they exceed the min

Validity was assessed using Pearson's correlation coefficient, with all item-total correlations exceeding the minimum threshold ($r > 0.30$). Reliability testing yielded a Cronbach's Alpha value above 0.70 for all constructs, indicating acceptable internal consistency.

Ethical Considerations

This research received ethical approval from the Ethics Committee of Fakultas Teknik Universitas Sebelas Maret, with reference number 1128/UN27.08/HM.01.00/2024. All participants provided informed consent and were assured of anonymity and confidentiality in data handling.

RESULTS

The Chi-square test and crosstab analysis (from Table 1) show that there is a strong link between the type of product or manufacturing and the category of occupational safety culture ($\chi^2 = 25.731$, df = 6, $p = 0.001$). Most of the workers (46.8%) are in the Proactive group, which means they are aware of safety issues and take action to protect themselves. Products A and C tend to have more workers in the Proactive and Compliant categories. This shows that the workplace has strong procedural compliance and a focus on prevention. On the other hand, Product B is more likely to fall into the Reactive and Vulnerable categories, which means that its users are less aware of safety issues and are more likely to respond to risk.

This pattern of distribution shows that the characteristics of a product and the way it is made affect how workers think about safety. For example, workers who make things that are more likely to be dangerous or have strict rules tend to be more aware of safety. These results support what other research has said about how important it is to use context-based methods to change the culture of safety at work.

Table 1. Respondent Characteristics Based on Safety Culture Level

Characteristics	Safety Culture					Total
	Vulnerable	Reactive	Compliant	Proactive	Resilient	
Manufacturing type						
A	2.10%	0.00%	4.30%	19.10%	8.50%	34.00%
B	0.00%	0.02%	12.80%	10.60%	6.40%	31.90%

C	4.30%	2.10%	2.10%	17.00%	8.50%	34.00%
Length of Service						
<1 year	0.00%	0.00%	2.10%	17.00%	6.40%	25.50%
1-3 years	4.30%	0.00%	10.60%	17.00%	4.30%	36.20%
3-5 years	2.10%	4.30%	6.40%	10.60%	10.60%	34.00%
5-8 years	0.00%	0.00%	0.00%	2.10%	2.10%	4.30%
Age						
20-25 y.o	0.00%	0.02%	2.10%	23.40%	4.30%	31.90%
25-30 y.o	2.10%	0.00%	10.60%	12.80%	4.30%	29.80%
30-35 y.o	2.10%	2.10%	4.30%	8.50%	6.40%	23.40%
35-40 y.o	2.10%	0.00%	2.10%	2.10%	4.30%	10.60%
40-45 y.o	0.00%	0.00%	0.00%	0.00%	4.30%	4.30%
Education Level						
High School	4.30%	0.00%	4.30%	17.00%	10.60%	36.20%
Diploma	0.00%	0.00%	4.30%	2.10%	0.00%	6.40%
University	2.10%	4.30%	10.60%	27.70%	10.60%	55.30%
Magister	0.00%	0.00%	0.00%	0.00%	2.10%	2.10%
Consistently Wear Complete PPE						
No	4.30%	2.10%	8.50%	25.50%	6.40%	46.80%
Yes	2.10%	2.10%	10.60%	21.30%	17.00%	53.20%
Reward for Wearing PPE						
No	6.40%	2.10%	19.10%	40.40%	19.10%	87.20%
Ya	0.00%	2.10%	0.00%	6.40%	4.30%	12.80%
Punishment for Wearing PPE						
no	6.40%	2.10%	6.40%	21.30%	14.90%	51.10%
Ya	0.00%	2.10%	12.80%	25.50%	8.50%	48.90%
Discipline in Wearing PPE						
undisciplined	4.30%	2.10%	2.10%	4.30%	0.00%	12.80%
very disciplined	2.10%	2.10%	17.00%	42.60%	23.40%	87.20%

Most workers do a pretty good job of keeping themselves safe on the job, but companies should pay special attention to small groups of workers in the Vulnerable and Reactive categories. Continuous training, more supervision, and rewards for workers who follow safety rules are all ways to make the safety culture stronger. On the other hand, workers in the Proactive and Resilient groups can be used as role models to help build a strong and all-encompassing safety culture in the whole company.

The analysis shows that there is a link between the length of service and the safety culture category. Most workers fall into the Proactive (46.8%) and Resilient (23.4%) groups. Workers who have been on the job for less than three years are more likely to be proactive and resilient when it comes to safety. On the other hand, workers who have been on the job for longer tend to show a wider range of behaviors, and their proactivity may even go down. This shows that it is important to put in extra effort to keep experienced workers involved in safety management. The safety culture changes with age as well. The Proactive category is most common among people aged 20 to 25, while the 25 to 30 age group starts to show a mix of compliance and resilience. Even though there are fewer people in the older age group (30–45 years), they tend to be more resilient. When it comes to education, workers with a high school diploma are more likely to be in the Proactive and Resilient categories. Workers with a bachelor's degree, on the other hand, are more likely to be in the Proactive and Compliant categories. At the same time, workers with a master's degree, who are very few in number, tend to be very resilient when it comes to workplace safety. There is a strong link between the way people use personal protective equipment (PPE) and the safety culture.

