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Food Safety Management and Sustainability Approaches in Selected Stakeholders

Zarządzanie bezpieczeństwem żywności i podejściem
do zrównoważonego rozwoju wśród wybranych interesariuszy

Doctoral thesis

Rozprawa doktorska

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Abstract

The dissertation aimed to evaluate the implementation and functioning of food safety management practices across selected food system stakeholders and to examine the association of food safety objectives with sustainability-oriented practices. The research was carried out in several phases covering different levels of the food supply chain. The first phase involved the assessment of the effectiveness of the food safety management in a small-scale food manufacturing company before and after certification according to ISO 22000:2018 and the Foreign Supplier Verification Program (FSVP). The second phase included physicochemical and microbiological analyses of selected traditional fried snack products produced between 2020 and 2023 in a certified FSMS environment. The third phase examined the level of compliance with food safety management requirements in 1000 food retail shops located in Mazovia (Poland) and Kerala (India). The final phase investigated the association between food safety practices and sustainability-oriented operational practices in grocerants across Poland, Ghana, and India. The results demonstrated that certification significantly improved compliance with food safety standards and regulatory requirements in the examined manufacturing company. Product quality analyses confirmed that physicochemical and microbiological parameters of the analysed fried snack products remained within acceptable safety limits over the study period. The assessment of retail shops revealed differences in compliance levels across retail formats, with higher adherence to food safety practices observed in larger retail outlets. In grocerants, a statistically significant positive association between food safety practices and sustainability practices was observed in Poland and Ghana, while no significant association was found in India.

The results confirm that effective implementation of food safety management approaches contributes to improved compliance with food safety standards and supports the association of sustainability-oriented practices across different stakeholders within the food system. The findings provide empirical evidence that may support the development of more effective food safety governance strategies and the advancement of sustainable food safety management practices across diverse food system environments.

Keywords: food safety compliance, sustainability, stakeholders, grocerants, audit, retail food safety.

Streszczenie

Praca doktorska miała na celu ocenę wdrożenia i funkcjonowania praktyk zarządzania bezpieczeństwem żywności wśród wybranych interesariuszy systemów żywnościowych oraz zbadanie związku celów bezpieczeństwa żywności z praktykami zorientowanymi na zrównoważony rozwój. Badania prowadzono w kilku fazach, obejmując różne poziomy łańcucha dostaw żywności. Pierwsza faza obejmowała ocenę skuteczności zarządzania bezpieczeństwem żywności w małej firmie produkującej żywność przed i po certyfikacji zgodnie z ISO 22000:2018 oraz Programem Weryfikacji Zagranicznych Dostawców (FSVP). Druga faza obejmowała analizy fizykochemiczne i mikrobiologiczne wybranych tradycyjnych smażonych przekąsek produkowanych w latach 2020–2023 w certyfikowanym środowisku FSMS. Trzecia faza analizowała poziom zgodności z wymogami zarządzania bezpieczeństwem żywności w 1000 sklepach spożywczych zlokalizowanych w Mazowsku (Polska) i Kerali (Indie). Ostatnia faza badała związek między praktykami bezpieczeństwa żywności a praktykami operacyjnymi zorientowanymi na zrównoważony rozwój w grocerantach w Polsce, Ghanie i Indiach. Wyniki wykazały, że certyfikacja znacząco poprawiła zgodność ze standardami bezpieczeństwa żywności i wymogami regulacyjnymi w badanej firmie produkcyjnej. Analizy jakości produktów potwierdziły, że parametry fizykochemiczne i mikrobiologiczne analizowanych smażonych przekąsek pozostawały w dopuszczalnych granicach bezpieczeństwa przez cały okres badania. Ocena sklepów detalicznych wykazała różnice w poziomie zgodności w różnych formatach handlowych, przy czym większe przestrzeganie zasad bezpieczeństwa żywności zaobserwowano w większych sklepach. W sklepach spożywczych zaobserwowano statystycznie istotną pozytywną korelację między praktykami bezpieczeństwa żywności a praktykami zrównoważonego rozwoju w Polsce i Ghanie, podczas gdy w Indiach nie stwierdzono istotnej korelacji.

