SHIFT
GLOBAL EHS RESEARCH TO PRACTICE

FORMAT: ONLINE
ISSN 2832-2681

VOLUME 4, ISSUE 1

April 2025

Rapid Screening of Benzene and Aromatic Hydrocarbons in Soil Samples Using Portable Gas Chromatography with Photoionization Detection

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Abstract

A procedure for rapid screening of aromatic hydrocarbons was developed to analyze soil samples using a portable gas chromatograph with a photoionization detector. Three types of soil samples were selected and spiked with different amounts of aromatic hydrocarbons, e.g., benzene, toluene, and xylenes, to determine the detection limits of the instrument and study the influence of the sample matrix on the detection of the studied compounds. Good chromatographic separation between the compounds was achieved at specific analytical conditions. The calibration curves for all target compounds showed correlation, R2 above 0.995 with RSD below 10%, demonstrating very good linearity and precision. The recoveries for all three types of soil samples were within 20%. The limits of quantitation for all compounds were determined between 2 and 7 µg/L in aqueous media, equivalent to 10 to 35 µg/kg in soil, which corresponds well with the requirements of EPA Method 8021B.

KEY WORDS: *aromatic hydrocarbons, benzene, gas chromatography, headspace sampling, photoionization detection*

1. Introduction

Benzene, toluene, ethylbenzene, and xylenes, referred to as BTEX, are aromatic hydrocarbons that naturally occur in crude oil. These compounds are found in gasoline and used in a wide range of industrial processes. Benzene is determined as a carcinogen to humans by both the International Agency for Cancer Research (IACR) and the Environmental Protection Agency (EPA). The EPA's Mobile Source Air Toxics (MSAT) gasoline fuel program aims at reducing hazardous air pollutants, also known as air toxics, emitted by cars and trucks, including benzene (EPA, n.d.a). According to the program, average gasoline benzene content should be decreased to 0.62 volume percent (vol%) for both reformulated and conventional gasoline, with a maximum average benzene standard of 1.3 vol%. Nationwide, there are approximately 550,000 underground storage tanks (USTs) for petroleum or hazardous substances (EPA, n.d.b). This poses a high risk for contamination of soil and groundwater, which is a source of drinking water for nearly half of the population.

According to the Toxic Release Inventory (TRI) from 2006, an estimated release of 24,033 pounds (~11 metric tons) of benzene to soils from 968 domestic manufacturing and processing facilities in 2004 accounted for about 0.3% of the estimated total environmental releases from facilities required to report to the TRI (ATSDR, 2007). An additional +435,000 pounds (~197 metric tons), constituting about 6% of the total environmental emissions, were released via underground injection. Benzene is released to soils through industrial discharges, land disposal of benzene-containing wastes, and gasoline leaks from underground storage tanks. There is a potential for release of benzene to soil from hazardous waste sites. Benzene has been detected in soil samples collected at 436 of the 1,684 sites and in sediment samples collected at 145 of the 1,684 sites where benzene has been reported in some medium.

Despite advances in technologies and safety practices in place, hazardous spills of chemical products containing aromatic hydrocarbons are not uncommon. The Center for Biological Diversity (n.d.) reported that between 1986 and 2013, there nearly 8,000 significant incidents with hazardous liquid spills from pipelines, resulting in an average quantity per spill of 76,000 barrels per year or more than 3 million gallons.

On December 7, 2022, a leak in the Keystone Pipeline released 14,000 barrels of oil into a creek in Washington County, Kansas. The leak was the largest in the United States since the 2013 North Dakota pipeline spill. It was the largest oil leak in the history of the Keystone Pipeline. As a result, the pipeline was shut down, and isolation valves were commanded closed (United States Department of Transportation [USDOT], 2023). The EPA recommended building an earthen dam to contain the spill. Clean-up efforts and reopening of the pipeline were time-sensitive. According to TC Energy, the spill cost about $480 million in clean-up efforts (TC Energy, 2023).

Monitoring of benzene and aromatic hydrocarbons in soil is of critical importance during emergencies and oil spills to avoid huge financial losses. The EPA has developed various methods for analysis of volatile organic compounds (VOC) in solid and liquid matrices, including soil. Methods 5021, 8021, and 8260 involve headspace sampling and gas chromatography analysis with an applicable concentration range between 0.1 and 200 µg/L (EPA, 2017; Zhao and Kira, 2017). Despite the robustness and low limits of detection, offsite analysis of samples has certain disadvantages. The normal procedure requires the collection of samples onsite and analysis of the samples offsite in a laboratory. This includes sample transportation, storage, and handling at specific conditions, such as cooling and longer sample preparation before analysis. In addition, recovery of target analytes may decrease over time due to volatility and degradation in the sample matrix.

In addition to offsite laboratory analysis, alternative methods for screening of VOCs in soil are also available. Hand-held photoionization detectors (PID) are often employed to measure VOC concentrations in water or soil (RAE Systems, 2005). Hewitt and Lukash (1999) reported a linear correlation when studying the headspace PID response of benzene, toluene, xylenes, dichloroethylenes, trichloroethylene, and perchloroethylene concentrations in soil samples with concentrations between 0.2 and 10 mg VOC/kg. Hand-held PIDs nowadays can detect VOCs at parts per billion (ppb) levels while also being capable of direct benzene measurements with pre-filter tubes (Draeger, n.d; Honeywell, 2004). Conventional benzene detector tubes could also be used to report benzene levels. However, both methods present challenges and do not provide as accurate results as field-portable and benchtop gas chromatographs.

During the last decades, a new segment has emerged in the field of analytical chemistry with the availability of portable gas chromatographs capable of analyzing samples onsite, straight after collection with little or no sample preparation (EPA, 1998; Soo et al., 2018). Portable gas chromatographs are equipped with PIDs, electron capture detectors (ECD), or even mass selective detectors (MSD). PIDs and ECDs are beneficial for portable applications due to their compact size, high sensitivity, and selectivity. Moreover, such detectors do not require auxiliary gases, e.g., hydrogen, nitrogen, or air to operate.

Photovac Voyager (Waltham, MI) is a field-portable, computer-controlled gas chromatograph that incorporates three columns and dual detectors, a PID, and an ECD to achieve broadened analytical capabilities (EPA, 1998). This instrument was developed with consideration of ergonomic and analytical performance demands in field environments. Photovac Voyager has a unique internal analytical engine that includes a specially designed miniature stainless steel valve array to provide fast sample delivery and minimize sample carryover and contamination caused by high VOC concentrations. The instrument also incorporates a unique triple-column arrangement, with pre-column and backflush, a port with a pump

for direct air sampling, and a syringe injection port for headspace sampling of aqueous and soil extract media. Ultra-pure air or nitrogen (99.999%) can be used as a carrier gas. Columns A, B, and C are intended for analysis of heavy (C7 to C12), midrange (C4 to C7), and light (C1 to C3) hydrocarbon compounds, respectively. The internal sampling train, sample loop, GC columns, valves, and injection port are heated isothermally at temperatures from 55 to 80°C. The Voyager is also unique being classified as intrinsically safe (Class 1, Division I, Groups A, B, C, and D), rendering it useful in hazardous locations. The Voyager can be effectively used to monitor many of the VOCs listed in EPA Method 8260D (EPA, 2017), including chlorinated and aromatic hydrocarbons. Sample matrices of applicability include soil, soil gas, water, and ambient air. The MDLs for VOCs range from parts per trillion (ppt) in water (ng/L) to about 500 parts per million (ppm) in ambient air, depending upon the type of compound and detector used. The use of robust columns and a photoionization detector give the instrument an additional advantage for large-volume gaseous samples, even with the presence of water vapors from headspace or ambient air.