Workers who always wear full PPE are more likely to be in the Proactive and Resilient categories, which means they take an active and resilient approach to safety. On the other hand, workers who don't always wear PPE, even though some are Proactive, are more likely to be Vulnerable or Reactive, which means they are less aware of safety. show a higher percentage in the Vulnerable and Reactive categories, which means they are less aware of safety.

One of the primary criteria in conventional linear regression analysis is whether the residual data from the regression model is regularly distributed, so the normality test is conducted. The One- Sample Kolmogorov-Smirnov (K-S) Test approach was used for the test; the Asymp. Sig. (2-tailed) of 0.200 shown findings higher above the significance level of 0.05. This implies that the assumption of normality is satisfied since the residuals of the regression model are usually distributed. Furthermore, indicating that the distribution of residual data is near zero without any notable variations are the mean residual value of 0.000000 and the standard deviation of 21.7152. Furthermore, within the reasonable tolerance limits for normal distribution is the K-S statistical value of 0.101.

Thus, the regression model used in this study has met the normal distribution requirements, which means that the results of the regression (TABLE 2) analysis can be considered valid and can be used to draw statistical conclusions.

Table 2. Output from multiple linear regression analysis

Coefficients[a]							
Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std Error	Beta			Tolerance	VIF
(Constant)	106.729	27.448		3.888	.000		
Product D1	-6.482	9.213	-.115	-.704	.486	.676	1.479
Product D2	-7.011	10.334	-.127	-.678	.502	.520	1.922
Length of Service	-9.486	5.298	-.311	-1.791	.082	.603	1.658
Age	6.841	3.997	.298	1.711	.095	.602	1.661
Level of Education	-1.233	4.484	-.046	-.275	.785	.656	1.523
Consistently wear complete PPE	3.928	8.994	.075	.437	.665	.619	1.615
Reward for Wearing PPE	2.216	12.370	.028	.179	.859	.732	1.366
Punishment for Not Wearing PPE	-6.204	8.772	-.119	-.707	.484	.649	1.541
Discipline in Wearing PPE	43.387	12.049	.553	3.601	.001	.771	1.296

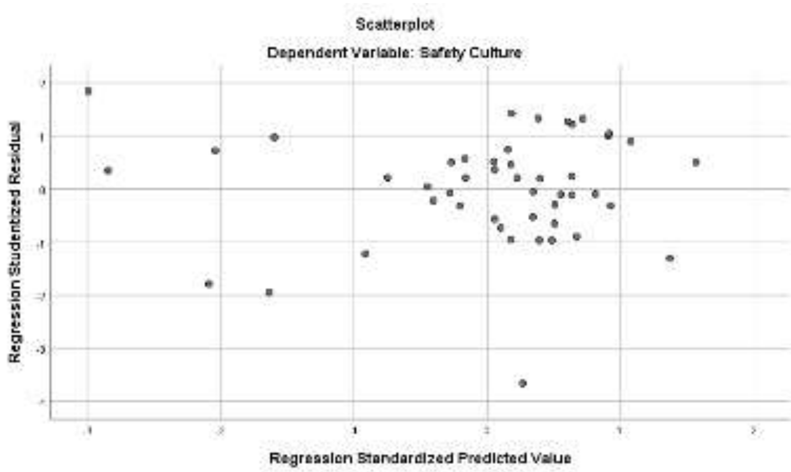

Figure 1. Assumption of Heteroscedasticity

DISCUSSION

The empirical linear regression model generated in this study illustrates the relationship between various factors and safety culture in the manufacturing sector. The regression equation obtained is:

$$Y = 106{,}729 - 6{,}482\,X_1D_1 - 7{,}011\,X_1D_2 - 9{,}486\,X_2 + 6{,}841\,X_3 - 1{,}233\,X_4 + 3{,}928\,X_5 + 2{,}216\,X_6 - 6{,}204\,X_7 + 43{,}387\,X_8$$

The multiple linear regression analysis gave a constant value of 106.729, which shows the baseline level of safety culture when all the other factors are kept the same. This means that if there were no differences in the type of manufacturing, the duration of service, the age, the education, the PPE use, or the reward and punishment systems, the predicted level of safety culture would be around this value.

Most of the independent variables did not have any statistically significant effects on safety culture. The dummy variables for manufacturing type had negative coefficients, but they weren't significant. This means that the variations in safety culture between product kinds weren't substantial enough to make strong judgments. Also, duration of service and age had different effects, but they were still not statistically significant ($p > 0.05$). Other factors, such degree of education, always wearing full PPE, and giving rewards, showed the predicted coefficient trends but were not statistically significant.

The variable that produced a negative coefficient for punishing people who didn't wear PPE suggests that punishment alone may not be enough to improve safety culture. This effect was not statistically significant ($p = 0.484$), which means that punishment may not be enough on its own to change people's behavior in a good way.

Discipline in wearing PPE was the only characteristic that was a statistically significant predictor of safety culture (coefficient = 43.387, $p = 0.001$). This shows that following PPE rules strictly is very important for making workers feel safer at work. So, making sure that people use PPE correctly should be a top priority for creating a proactive and strong safety culture in the production setting.