Wyniki potwierdzają, że skuteczne wdrożenie podejść do zarządzania bezpieczeństwem żywności przyczynia się do lepszej zgodności ze standardami bezpieczeństwa żywności i wspiera współpracę praktyk zorientowanych na zrównoważony rozwój między różnymi interesariuszami w systemie żywnościowym. Wyniki dostarczają empirycznych dowodów, które mogą wspierać rozwój skuteczniejszych strategii zarządzania bezpieczeństwem żywności oraz rozwój zrównoważonych praktyk zarządzania bezpieczeństwem żywności w różnych środowiskach systemów żywnościowych.

Słowa kluczowe: zgodność z przepisami dotyczącymi bezpieczeństwa żywności, zrównoważony rozwój, interesariusze, sklepy spożywcze, audyt, bezpieczeństwo żywności w handlu detalicznym.

List of Publications and Supplementary Investigations included in the Hybrid Doctoral Thesis

Publication 1 (P1):

Nair, S. S.; Czarnecka-Skubina, E.; Jakubowska-Gawlik, K.; Trafiałek, J. American Foreign Supplier Verification Program (FSVP)-Requirements, Benefits or Burdens for Indian Food Companies, and Difficulties in the Implementation. *Technological Progress in Food Processing* 2022, 32 (2), 176–183.

Impact Factor: 0.0, Ministry Point: 20

Publication 2 (P2):

Sasikumar Nair, S.; Mazurek-Kusiak, A. K.; Trafiałek, J.; Kolanowski, W. Assessing Food Safety Compliance in a Small-Scale Indian Food Manufacturer: Before and after Certification of the Food Safety Management System and Foreign Supplier Verification Program. *Applied Sciences* 2023, 13 (22), 12190.

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Publication 3 (P3):

Sasikumar Nair, S.; Varghese, A.; Trzaskowska, M.; Kolanowski, W.; Mazurek-Kusiak, A. K.; Trafiałek, J. Post-Certification Quality Analysis of Traditional Indian Fried Snacks. *Applied Sciences* 2025, 15 (13), 7404.

<https://doi.org/10.3390/app15137404>. **Impact Factor: 2.5, Ministry Point: 100**

Publication 4 (P4):

Nair, S. S.; Murali, A. P.; Kolanowski, W.; He, S.; Trafiałek, J. Food Safety Management System Compliance of Food Retail Shops: A Comparative Study Between Mazovia and Kerala. *Applied Sciences* 2026, 16 (7).

<https://doi.org/10.3390/app16073130>. **Impact Factor: 2.5, Ministry Point: 100**

Publication 5 (P5) – Resubmitted to the Wiley journal after minor revision.

Sasikumar Nair, S.; Murali, A. P.; Atuna, R. A.; Akabanda, F.; Kolanowski, W.; He, S.; & Trafiałek, J. Prevailing Food Safety and Sustainability Practices in Grocerants: A Cross-Sectional Study in Three Countries. *International Journal of Food Science* 2026. (Manuscript ID:9949256).

Total Impact Factor: 7.5, Total Ministry Points: 320

Abbreviations

FSMS - Food Safety Management System (as per ISO 22000 standard in food safety)

SDGs - Sustainable Development Goals

PRPSs - Prerequisite programs

SMEs - Small and Medium-Sized Enterprises

HACCP - Hazard Analysis and Critical Control Points

ISO - International Organization for Standardization

FSVP - Foreign Supplier Verification Program

FSMA - Food Safety Modernisation Act

BRC - British Retail Consortium

IFS - International Featured Standard

FSSC - Food Safety System Certification

WHO - World Health Organization

EU - European Commission

RASFF - Rapid Alert System for Food and Feed

PCA - Principal Component Analysis

QA - Quality Assurance

TPC - Total Plate Count

APC - Aerobic Plate Count

PL - Poland

IN - India

FSP - Food Safety Plan

SUST - Sustainability

1. Introduction

Food safety is a shared responsibility, strongly influenced by the effectiveness of safety measures throughout the food supply chain. Microbial pathogens, toxic chemicals, and other hazardous substances may cause foodborne illnesses at any stage of food production, processing, distribution, and consumption. The importance of food safety has increased in recent years due to changing dietary habits, growing consumer awareness, globalisation of food supply chains, and the expansion of mass catering and ready-to-eat food services.