An analysis of VOCs in aqueous and soil samples has been extensively studied, with results meeting or exceeding the requirements outlined in the abovementioned EPA methods. Some of the studies (EPA, 1998; Zhang, 2019; Soo et al., 2018) point out the challenges in separating two of the xylene isomers, specifically m-, and p-xylene. The use of polar columns, for example, polyethylene glycol (PEG) stationary phase column, also known as WAX column, provides good separation between the components in the BTEX mixture despite the increase of the peak width for high boiling compounds.

This study focuses on developing a rapid procedure for the analysis of BTEX compounds in soil samples using a portable gas chromatograph with a photoionization detector. The soil samples are dissolved in purified water, and after an equilibrium is reached in the vial, a headspace sample is introduced into the system for analysis. The obtained results can be viewed on the instrument screen and transferred to a computer for further data processing.

2. Methods

2.1 Chemicals and Standards

A certified mixture of BTEX, including benzene, toluene, ethylbenzene, p-xylene, m-xylene, and o-xylene with concentrations of analytes 2,000 µg/mL in methanol was obtained from Restek (Bellefonte, PA) to prepare calibration standards in step dilutions. Fluorobenzene, 2,000 µg/mL in methanol, used as an internal standard, was also obtained from Restek. Analytical grade methanol (≥99.9%) was purchased from Sigma-Aldrich (St. Louis, MO), and ultrapure water (MilliporeSigma, Rockville, Maryland) was used for sample preparation.

Calibration standards were prepared from stock standards with dilution in methanol, resulting in final concentrations in sample vials of 10, 20, 50, 100, and 200 µg/L for the BTEX mixture and 100 µg/L for fluorobenzene at all calibration levels.

Three types of soil matrices were used in the study, including sand, farmland soil, and clay. The soils were air-dried and passed through no. 18 soil sieve (diameter <0.991 mm) but retained on a no. 120 soil sieve (diameter >0.125 mm). Glass beads with similar size were added to blank and calibration samples to compensate for volume change in the sample vials. All matrices were analyzed for interfering compounds prior to experiments.

2.2 Sample Preparation

The sample procedure was as follows: certified pre-cleaned 40-mL vials were filled with 10 mL of deionized water. Two grams of solid samples, e.g., glass beads or soil, were added to the vials followed by spiking with 100 µL stock standard of BTEX solution and 50 µL of internal standard. The vials were sealed immediately and shaken for two minutes.

After that, the vials were equilibrated at room temperature (25°C) for 30 minutes. Samples (200 µL) were withdrawn manually with a gas-tight syringe penetrating through the septum of the vial cap and inserted straight into the injection port of the gas chromatography system.

2.3 Sample Analysis

A portable gas chromatograph (GC) with a PID and Photovac Voyager (Waltham, MI) was selected as an instrument to analyze the samples containing aromatic hydrocarbons. The design allows the instrument to be carried on site and analyze samples straight after collection or requires little sample preparation. The portable GC can be deployed and reach equilibrium within one hour (EPA, 1998). The selection of PID has many benefits for this application, including compact size, no need for auxiliary or makeup gases, wide linear range, and selectivity based on the ionization potential of the analytes. Although the instrument can operate with pure air or nitrogen (99.999%) as a carrier gas, nitrogen was selected due to improved peak shape and resolution. Voyager SiteChart LX Version 1.23 software was used to transfer and integrate the results of the analysis, and Microsoft Excel was used to further process the obtained data.

2.4 Method Optimization

During the method development, different parameters were optimized to improve the resolution of target compounds and reduce the time of analysis, including carrier gas pressure and column temperature. Initially, samples were analyzed on both A and B columns to determine the presence of co-eluting peaks of the target analytes due to different stationary phases and elution order of compounds. It was found that the compounds of interest have well-separated peaks without interferences on Column B (20m x 0.32mm x 1.0µm, Supelcowax10). The carrier gas pressure was set to 10 psi with a column temperature of 60°C and a total run time of 10 minutes without sacrificing peak resolution. Detailed information on the analytical parameters is presented in Table 1. The injection volume was also optimized, and it was found that the best reproducibility was achieved at 200 µL, compared to injection volumes between 100 and 500 µL. The presence of traces of methanol in the samples from the spiking with calibration solutions did not have an observable effect on the early eluting compounds, e.g., benzene. This can be explained by the high value of the partition coefficient (K) of methanol in aqueous solution. Furthermore, the UV lamp used in the PID with an intensity of 10.6 eV has a low affinity to methanol with an ionization potential of 10.85 eV (Rae Systems, 2005).

Table 1. Analytical Parameters of Photovac Voyager

Gas Chromatograph	
Injection Type	Manual injection, 1 mL gastight syringe, 200 µL sample
Carrier Gas	Nitrogen (99.999%)
Analytical Column	20m x 0.32mm x 1.0µm, Supelcowax10
Column Temperature	60°C
Column Pressure	10 psi
Run Time	600 seconds
Photoionization Detector	
Detector Temperature	60°C
Offset, mV	250-350
Tune, V	2.600
Detector Sensitivity	High

3. Results

A typical chromatogram of the analysis of BTEX mixture with fluorobenzene as an internal standard demonstrating the elution of compounds and separation of peaks is depicted in Fig. 1. The results of analysis for linearity, precision (%RSD), method limits of detection (LODs), and limits of quantitation (LOQs) are presented in Table 2. The linearity was determined from a five-point calibration between 10 µg/L and 200 µg/L with an internal standard concentration of 100 µg/L. The analysis of the target compounds demonstrated good linearity, with coefficients of the linear regression R2 exceeding 0.995. The precision was measured by analysis of six replicate samples at 50 µg/L and 100 µg/L. Based on the results, the relative standard deviations for all six compounds were in the range between 8% and 10% at 50 µg/L and between 0.4% and 1.7% at 100 µg/L, thus demonstrating excellent quantitation precision. The limits of detection and limits of quantitation were calculated from seven replicate samples at a concentration of 10 µg/L. It was determined that the detection limits were between 0.5 and 2.0 µg/L, which translated into quantitation limits between 1.8 and 7.1 µg/L. Furthermore, samples with concentrations of the target compounds at 2 µg/L, corresponding to 10 µg/kg in soil, were analyzed to verify the limits of quantitation. The results confirmed that all six analytes were detected and quantitated at the expected quantitation limits.

Figure 1. Chromatogram of BTEX Analysis and Fluorobenzene with Concentration of 100 µg/L on Column B.