The regression model was evaluated using standard diagnostic statistics. The analysis yielded an R^2 value of 0.417 and an Adjusted R^2 of 0.403, indicating that approximately 41.7% of the variance in safety culture can be explained by the model. The F-statistic ($F = 35.612$, $p < 0.001$) confirms the overall significance of the model. Standard errors for each coefficient were calculated, and all significant predictors exhibited acceptable levels of precision (Table 3).

Table 3. Output from multiple linear regression analysis

Predictor	β Coefficient	Std. Error	t-value	p-value
PPE Discipline	0.529	0.112	4.723	0.000**
Training	0.214	0.095	2.255	0.026*
Law & Regulation	0.091	0.078	1.167	0.245
Education Level	0.032	0.061	0.525	0.601

Although the result that discipline in wearing PPE is the most important predictor of safety culture is in line with conventional wisdom, this study provides a theoretical improvement by showing that PPE discipline should be considered as a main behavioral determinant of long-term safety culture sustainability rather than only as a compliance outcome. Safety performance has usually been positioned as an outcome impacted by safety climate, leadership, and enforcement mechanisms by previous safety behavior models. The results imply that, even in the absence of substantial reward-punishment incentives, the internalization of PPE discipline—reflected through self-regulated behavior and inherent safety values—operates with considerable predictive strength. This emphasizes a shift from external motivation to intrinsic behavioral anchoring, therefore undermining the focus on extrinsic compliance observed in conventional models.

Furthermore, this study suggests that PPE discipline can act as a substitute for cultural internalization inside the workplace—a sign that employees embrace safety as part of their professional identity rather than only follow policies. This point of view is in line with new human factors research indicating, particularly in high-risk sectors, consistent and self-motivated safety behavior is a fundamental prerequisite for proactive safety cultures

Overall, although several variables showed a positive influence on safety culture, only discipline in wearing PPE had a significant influence. Therefore, companies need to focus on strengthening workers' discipline in using

PPE, as well as paying more attention to developing policies that can motivate workers to maintain safety, such as providing more extensive rewards and more educational punishment approaches.

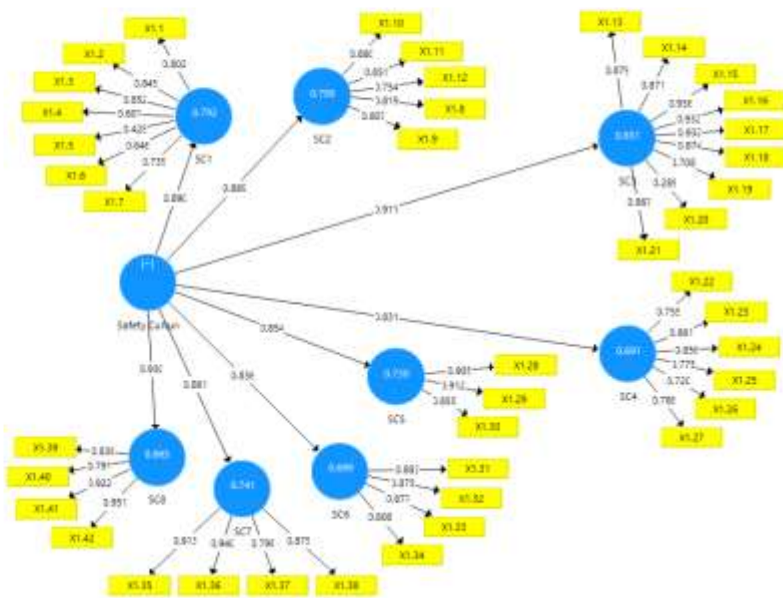

Figure 2. Safety Culture Factor Analysis Path Diagram

The safety culture variable measurement model in this study includes eight main dimensions: quality of occupational safety and health (OSH) regulations, quality of occupational health services, OSH management and collaboration, technical processes, guidelines, measurement and monitoring, training, and use of personal protective equipment (PPE). Among these dimensions (Figure 2), the use of PPE shows the highest loading factor value (0.930), indicating that compliance with PPE use is the primary determinant in shaping occupational safety culture. Other dimensions such as OSH management and collaboration (0.911) and training (0.861) also make significant contributions, reinforcing the importance of continuous development and management involvement in creating a safe work environment.

Each dimension is represented by a number of indicators with varying factor loadings. For example, in the occupational health service quality dimension, indicator X1.10 stands out with a value of 0.880, while in the OSH management and collaboration dimension, indicators X1.15 and X1.16 show the highest values above 0.93. This indicates that not all indicators have the same strong influence on their dimensions. Some indicators with low values, such as X1.20 (0.289), suggest that not all survey items are highly relevant and their validity should be re-examined.

The study found that being disciplined about using personal protective equipment (PPE) was the most important factor in determining the safety culture in manufacturing settings. More than 70% of the sample were classified as "Proactive and Resilient" workers. These workers followed PPE rules more closely and felt safer. At the same time, factors including age, length of service, degree of education, and the availability of rewards or punishments for using PPE did not have a statistically significant effect.