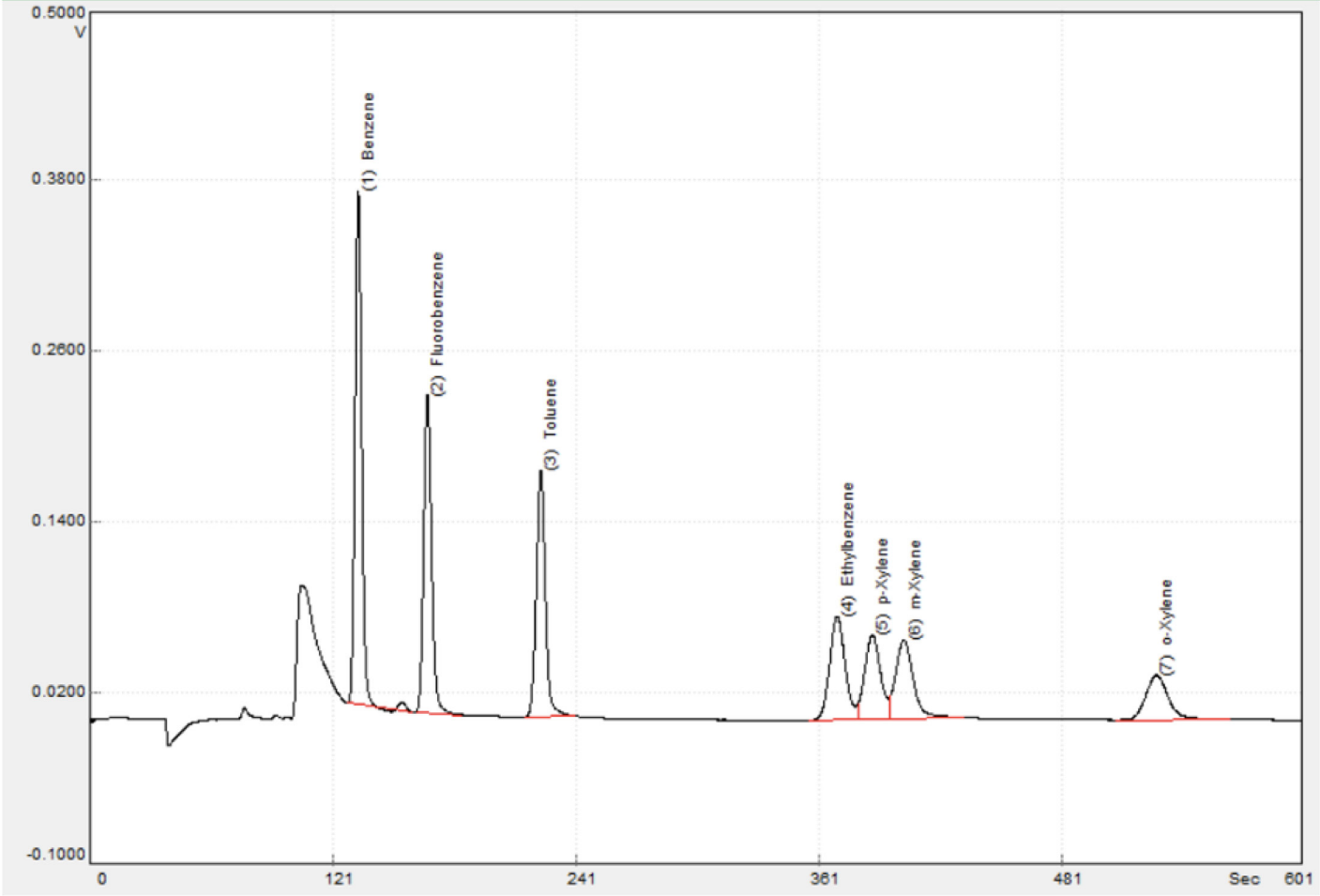

Table 2. Summary of Results for Linearity, Precision, Limit of Detection, and Limit of Quantitation

Compound	Retention Time, seconds	Linearity		RSD, %		LOD, µg/L	LOQ, µg/L
		Calibration Curve	Correlation, R2	50 µg/L	100 µg/L		
Benzene	132.0	y = 1.289x – 0.0241	0.9956	8.53	0.59	0.54	1.79
Toluene	222.0	y = 0.837x + 0.0081	0.9953	8.80	0.44	2.14	7.12
Ethylbenzene	368.3	y = 0.62x – 0.0114	0.9967	9.32	1.34	1.26	4.20
p-Xylene	385.7	y = 0.536x – 0.0162	0.997	9.00	1.35	1.31	4.35
m-Xylene	401.3	y = 0.546x – 0.0173	0.9972	8.94	1.71	1.47	4.88
o-Xylene	526	y = 0.384x – 0.0014	0.9955	9.27	1.29	1.4	4.65

The recoveries of the analytes were determined by analyzing six replicate samples at 50 µg/L and 100 µg/L in three different solid matrices: sand, farmland soil, and clay. The results of the analysis are presented in Table 3. The recovery varied from 74% to 99% for sand, 87% to 112% for soil, and 91% to 123% for clay.

Table 3. Summary of Results for Recovery

Compound	Sand		Soil		Clay	
	50 µg/L	100 µg/L	50 µg/L	100 µg/L	50 µg/L	100 µg/L
Benzene	98.72	82.99	105.19	100.70	119.95	98.50
Toluene	93.01	77.05	102.26	91.92	114.15	94.04
Ethylbenzene	91.30	77.14	105.01	93.41	119.77	93.39
p-Xylene	89.50	75.59	105.07	90.37	118.98	93.71
m-Xylene	88.77	74.23	103.44	87.45	116.32	91.05
o-Xylene	92.75	80.58	112.66	93.68	123.06	95.24

4. Discussion

In this study, various analytical parameters were optimized towards peak resolution, peak shape, and run time of the instrument. Co-elution of compounds in the BTEX mixture, more specifically p- and m-xylene, were reported in multiple studies (EPA, 1998; Soo et al., 2018). The selected instrument has three analytical columns, including a polar and a PEG capillary column reported to separate the isomers of xylene. To achieve a good separation between the peaks of p- and m-xylene, nitrogen was selected instead of oxygen as a carrier gas. Column temperature and pressure were optimized to achieve good separation between the peaks. It was found that good analytical conditions are met at a column temperature of 60°C and pressure at 10 psi, maintained throughout the analysis. All analytes in the mixture elute within 600 seconds (10 minutes) at the selected conditions. No co-eluting peaks were registered from the selected solid matrices. In addition, maintaining the temperature of the detector at 60°C improves the peak shapes. Although no late eluting compounds were detected in the samples, in case of less volatile components present in solid samples, the runtime of the instrument can be extended to 3200 seconds. The addition of fluorobenzene to the BTEX mixture improved the calibration and precision of the results.

The headspace sampling procedure was also optimized in relation to the amount of water added to the vials and injection volume of samples in the instrument. Vials with a volume of 40 mL were selected to facilitate the handling of solid samples, considering the procedure is applied onsite. Different volumes of ultrapure water, between 10 and 20 mL, were added to the vials to study detector response and repeatability. It was found that adding 10 mL of water provides

better response of the detector compared to samples with 20 mL of water. In addition, increasing the headspace allows for larger volume injections in the system for analysis. The volume of injected samples was also optimized. The experiments demonstrated that injection volume of 200 µL provided excellent results for calibration and repeatability.

The presence of traces of methanol in the samples from the spiking solutions did not interfere with elution of peaks, especially benzene, the first eluting compound in the mixture. This can be explained by the high partition coefficient of methanol. Moreover, the photoionization detector has low affinity to methanol due to higher ionization potential.

The results of the analysis demonstrated that the selected instrument is capable of separating, detecting, and quantifying all six components in the BTEX mixture. The achieved linearity was above 0.995, precision below 10%, recovery within 25%, and detection limits in the single range parts per trillion (ppt). The detection limits can be further improved by reaching headspace equilibrium at elevated temperatures, using heating blocks for the sample vials, although this would require use of additional equipment. The injection volume can be also increased to 500 µL or even larger volumes. The recoveries for the selected solid matrices did not represent a significant drop in the response at the selected spike concentrations. This can be attributed to the short time between spiking and analysis.