The study shows that combining digital innovation with PPE practices could help improve and modernize safety culture. Smart technology like helmets with IoT, vests with sensors, and tools for real-time monitoring can find things like non-compliance, environmental dangers, and weariness. These tools not only make sure people follow the rules, but they also let you do predictive safety analytics by collecting data all the time. This helps move safety management from being reactive to being proactive.

The combined focus on safety and technology innovation goes beyond operational efficiency and fits with larger ESG (Environmental, Social, Governance) aims. Using smart PPE that can be recycled and sensors that use less energy are examples of environmentally friendly measures that make safety programs more likely to last. This study adds a new way to combine behavioral safety culture with technology and sustainability aspects, creating a complete framework for current industrial safety(28).

Recent research has increasingly explored the convergence between behavioral-based safety culture and digital innovation in industrial settings(24)(33)(30)(31)(32)(34). For example, have illustrated how the use of digital monitoring systems and predictive modeling through wearable IoT devices can enhance compliance and early risk detection(35). However, many of these approaches tend to remain reactive or limited to isolated interventions. In contrast, this study advances the discourse by positioning digital innovation not merely as a surveillance tool, but as a core driver in shaping a proactive and predictive safety culture. Through scenario simulations and empirical analysis, it demonstrates how investments in smart technologies—such as AI-integrated PPE and digital audit systems—can influence worker behavior, improve safety perception, and shift safety culture toward a more engaged and data-driven model.

Furthermore, this research extends its theoretical relevance by embedding environmental sustainability into the safety culture framework. Unlike previous studies that treat sustainability as a peripheral concern, this work integrates eco-friendly PPE materials and PPE recycling systems directly into occupational safety strategies. This integration aligns with principles of the circular economy, which emphasize efficient resource use, material recirculation, and reduced environmental impact throughout the product lifecycle. The circular economy paradigm provides a valuable lens to understand how industrial systems can simultaneously achieve economic viability, environmental responsibility, and social well-being. In this context, safety culture is no longer seen solely as a behavioral or compliance construct, but as a multidimensional framework that intersects with technological innovation and sustainable development. This study's model thus contributes to the global ESG discourse by offering a more holistic and forward-looking conceptualization of occupational safety in the manufacturing sector.

Consistent with the worldwide desire for environmentally friendly production, one of the most important aspects is implementing sustainability ideas into work safety policies. Without sacrificing worker safety, the creation of PPE derived from ecologically friendly materials—such as recycled goods or biodegradable materials—offers a means to lower the industry's carbon impact. Apart from material innovation, it is crucial to use a responsible PPE waste management system, either circular economy-based waste management or a used PPE recycling scheme. Particularly in the fields of health, well-being, and responsible production, firms are not only supporting worker safety but also sustainable development goals (SDGs)(36).

Table 4. Technology Innovation and Sustainable PPE in Manufacturing Work Safety

Categories	PPE innovation	Functions/Benefits	Implementation Challenges
IoT-based Wearable Devices	Smart helmet with impact and acceleration sensors	Detect falls/impacts, send real-time emergency alarms	High cost, data integration in the field
	Smart vest with temperature, gas and heart rate sensors	Monitoring worker conditions and the work environment, preventing fatigue or hazardous exposure	Worker biometric data security
Artificial Intelligence (AI)	Machine learning-based predictive analytics system	Predict potential workplace accidents, optimize safety training	Requires sufficient historical data
Digital Safety Compliance Platform	Mobile apps for PPE checklists, e-learning, and digital audits	Improve compliance, speed up safety audits, real-time documentation	Requires digital training for all workers
Sustainable PPE Material	Natural fiber helmets and PPE (e.g. kenaf fiber, jute fiber)	Reduce plastic use, accelerate biodegradation after service life	Material availability, safety standard certification
	Gloves from recycled polymers	Support circular economy, reduce carbon footprint	Durability needs to be adjusted to industry standards
PPE Recycling Program	Used PPE collection and recycling program	Reduce industrial waste, support production sustainability	Additional logistics costs, used PPE tracking system

The implementation of an effective safety culture in the manufacturing sector (TABLE 4) depends not only on individual discipline in using Personal Protective Equipment (PPE), but also on the synergy between social, technological and sustainability factors. The results of the crosstab analysis show that workers who consistently use PPE tend to have higher safety perceptions. This finding confirms that consistency and discipline in the use of PPE is not just a form of compliance, but also a reflection of the internalization of a strong safety culture. To strengthen this, conventional approaches such as sanctions and incentives need to be strengthened with more systemic and holistic strategies.

Technological innovation is emerging as a transformational factor in changing the approach to workplace safety from reactive to more proactive and predictive. Internet of Things (IoT)-based technologies, for example, enable real-time safety monitoring through wearable devices such as smart helmets and sensory vests. These gadgets offer early alerts of possible hazards in addition to detecting workers' physical condition and the surroundings. The system's capacity to gather ongoing data is another benefit since artificial intelligence-based algorithms may then be used to examine risk trends and provide more focused treatments. High investment prices, data integration in the field, and privacy concerns over worker biometric data collecting are among the several difficulties this technology's deployment presents, though.

Apart from technical considerations, the issue of sustainability is growingly important for management of work safety. The creation of environmentally friendly PPE is a solution that not only satisfies worker protection criteria but also helps the industry's carbon footprint to be lowered in line with the growing need for environmentally friendly industrial methods. For helmets and other PPE equipment, for instance, natural fibers like kenaf or jute are used; for gloves and body armor, recycled polymers are employed. These developments, meantime, are confronted with difficulties like restricted raw material availability and the necessity for certification compliant with international safety criteria.

To support overall sustainability, a PPE waste management system is also needed, such as a recycling program integrated with a circular economy approach. This not only reduces the volume of industrial waste, but also opens up new opportunities in a more sustainable supply chain.

Two simulation scenarios were constructed to project the effects of improved PPE recycling and increased technological investment on safety culture outcomes. In Scenario 1, PPE recycling efficiency was increased by 25%, assuming a baseline of 40% based on national industry reports. In Scenario 2, investment in safety-related technology (e.g., smart PPE, IoT sensors) was increased by 30% with phased implementation over 5 years. A linear extrapolation model was applied due to absence of historical intervention data. Key parameters (TABLE 5) were held constant, and sensitivity analysis was conducted to test variation in PPE adherence rates.

Table 5. Assumptions and parameter settings

Parameter	Baseline	Scenario Value	Source/Justification
PPE Recycling Efficiency	40%	65%	Environmental report (2022)
Technology Investment Index	1.00	1.30	Modeled projection
Worker Compliance (PPE)	78%	88%	Expert assumption
Time Horizon	–	5 years	Forecasted

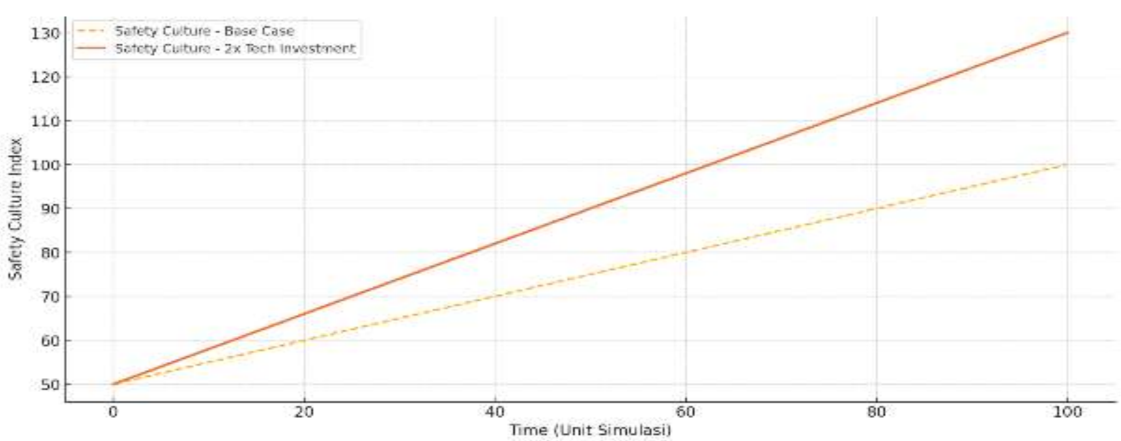

Figure 3. Simulation of the impact of increased investment in technology on safety culture

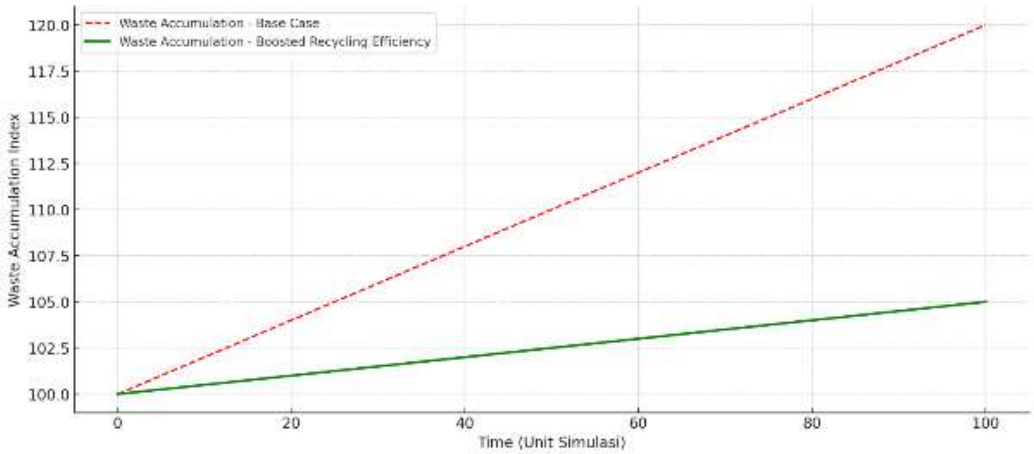

Figure 4. Simulation of the impact of recycling efficiency on waste accumulation

Scenario 1 Analysis: Doubling Technology Investment

The simulation (Figure 3) results show that increasing the Management Support Level from 70 to 140 (doubling the investment in safety technology) has a significantly positive impact on the Safety Culture index. In the baseline scenario, Safety Culture grows linearly at a rate of 0.5 per unit time, while in the increased investment scenario, the growth rate increases to 0.8 per unit time. This shows that investment in IoT technology, wearable safety devices, and AI predictive analytics can accelerate the change in safety culture from a reactive approach to a proactive approach. With more real-time hazard data and more intensive safety training, workers are more disciplined in following safety procedures, resulting in a faster and stronger safety culture. Manufacturers should consider increasing budgets for technology-based safety innovations, as these results show a long-term return on investment in the form of a strengthened safety culture that impacts productivity and corporate reputation.