This short study has certain limitations. The study involved specific portable gas chromatograph with analysis conducted at a constant column temperature and pressure. Portable gas chromatographs vary in parameters, including temperatures of column and detector, column stationary phase, detector sensitivity, and sample introduction in the system. Although a direct comparison between instruments from different manufacturers is not always possible, optimized method parameters from this study can be tested and transferred to other systems. Sample preparation and analysis were conducted in an offsite laboratory with maintained temperature and relative humidity. Nevertheless, preparation of samples is pretty straightforward and requires only basic analytical equipment, readily available in mobile and field laboratories. The study was also limited to three types of solid matrices. Further study of different soils can be beneficial to evaluate the recoveries of analytes depending on the matrix.

5. Conclusion

This procedure for rapid screening can provide valuable results for the presence of specific VOCs in solid samples straight onsite with limited time for instrument equilibration and sample preparation. It has to be noted that the instrument is intrinsically safe and can operate without power and carrier gas supply for 6 to 8 hours using a battery pack and built-in cylinder. The procedure can be applied successfully in emergency response clean-up operations and environmental remediation. The advantages of this approach include a simplified sample preparation procedure (compared to laborious analytical methods), analysis of samples onsite without the need to transport samples, short duration between sampling and reporting results, and low cost. These types of instruments can also be used to aid onsite exposure monitoring of the personnel involved in sampling and excavation of soils.

Despite the limitations of this study, the results provide relevant information on the preparation and analysis of solid sample matrices containing aromatic hydrocarbons using portable chromatography with photoionization detection. The results of the analysis are similar to the expected lower limits of quantitation, as outlined in EPA Method 8021—approximately 1 µg/kg for soil/sediment samples and 1 µg/L for groundwater. In addition, samples prepared and analyzed onsite can yield higher recoveries due to the short time between sample collection and analysis, thus overcoming losses in offsite analysis due to sample transportation, storage, matrix effects, and handling.

6. Recommendations

Although this study covers the use of a single instrument, sample preparation in an offsite laboratory, and selection of three types of solid samples, the results demonstrate that portable gas chromatographs can be utilized and successfully used in the field for emergency response and remediation cleanup operations in the screening of contaminated soil for VOCs. Such instruments are available in different configurations, including mass selective detection to provide relevant information on the type of contaminants and levels of contamination in low parts per billion concentrations. The procedure can also be applied for routine screening of underground storage tanks or pipelines to detect early leakage and contamination of soil and groundwater.

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Enhancing OSH Performance: The Impact of ISO 45001

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Abstract

This study investigates the impact of certification to the ISO 45001 standard, an occupational health and safety management system (OHSMS), on safety performance in organizations. Utilizing a mixed-methods approach, the research combines analysis of environmental, social, and governance (ESG) data from 100 organizations and the data acquired from survey responses from 151 participants. Results indicate that certified organizations demonstrated superior lagging indicator safety performance, including lower total recordable injury frequency rates (TRIFR), lost time injury frequency rates (LTIFR), and fewer workplace fatalities compared to non-certified organizations. The survey findings support these results, with participants acknowledging the positive aspects of certification, such as reputation enhancement and improved safety outcomes, while also highlighting concerns regarding initial investment and ongoing costs. The study contributes empirical evidence supporting the effectiveness of ISO 45001 certification in enhancing safety performance and underscores the importance of adopting certified OHSMS to ensure employee safety, well-being, and organizational resilience in managing occupational health and safety risks.

KEY WORDS: *ISO 45001, occupational safety and health, safety performance, certification, workplace fatalities*

1. Introduction

Ensuring the health and safety of employees in the workplace is paramount for organizations striving for sustainability and success. The implementation of effective OHSMS plays a crucial role in mitigating risks and fostering a safe working environment. Over the last several years, certification to standards such as ISO 45001 (2018) has gained prominence as a means to formalize and improve occupational health and safety practices within organizations. However, the extent to which achieving certification to ISO 45001 influences safety performance remains a subject of debate and investigation.

The primary objective of this study is to explore the impact of ISO 45001 certification on safety performance in organizations. In order to achieve this, the author employed a comprehensive research approach, combining analysis of ESG reports from 100 large, global organizations obtained from the Global Reporting Initiative (2020) and using the survey response data gathered from 151 anonymous participants. By examining both quantitative metrics and qualitative feedback, the author aimed to provide a holistic understanding of the relationship between ISO 45001 certification and safety performance.

Previous research has highlighted the benefits of OHSMS certification on safety outcomes. Studies by Abad et al. (2013), Ghahramani and Salminen (2019), and Kim et al. (2019) have demonstrated a positive correlation between OHSMS certification and improved safety performance metrics, such as reduced injury rates and fewer workplace fatalities.

Similarly, Fernández-Muñiz et al. (2009) and Mohammadfam et al. (2017) found that organizations with a certified OHSMS exhibited better overall organizational safety performance.

ISO 45001 (2018), the latest international standard for OHSMS, aims to provide a framework for organizations to proactively manage occupational health and safety risks. With the standard's focus on continuous improvement and worker participation, ISO 45001 emphasizes a systematic approach to hazard identification, risk assessment, and mitigation strategies. Organizations seeking to achieve certification to ISO 45001 are required to undergo a rigorous audit and assessment process to ensure compliance with the standard's requirements. The significance of ISO 45001 lies not only in enabling an organization to achieve regulatory compliance but also in its potential to enhance organizational reputation and competitiveness. Santos et al. (2013) highlighted the positive association between achieving OHSMS certification and an improved organizational image, leading to increased stakeholder trust and market advantage. Furthermore, achieving and maintaining certification to ISO 45001 enables organizations to demonstrate their commitment to worker safety and well-being (both physical and psychological) and societal responsibility, aligned with the 17 United Nations global sustainability goals.

Despite the perceived benefits of achieving certification to ISO 45001, concerns regarding the initial investment and ongoing costs associated with implementation remain prevalent. Bevilacqua et al. (2016) underscored the importance of understanding the financial implications of OHSMS implementation, urging organizations to weigh the costs against the potential benefits.

In this context, our study seeks to address the following research questions.

1. Does certification to ISO 45001 lead to better safety performance in organizations compared to non-certified organizations?
2. What are the perceived positive and negative impacts of ISO 45001 certification on an organization's occupational health and safety management systems?

By examining these questions, we aim to provide empirical evidence to enable more informed organizational decision-making regarding ISO 45001 certification and its implications on safety performance.

2. Literature Review

An organization's OHS and management systems play a crucial role in safeguarding employees' safety and well-being and mitigating workplace hazards and risks. This literature review examines existing research on the impact of the ISO 45001 certification on safety performance and explores the perceived benefits and challenges associated with implementing certified OHS management systems.

2.1 ISO 45001 Certification and Safety Performance

Abad et al. (2013) conducted a study evaluating the Occupational Health and Safety Assessment Series (OHSAS) 18001 certification process' objective drivers and its consequences on safety performance and labor productivity. Their findings suggested that organizations certified to OHSAS 18001, a predecessor of ISO 45001, exhibited better safety performance compared to non-certified organizations. This conclusion is consistent with the results obtained from the analysis of ESG data in the present study, which revealed a significant difference in safety performance metrics between certified and non-certified organizations.

Moreover, Ghahramani and Salminen (2019) evaluated the effectiveness of OHSAS 18001 on safety performance in

manufacturing companies in Iran. Their research demonstrated a positive correlation between the OHSAS 18001 certification and improved safety performance indicators, supporting the argument for implementing certified OHSMS. These findings align with the survey responses collected in the current study where the majority of participants believed that organizations certified to ISO 45001 would have better safety performance than non-certified organizations.

2.2 Benefits of ISO 45001 Certification

The benefits associated with the ISO 45001 certification extend beyond safety performance. Santos et al. (2013) explored the advantages of health and safety management systems certification in Portuguese small and medium enterprises post ISO 9001 certification. They found that certification positively impacted organizational practices, employee morale, and customer satisfaction. Similarly, Bevilacqua et al. (2016) highlighted the successful implementation of OHSAS 18001 in the Italian context, emphasizing its role in enhancing risk management practices and organizational resilience.

In line with these findings, the survey conducted as part of the present study identified several perceived positive aspects of achieving ISO 45001, including enhanced organizational reputation, increased competitiveness in tendering processes, and improved safety performance. These findings underscore the multifaceted benefits of certified OHSMS and provide insights into the strategic advantages for businesses seeking certification.

2.3 Challenges of ISO 45001 Certification

While the benefits of ISO 45001 are evident, organizations may encounter challenges during the certification process. Karapetrovic and Casadesús (2009) examined the implementation of environmental management systems alongside other standardized management systems, highlighting the complexities of integration and coordination. Similarly, the survey responses obtained in the current study identified several perceived negative aspects of working towards, achieving, and maintaining ISO 45001. These included the initial investment required, ongoing certification costs, and the time-consuming nature of the certification process.

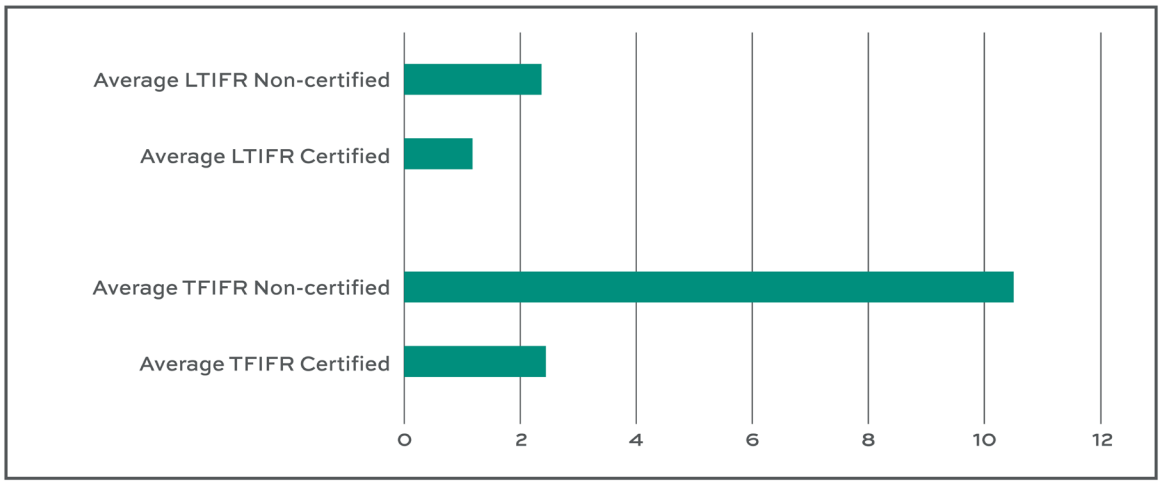
These challenges underscore the importance of strategic planning and resource allocation to facilitate a smooth transition to ISO 45001. Organizations must weigh the potential benefits against the associated costs and consider long-term sustainability in their decision-making processes.

The literature review highlights the significant role that ISO 45001 can play in enhancing safety performance and organizational practices. Studies examining the impact of certified OHSMS consistently demonstrate improvements in safety performance and organizational resilience. Whilst challenges exist in the certification process, the overall benefits outweigh the associated costs, positioning ISO 45001 as a valuable investment in organizational health and safety.

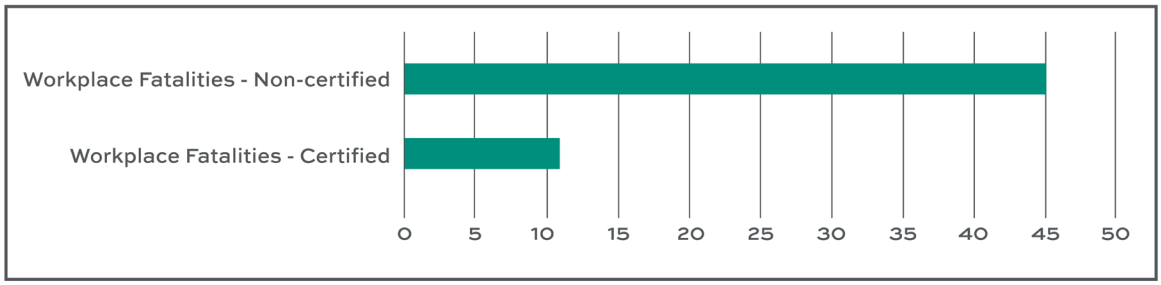
The results of the research study provided insights into the safety performance of organizations certified to ISO 45001 compared to those organizations who were non-certified, as well as the perceived positive and negative aspects of achieving certification to standards such as ISO 45001.

2.4 Safety Performance

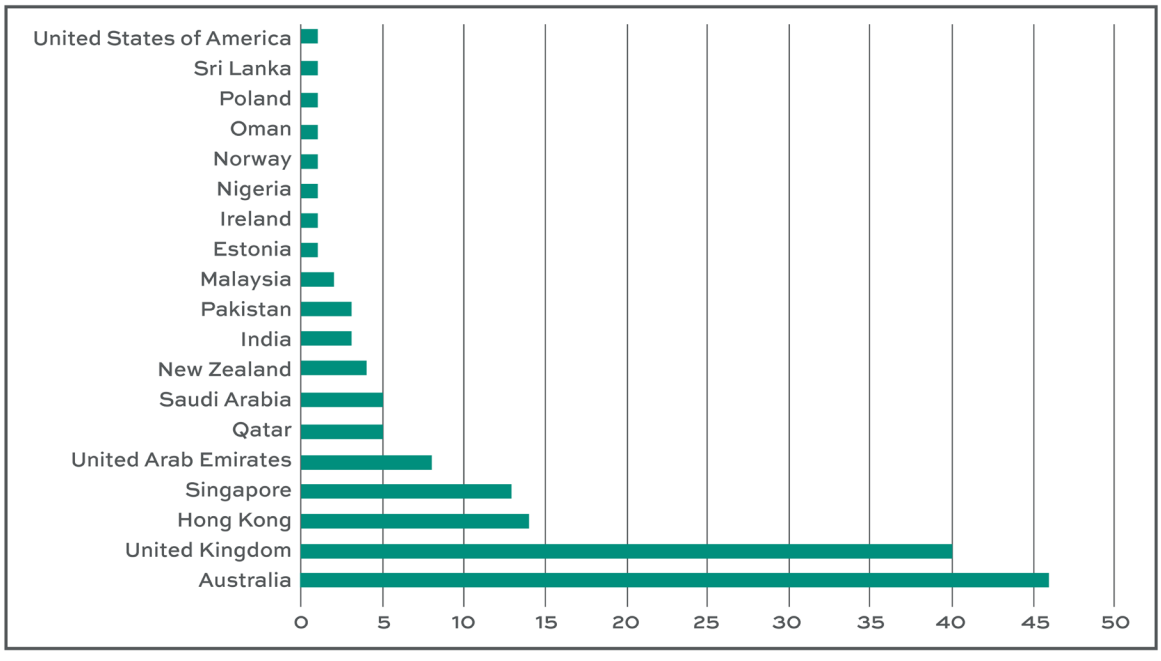
An analysis of the ESG data from 100 organizations revealed significant differences in safety performance between certified and non-certified organizations. Certified organizations reported lower TRIFR and LTIFR compared to non-certified organizations (Fig. 1). Specifically, certified organizations recorded an average TRIFR of 2.29 per 1,000,000 hours, while non-certified organizations reported an average TRIFR of 10.4 per 1,000,000 hours. Certified organizations recorded an average LTIFR of 1.16 per 1,000,000 hours, whereas non-certified organizations reported an average LTIFR of 2.21 per 1,000,000 hours.