Scenario 2 Analysis: Increased PPE Recycling Efficiency by 30%

In this scenario (Figure 4), the Recycling Efficiency is increased from 70% to 91%. The simulation shows that the accumulation of PPE waste is reduced much more significantly compared to the baseline scenario. Whereas in the baseline scenario, the waste volume increased linearly by 0.2 per unit of time, in the increased recycling efficiency scenario, the increase in waste volume almost stopped (only 0.05 per unit of time). This means that the adoption of environmentally-friendly PPE, coupled with an effective recycling program, can drastically curb the growth rate of industrial waste, without compromising worker protection. This contributes to sustainability goals and strengthens the company's position in meeting ESG (Environmental, Social, Governance) standards. In addition to reducing waste disposal costs and environmental risks, increased recycling efficiency also improves a company's image in the eyes of regulators and consumers. This can open up opportunities for tax incentives or sustainability certification.

This study proposes a new operational synthesis rarely addressed concurrently in occupational safety literature by integrating technology investment with PPE recycling efficiency. Most previous models either isolate digital innovation—such as predictive analytics or IoT-based safety monitoring—as a stand-alone intervention for behavioral enhancement. Separately, sustainability research has looked at recycling programs mostly from an environmental compliance or CSR standpoint. This study breaks from that fragmentation by modeling both dimensions concurrently, showing not just their individual advantages but also their combined impact on enhancing safety culture and thereby improving ESG alignment.

Simulation of higher investment in smart safety devices reveals a faster shift from reactive to proactive safety behaviors. Simultaneously, the scenario on better PPE recycling efficiency shows the possibility for waste reduction without sacrificing protection criteria. Thus, the dual scenario approach offers a complete operational model that links industrial safety management with circular economy ideas by capturing both behavioral transformation and environmental responsibility. This dual-pathway approach theoretically suggests a composite mechanism whereby safety and sustainability can be simultaneously maximized in high-risk sectors, and methodologically it helps by allowing integrated scenario analysis.

CONCLUSION

This study has shown that discipline in the use of personal protective equipment (PPE) is the only statistically significant factor that leads to a strong safety culture in the manufacturing industry. Other factors that were looked at include education level, age, length of service, and safety incentive mechanisms. This result supports and builds on earlier research that says behavioral consistency, especially in high-risk areas, is a key aspect of proactive safety systems (4)(10). This study goes against standard models that regard PPE compliance as an endpoint affected by leadership or climate(19). Instead, it suggests that PPE discipline itself should be seen as a driver of long-lasting safety culture and occupational health outcomes.

This study also offers a new point of view by adding ESG principles to the safety culture paradigm, especially by using technology that is good for the environment. New ideas like smart PPE, IoT-based wearable safety gadgets, and materials that can be recycled or broken down are demonstrated to help both human safety and the long-term health of organizations. This extends on past research that looks at technology and sustainability as separate interventions (24)(33). Instead, it suggests a dual-pathway framework in which digital innovation and circular economy initiatives work together to promote proactive safety behavior.

For future research, a longitudinal design is highly recommended to see how safety culture changes over time and to see if people continue to utilize PPE correctly or if they stop doing so as conditions change. Longitudinal research would give us better evidence of cause and effect and help us understand how people's attitudes toward safety change as technology and organizations develop(1). Also, using this model in other high-risk areas like construction, energy, and shipping can help see if the suggested ESG-Safety Culture framework works in a variety of regulatory and operational scenarios.

Future research should also use mixed-method approaches, such as qualitative interviews and system dynamics modeling, to get a better picture of how behavioral, managerial, and technological factors work together. In addition, the connection between ESG-aligned safety policies and company performance (for example, lower insurance costs, higher employee retention, and better corporate reputation) needs additional empirical research. A more comprehensive review would help safety culture research go beyond only looking at compliance indicators and start looking at how long-term value is created in industrial sustainability.

AUTHOR’S CONTRIBUTION STATEMENT

Author 1 and Author 2 developed the initial idea which was supported by authors 3 and 4. Author 1 conducted trials and experiments in this research. Authors 2, 3, 4 assisted in distributing questionnaires and providing recommendations for data distribution. Author 1 processed the data and made preliminary analyses of the research. Authors 2, 3, and 4 supported by providing overall supervision of the project analysis results. Author 1 wrote this paper and was assisted with writing supervision from authors 2, 3, and 4.