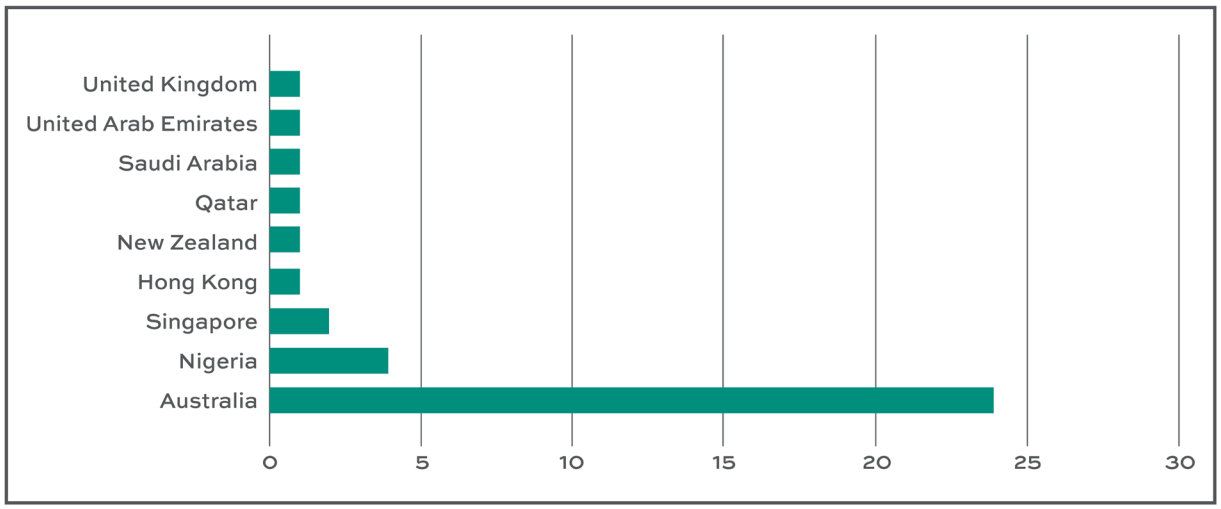
The collected ESG workplace fatality data revealed that certified organizations reported fewer workplace fatalities compared to non-certified organizations (Fig. 2). Organizations certified to standards such as the old OHSAS 18001 or the new ISO 45001 recorded 11 workplace fatalities, whereas non-certified organizations reported 45 workplace fatalities.



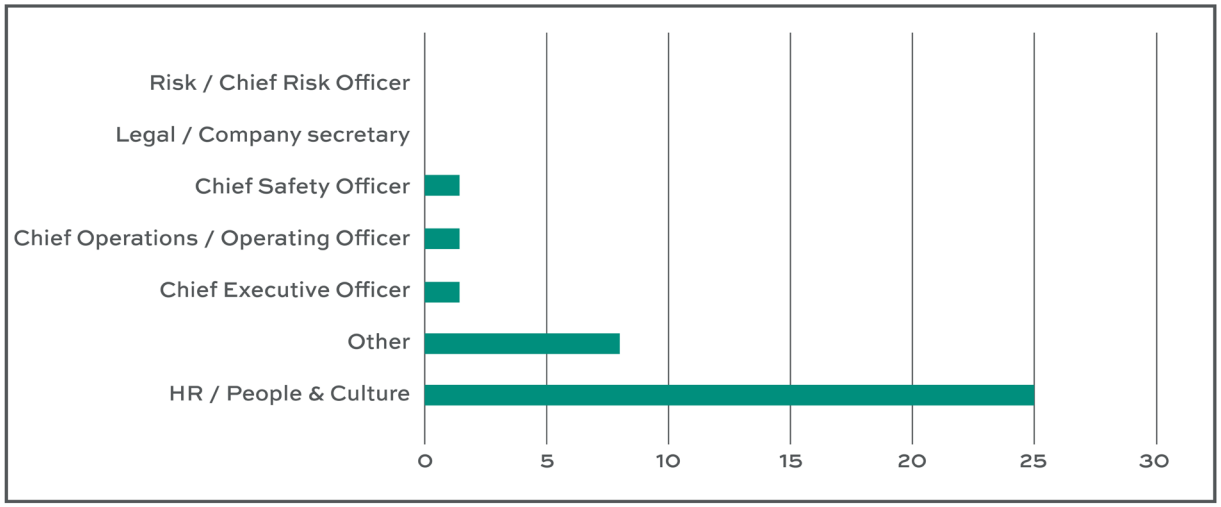
Analysis of the data revealed notable disparities in workplace fatality rates across different industries and countries. Thirty percent of survey respondents reported being based in Australia, while 26% came from the United Kingdom. Hong Kong and Singapore accounted for 18% of respondents, and the remaining 26% of respondents came from other countries (Fig. 3).



Among the industries surveyed, construction emerged as the sector with the highest incidence of workplace fatalities, followed closely by manufacturing and transportation. A noteworthy contrast was observed between countries, with Australia reporting significantly higher levels of workplace fatalities compared to the United Kingdom (Fig. 4). This discrepancy underscores the importance of considering regional and sector-specific factors when assessing safety performance and implementing preventative measures. The findings highlight the need for targeted interventions and regulatory measures tailored to specific industries and geographical regions to address the underlying causes of workplace fatalities effectively. Further research into the underlying factors contributing to these disparities could provide valuable insights for policymakers and safety practitioners aiming to improve occupational safety outcomes globally.

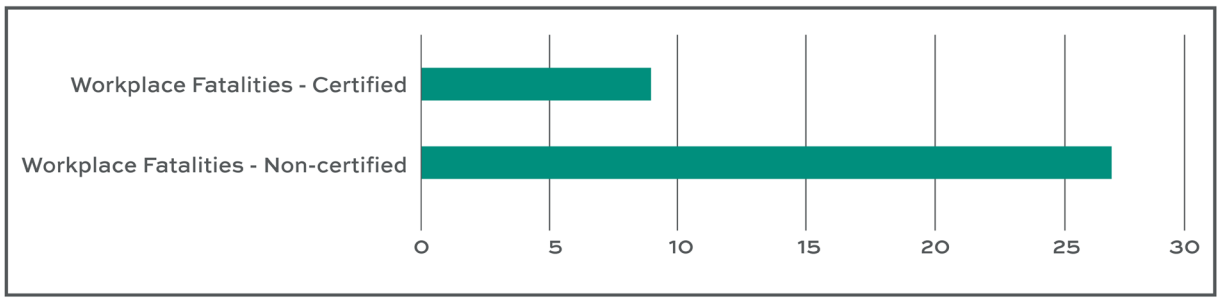


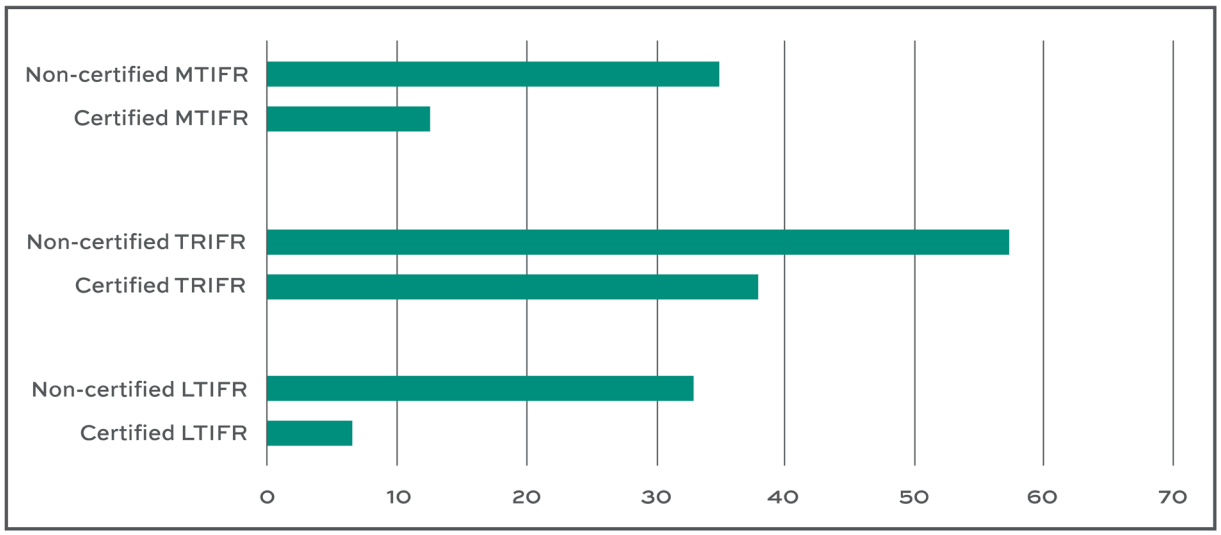
Furthermore, an intriguing observation emerged from the analysis of the survey data, revealing a correlation between the reporting lines for occupational safety and health (OSH) functions and workplace fatality rates. Organizations where the OSH reporting structure was integrated within the Human Resources (HR) department or had OSH reporting directly to a chief human resources officer or chief people officer exhibited a higher level of workplace fatalities compared to those with alternative reporting structures (Fig. 5).



This finding underscores the importance of exploring the organizational dynamics and communication channels within companies concerning safety management. Further research into the underlying reasons for this trend could provide valuable insights into how organizational structures impact safety performance and inform strategies to mitigate workplace risks effectively.

The survey questionnaire, completed by 151 respondents, provided additional insights into safety performance. Of the respondents, 91 believed that organizations certified to ISO 45001 have better safety performance than non-certified organizations. This perception was supported by the survey data, which showed that certified organizations were exposed to fewer workplace fatalities than non-certified organizations (Fig. 6) and that certified organizations outperformed non-certified organizations (Fig. 7) across various safety performance metrics, including LTIFR, TRIFR, and medically treated incident frequency rates (MTIFR).





2.5 Perceived Positive and Negative Aspects of Certification

The survey responses also shed light on the perceived positive and negative aspects of achieving certification to standards such as ISO 45001. Among the positive aspects, respondents identified enhanced organizational reputation, increased opportunities for tendering or winning additional work, and improved safety performance as some of the key benefits of achieving ISO 45001. These findings align with previous research, highlighting the strategic advantages of certified OHSMS in improving organizational practices and competitiveness.

However, respondents also identified several challenges associated with certification, including the initial investment required in terms of time, money, effort, ongoing certification costs, and the time-consuming nature of the certification process. Despite these challenges, the overall sentiment among respondents favored certification, with more positive aspects identified compared to negative impacts.

The results of the research study confirm the hypothesis that organizations certified to ISO 45001 have better safety performance than non-certified organizations. Analysis of ESG data and survey responses consistently demonstrated lower incident rates and workplace fatalities among certified organizations, supporting the strategic benefits of implementing certified OHSMS.

Moreover, the perceived positive aspects of certification, including enhanced reputation and improved safety performance, outweigh the identified challenges, indicating a strong case for businesses to consider working towards and achieving certification to ISO 45001. However, further research is recommended to explore the long-term impacts of certification and address existing challenges to facilitate informed decision-making among organizations.

3. Materials and Methodology

This study adopts a mixed-methods approach to investigate the impact of ISO 45001 on safety performance in organizations. The methodology comprises two main components: analysis of ESG data from 100 large global organizations obtained from the Global Reporting Initiative (2020) and a survey administered to 151 participants to gather qualitative insights. The combination of quantitative analysis and qualitative feedback allows for a comprehensive understanding of the relationship between ISO 45001 certification and safety performance.

3.1 Analysis of ESG Data

- ESG reports and the data included within them from 100 large global organizations were reviewed to assess safety performance.
- The analyzed ESG data included reported lag indication data on TRIFR, LTIFR, Recordable Incident Rates (RIR), and days away, restricted, or transferred (DART) rates.
- Workplace fatality data from certified and non-certified organizations were compared to evaluate the impact of ISO 45001 on reducing fatalities.
- Statistical analysis was conducted to determine significant differences in safety performance between certified and non-certified businesses.

3.2 Survey Questionnaire

- A survey questionnaire was developed to gather qualitative insights from participants regarding the perceived positive and negative impacts of ISO 45001 certification.
- The questionnaire comprised structured questions addressing various aspects of ISO 45001 certification, including its influence on safety performance, organizational reputation, risk management, and financial considerations.
- The questions asked of the participants were as follows:
    1. Please select your gender.
    2. What is your age demographic?
    3. What is your job title?
    4. Within your business/organization, what department does health and safety report into?
    5. What country are you based in?
    6. In what industry does your business/organization primarily operate?
    7. How does your business/organization record its LTIFR, MTIFR, and TRIFR data, e.g., per 100,000 hrs, per 200,000 hrs, etc.?
    8. What is your business/organizations LTIFR for the last 12 months?
    9. What is your business/organizations TRIFR for the last 12 months?
    10. What is your business/organizations MTIFR for the last 12 months?
    11. In the last 12 months, how many workplace fatalities has your business/orginization had?
    12. Does your business/organization hold ISO 45001:2018 certification?
    13. In your opinion, what are the benefits of a certified OHSMS such as ISO 45001?
    14. In your opinion, what are the negative impacts of operating a certified OHSMS such as ISO 45001?
    15. In your opinion, do you believe that a business/organization that holds a management system certification such as ISO 45001 would have a better safety performance than those who are not certified?

Participants were selected using purposive sampling, targeting individuals with knowledge and experience in occupational health and safety management. Survey responses were collected electronically, ensuring anonymity and confidentiality. Data analysis involved thematic analysis to identify recurring themes and patterns in participants' responses. Descriptive statistics were used to summarize survey findings and identify predominant perceptions regarding ISO 45001 certification.

3.3 Integration of Data

- The findings from the analysis of ESG data and survey responses were integrated to provide a comprehensive assessment of the impact of ISO 45001 certification on safety performance.
- Triangulation of data sources allowed for validation and cross-referencing of results, enhancing the reliability and validity of the authors' findings.
- Comparative analysis was conducted to identify consistency or any discrepancies between quantitative safety performance metrics and qualitative perceptions of ISO 45001 certification.