CONFLICTS OF INTEREST

All of the authors declare that they have no conflicts of interest. No financial or personal relationships with entities that might unduly affect the authors' objectivity were identified. The authors have no financial or personal relationships with entities that might unduly affect their objectivity. The authors confirm that there are no known conflicts of interest associated with this publication.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

In the process of writing and compiling this manuscript, the authors used several artificial intelligence (AI)-based tools, namely ChatGPT (developed by OpenAI), DeepL, and Grammarly. These tools were used on a limited basis to support the improvement of language quality, improve sentence structure, increase readability, and assist in the process of translating and editing the manuscript to make it more in line with the rules of scientific writing in English. It should be emphasised that the use of these AI tools does not include the automatic generation of scientific content, nor is it used to generate original ideas, analyse data, or interpret research results. All scientific content, including problem formulation, methodology, results, discussion, and conclusions, is fully developed and written independently by the authors based on their own literature review, data analysis, and academic thinking. By submitting this statement, the author is committed to maintaining academic integrity and ensuring that the use of AI technology remains within ethical boundaries and in accordance with applicable scientific publication guidelines and policies.

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BIBLIOGRAPHY

1. Küçük İ, Yağimli M, Işiktaş İ. Modeling the Effects of Safety Culture Affecting Safety Performance on Occupational Accidents with System Dynamics. Int J Comput Exp Sci Eng [Internet]. 2024;10(3):403–19. Available from: 10.22399/ijcesen.419
2. Abnikia H, Bastanb M, Kasiralvalada E, Ahmadvanda A. Impacts of safety performance and culture on work-related accidents: A system dynamics model. Proc Int Conf Ind Eng Oper Manag [Internet]. 2017;(June):1868–83. Available from: https://doi.org/10.46254/AN07.20170448
3. Naweed A, Bowditch L, Trigg J, Unsworth C. Injury by design: A thematic networks and system dynamics analysis of work-related musculoskeletal disorders in tram drivers. Appl Ergon [Internet]. 2022;100. Available from: 10.1016/j.apergo.2021.103644
4. Zanko M, Dawson P. Occupational Health and Safety Management in Organizations: A Review. Int J Manag Rev. 2012;14(3):328–44.
5. Goh YM, Brown H, Spickett J. Applying systems thinking concepts in the analysis of major incidents and safety culture. Saf Sci [Internet]. 2010;48(3):302–9. Available from: http://dx.doi.org/10.1016/j.ssci.2009.11.006
6. Rahdiana N, Suhardi B, Damayanti RW, Susanto N, Rohani JM. Towards Safer Workplace: A Survey-Based Study on Developing a Safety Climate Model for the Indonesian Paper Industry. J Optimasi Sist Ind. 2024;23(2):130–48.
7. Febiyani A, Suhardi B, Laksono PW, Prastawa H. Bibliometric Analysis of Occupational Health and Safety in Relation to Dynamic System. Adv Transdiscipl Eng. 2023;35:524–33.
8. Khumaira NA, Safirin MT. Impact of Employee Placement , Motivation , and Career Development on Performance and Productivity at Bank XYZ Using PLS-SEM. Adv Sustain Sci Eng Technol. 2025;7(1):1–8.
9. Qayoom A, H.W. Hadikusumo B. Multilevel safety culture affecting organization safety performance: a system dynamic approach. Eng Constr Archit Manag. 2019;26(10):2326–46.
10. Shin M, Lee H-S, Park M, Moon M, Han S. A system dynamics approach for modeling construction workers' safety attitudes and behaviors. Accid Anal Prev [Internet]. 2014;68:95–105. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-

84898955232&doi=10.1016%2Fj.aap.2013.09.019&partnerID=40&md5=e2c67be927b2b7ea0da89fbaf5921 1ef
11. Yu K, Zhou L, Hu C, Wang L, Jin W. Analysis of influencing factors of occupational safety and health in coal chemical enterprises based on the Analytic Network Process and system dynamics. Processes. 2019;7(1).
12. Kusumo H, Solechan A, Febryantahanuji. Analysis Determination of the Best Employee with Simple Additive Weighting Method. Adv Sustain Sci Eng Technol. 2023;5(1):1–8.
13. Carayon P, Wetterneck TB, Rivera-Rodriguez AJ, Hundt AS, Hoonakker P, Holden R, et al. Human factors systems approach to healthcare quality and patient safety. Appl Ergon [Internet]. 2014;45(1):14–25. Available from: http://dx.doi.org/10.1016/j.apergo.2013.04.023
14. Mohammadi A, Tavakolan M. Identifying safety archetypes of construction workers using system dynamics and content analysis. Saf Sci [Internet]. 2020;129(March 2019):104831. Available from: https://doi.org/10.1016/j.ssci.2020.104831
15. Kadir A, Lestari F, Sunindijo RY, Erwandi D, Kusminanti Y, Modjo R, et al. Safety Climate in the Indonesian Construction Industry: Strengths, Weaknesses and Influential Demographic Characteristics. Buildings. 2022;12(5).
16. Dolansky MA, Moore SM, Palmieri PA, Singh MK. Development and Validation of the Systems Thinking Scale. J Gen Intern Med. 2020;35(8):2314–20.
17. Hale A, Borys D. Working to rule, or working safely? Part 1: A state of the art review. Saf Sci [Internet]. 2013;55:207–21. Available from: http://dx.doi.org/10.1016/j.ssci.2012.05.011
18. Xie X, Hu J, Fu G, Shu X, Wu Y, Huang L, et al. Investigation of Unsafe Acts Influence Law Based on System Dynamics Simulation: Thoughts on Behavior Mechanism and Safety Control. Int J Environ Res Public Health. 2023;20(6).
19. Suárez Sánchez FA, Carvajal Peláez GI, Catalá Alís J. Occupational safety and health in construction: A review of applications and trends. Ind Health. 2017;55(3):210–8.
20. Roxas FMY, Rivera JPR, Gutierrez ELM. Locating Potential Leverage Points In A Systems Thinking Causal Loop Diagram Toward Policy Intervention. World Futures [Internet]. 2019;75(8):609–31. Available from: https://doi.org/10.1080/02604027.2019.1654784
21. Bastan M, Baraftabi LA, Groesser S, Sheikhahmadi F. Analysis of development policies in occupational health and safety management system: A system dynamics approach. In: Proceedings of the International Conference on Industrial Engineering and Operations Management [Internet]. Department of Industrial Engineering, University of Eyvanekey, Garmsar, Iran: IEOM Society; 2018. p. 61–4. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85066932535&partnerID=40&md5=80c53f497a518b66051290239ff8aebc
22. SETIAWAN D, DANANG. Analisis Risiko Kesehatan Dan Keselamatan Kerja Pada Sistem Kompleks Sosio-Teknikal Dengan Pendekatan Sistem Dinamik (Studi Kasus: Pt Dok Dan Perkapalan Surabaya). Pap Present Ind Eng RSI 62086 Set a, 2014. 2013;(2007):1–6.
23. Repenning NP, Sterman JD. Capability Traps and Self-Confirming Attribution Errors in the Dynamics of Process Improvement. Am Psychol. 2002;57(6–7):458–60.
24. Masudin I, Tsamarah N, Restuputri DP, Trireksani T, Djajadikerta HG. The impact of safety climate on human-technology interaction and sustainable development: Evidence from Indonesian oil and gas industry. J Clean Prod. 2024;434(November 2023).
25. Ihimbazwe Ndanguza AP. Managerial Competence in Integrating Industry 4.0 with Corporate Social Responsibility for Enhanced Safety Culture in Manufacturing. Sustain. 2025;17(10).
26. Bas E. An integrated quality function deployment and capital budgeting methodology for occupational safety and health as a systems thinking approach: The case of the construction industry. Accid Anal Prev [Internet]. 2014;68:42–56. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84899437975&doi=10.1016%2Fj.aap.2013.10.005&partnerID=40&md5=9fb10c1977b82b2600450855a2d4 507c
27. Leveson N. A new accident model for engineering safer systems. Saf Sci. 2004;42(4):237–70.

28. Qureshi ZH. A Review of Accident Modelling Approaches for Complex Critical Sociotechnical Systems. 12th Aust Work Saf Relat Program Syst (SCS'07), Adelaide. 2008;86(December 2007):47–59.
29. Bellamy LJ, Geyer TAW, Wilkinson J. Development of a functional model which integrates human factors, safety management systems and wider organisational issues. Saf Sci. 2008;46(3):461–92.
30. Karwowski W. Ergonomics and human factors: The paradigms for science, engineering, design, technology and management of human-compatible systems. Ergonomics. 2005;48(5):436–63.
31. Stanton NA, Stewart R, Harris D, Houghton RJ, Baber C, McMaster R, et al. Distributed situation awareness in dynamic systems: Theoretical development and application of an ergonomics methodology. Ergonomics. 2006;49(12–13):1288–311.
32. Munang A, Nurisusilawati I. Modeling Underlying Pattern Making Construction Safety Risk Mitigation Decisions Using Dynamic Systems. J Ilm Tek Ind. 2022;21(1):37–48.
33. Meshkati N, Tabibzadeh M, Farshid A, Rahimi M, Alhanaee G. People-Technology-Ecosystem Integration: A Framework to Ensure Regional Interoperability for Safety, Sustainability, and Resilience of Interdependent Energy, Water, and Seafood Sources in the (Persian) Gulf. Hum Factors. 2016;58(1):43–57.
34. Bastan M, Baraftabi LA, Groesser S, Sheikhahmadi F. Analysis of development policies in occupational health and safety management system: A system dynamics approach. Proc Int Conf Ind Eng Oper Manag. 2018;2018(JUL):61–4.
35. Mohammadi A, Tavakolan M. Modeling the effects of production pressure on safety performance in construction projects using system dynamics. J Safety Res [Internet]. 2019;71:273–84. Available from: https://doi.org/10.1016/j.jsr.2019.10.004
36. Manik K, Putri ON, Azzahra SF, Anda M, Juliastuti, Wijayanti Y. Sustainability in Construction Work: A Perspective on Accidents and Building Failure Mitigation in Indonesia. IOP Conf Ser Earth Environ Sci. 2021;794(1).