3.4 Ethical Considerations

- Ethical approval was obtained from the relevant institutional review board to ensure compliance with ethical guidelines for research involving human participants.
- Informed consent was obtained from all survey participants prior to their participation in the study, and measures were implemented to safeguard their anonymity and confidentiality.
- Data handling and storage procedures adhered to data protection regulations to prevent unauthorized access or disclosure.

3.5 Limitations

- The study's reliance on ESG data may be subject to limitations inherent in the reporting accuracy and consistency of the data sources.
- The survey questionnaire's self-reported nature may introduce response bias or social desirability bias, affecting the reliability of the qualitative findings.
- The generalizability of the study findings may be limited by the specific industry sectors and geographic regions represented in the sample.
- While the survey data was collected via Google form and the survey was posted on LinkedIn, the author acknowledges there could be a bias in the collection methodology in the selection criteria.

Despite these limitations, the mixed-methods approach employed in this study offers valuable insights into the impact of ISO 45001 certification on safety performance in organizations, contributing to the body of knowledge on occupational health and safety management systems

4. Discussion

The results of the research study corroborate previous findings that businesses certified to OHSMS standards, such as ISO 45001, exhibit better safety performance compared to non-certified organizations. The significant differences in safety performance metrics, including TRIFR, LTIFR, and workplace fatality rates, highlight the effectiveness of certification in mitigating occupational hazards and promoting a safer work environment. This finding aligns with studies by Abad et al. (2013), Ghahramani and Salminen (2019), and Yoon et al. (2013), which have reported similar trends in safety performance improvement following OHSMS certification.

Certified organizations reported lower incident rates and fewer workplace fatalities, indicating the tangible benefits of implementing a structured OHSMS framework. The positive correlation between certification status and safety performance highlights the importance of organizational commitment to safety, proactive risk management practices, and compliance with regulatory requirements. Moreover, the survey responses affirm the perceived value of certification among stakeholders, with the majority of respondents recognizing the strategic advantages of ISO 45001 in enhancing organizational reputation and competitive positioning.

4.1 Perceived Benefits and Challenges of Certification

While the research findings suggest clear advantages associated with OHSMS certification, it is essential to acknowledge the challenges and limitations inherent in the certification process. The survey responses identified several barriers to certification, including the initial investment required in terms of time, financial resources, and organizational commitment. These findings echo the research by Karapetrovic and Casadesús (2009) and Bevilacqua et al. (2016), which have highlighted the resource-intensive nature of implementing and maintaining OHSMS certification.

Despite these challenges, the perceived benefits of certification outweigh the identified drawbacks, indicating a positive impact on organizational performance and a positive safety environment within an organization. The enhanced reputation, improved stakeholder confidence, and access to new business opportunities associated with certification provide compelling incentives for organizations to pursue ISO 45001. The alignment of OHSMS certification with broader quality and environmental management systems underscores the synergistic benefits of integrated management approaches, as noted by Santos et al. (2013) and Ramos et al. (2020).

4.2 Limitations and Future Research Directions

While the research study provides valuable insights into the relationship between OHSMS certification and safety performance, several limitations should be considered. First, the reliance on secondary ESG data and self-reported survey responses may introduce bias and inaccuracies in the analysis. Future research should incorporate more robust methodologies, such as longitudinal studies and randomized controlled trials to validate the findings and assess the long-term impacts of certification.

Additionally, the research focused primarily on quantitative measures of safety performance, overlooking qualitative aspects such as safety culture, employee engagement, and leadership commitment. Future studies should adopt a more holistic approach to evaluate the multifaceted dimensions of safety management and explore the interactions between organizational factors and safety outcomes.

The generalizability of the findings may be limited by the sample size and industry-specific characteristics of the organizations included in the study. Future research should aim to replicate the study across diverse sectors and geographical regions to enhance the external validity of the findings and identify sector-specific challenges and opportunities.

Finally, while the survey data was collected via Google form and the survey was posted on LinkedIn, the author acknowledges there could be a bias in the collection methodology in the selection criteria. Further research should consider a more targeted approach to ensure a broader cohort of professional and executive leaders beyond the realm of the OSH professional.

Despite the challenges inherent in the certification process, the findings underscore the strategic advantages of implementing a certified OHSMS framework in enhancing safety outcomes and organizational resilience. By addressing

the identified limitations and exploring new avenues for research and academics, practitioners can further advance our understanding of the role of certification standards in promoting workplace safety and well-being.

5. Conclusion

The research study aimed to investigate the relationship between OHSMS certification, particularly ISO 45001, and safety performance in organizations. Through a comprehensive analysis of both secondary ESG data and primary survey responses, the study provided valuable insights into the impact of certification on safety outcomes and identified key benefits and challenges associated with the certification process.

The findings of the research study support the hypothesis that organizations certified to OHSMS standards exhibited better safety performance compared to non-certified organizations. Analysis of safety performance metrics, including TRIFR, LTIFR, MTIFR, and workplace fatality rates, revealed significant differences between certified and non-certified organizations. Certified organizations consistently reported lower incident rates and fewer workplace fatalities, underscoring the effectiveness of certification in mitigating occupational hazards and promoting a safer work environment. These findings are consistent with previous research by Abad et al. (2013), Ghahramani and Salminen (2019), and Yoon et al. (2013), which have demonstrated similar trends in safety performance improvement following OHSMS certification.

The study identified several perceived benefits of OHSMS certification, including enhanced organizational reputation, improved stakeholder confidence, and access to new business opportunities. Despite the initial investment required in terms of time, financial resources, and organizational commitment, the majority of survey respondents recognized the strategic advantages of ISO 45001 in driving continuous improvement in safety performance and compliance with regulatory requirements. These findings are consistent with studies by Santos et al. (2013) and Ramos et al. (2020), which have highlighted the synergistic benefits of integrated management systems and the positive impact of certification on organizational performance.

The research contributes to the growing body of literature on OHSMS certification and safety performance by providing empirical evidence of the benefits associated with ISO 45001. By embracing certified OHSMS frameworks and leveraging the strategic advantages of certification, organizations can foster a positive environment of safety excellence and protect the health and well-being of their employees.

6. Recommendations

Based on the findings of the research study, several recommendations can be made for organizations, policymakers, and future research.

1. Organizations should consider adopting and implementing certified OHSMS frameworks, such as ISO 45001, to improve safety performance, enhance stakeholder confidence, and gain a competitive edge in the market. Despite the initial investment required, the long-term benefits of certification outweigh the associated costs, leading to improved safety outcomes and organizational resilience.
2. Policymakers should promote the adoption of OHSMS certification standards by providing incentives, subsidies, and regulatory support to encourage organizations to invest in safety management systems. Moreover, policymakers should prioritize the development of robust monitoring and evaluation mechanisms to ensure the effectiveness and accountability of certified OHSMS frameworks.
3. Future research should focus on addressing the limitations of the current study by adopting more robust

methodologies, such as longitudinal studies and randomized controlled trials, to validate the findings and assess the long-term impacts of certification. Additionally, future studies should explore the qualitative dimensions of safety management, including safety culture, employee engagement, and leadership commitment, to provide a more comprehensive understanding of the factors influencing safety outcomes.

ACKNOWLEDGMENTS

The author would like to express their gratitude to all individuals who contributed to the completion of this research study. Special thanks to Dr. Ikpe Ibanga and Dr. Udeme Umoren for their invaluable support and guidance throughout the research process while conducting my MSc with the University of Greenwich, UK. The author also acknowledges the survey respondents who generously shared their insights and data, without which this study would not have been possible.

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