When food is unsafe, individuals cannot benefit from its nutritional value, which may hinder growth, development, and overall health (Babeker et al., 2022). Consequently, a consistent and integrated approach to food safety management across the entire food supply chain, from farm to fork, has become essential. A food safety management system (FSMS) encompasses technological, managerial, and behavioural measures designed to control food safety hazards and ensure the safe production of food. Contemporary FSMS frameworks emphasize systemisation of food safety through prerequisite programs (PRPSs), Hazard Analysis and Critical Control Points (HACCP) principles and Codex Alimentarius guidelines, and continuous monitoring, thereby embedding food safety responsibilities into routine organizational processes (Codex Alimentarius Commission, 2023). Moreover, FSMS also shape organizational culture, employee behaviour, and decision-making process, which are critical for ensuring sustained compliance and continuous improvement in food quality. However, the implementation of international food safety requirements remains challenging due to differences in national regulations, enforcement mechanisms, and organisational interpretations, leading to variability in food quality across regions and sectors (Kirkil, 2024). Such variability is particularly noticeable among small and medium-scale stakeholders, where differences in capacity and operating conditions may affect the consistency and effectiveness of food safety practices.

Environmental sustainability is an integral component within all 17 Sustainable Development Goals (SDGs) to a varying extent. Sustainability in food systems is commonly framed through environmental, social, and economic pillars, including responsible resource use, waste minimisation, and long-term viability of food production and supply activities. Poor food safety practices can undermine these goals by increasing product withdrawals and recalls, which ultimately lead to food loss and waste, as well as associated environmental burdens and substantial public health and economic costs. Therefore, effective food safety management systems support preventive control,

systematic hazard management, and workforce competence, and recent certification schemes increasingly link FSMS implementation with food loss and waste reduction strategies. Despite these organizational controls, technological interventions that enhance product stability and safety, such as advances in food packaging systems, are increasingly recognized as complementary tools for supporting food safety objectives while contributing to sustainability through shelf-life extension and food waste reduction.

Differences in business scale, organizational structure, regulatory oversight, and market orientation lead to significant variability in FSMS implementation among stakeholder groups. Small-scale food businesses and retail establishments often face constraints related to limited financial resources, workforce turnover, and reduced access to technical expertise, which can hinder consistent and effective application of food safety management systems despite formal compliance or certification (Cunha et al., 2018). These disparities highlight the need for assessments that go beyond certification status to examine the actual implementation and functioning of food safety management practices across stakeholders, as well as their association with sustainability. Such an approach is necessary to understand how regulatory frameworks, management systems, product quality outcomes, and retail practices collectively influence food safety and sustainability performance within contemporary food systems.

2. Review of literature

Food is fundamental to human survival and economic development; however, its production, processing, and distribution present significant safety challenges. Modern food systems increasingly rely on pesticides, preservatives, veterinary drugs, and processing aids to protect crops, extend shelf life, and enhance product quality. Simultaneously, physical, chemical, and biological hazards may be introduced into food either unintentionally through inadequate sanitation, environmental contamination, and improper handling practices, or intentionally through adulteration and misuse of additives. Inappropriate antibiotic use in food-producing animals further contributes to chemical residues and the emergence of antimicrobial resistance within the food chain. These hazards are associated with a wide range of adverse health outcomes, including acute foodborne infections and long-term chronic diseases (Duan et al., 2025; Guo et al., 2021).

2.1. Food Safety Management System (FSMS)

In response to persistent food safety risks, many countries have adopted the Hazard Analysis and Critical Control Point (HACCP) system as mandatory and, voluntarily standardized Food Safety Management Systems (FSMS), primarily based on international food safety standards and certification such as the International Organization for Standardization 22000 (ISO, 2018a), the British Retail Consortium Global Standard (BRC Global Standards, 2018), the International Featured Standard (IFS, 2023), and the Food Safety System Certification 22000 (FSSC, 2023). The FSMS facilitates identifying, evaluating, and controlling food hazards; establishing monitoring and verification procedures; addressing nonconformities; and pursuing continual improvement. Developed regions, including the European Union and the United States, benefit from advanced regulatory infrastructures enabling the timely detection of food safety failures and the effective enforcement of preventive measures (European Commission, 2020; FSMA, 2024). In contrast, resource-constrained regions continue to experience substantial challenges in implementing and enforcing food safety regulations (Kang, 2025; Psomatakis et al., 2024; Sasikumar Nair et al., 2023). Effective implementation of FSMS supports systematic hazard control across operations (Sartoni et al., 2025). The International Organization for Standardization (ISO) developed the ISO 22000 standard, providing a harmonized framework integrating HACCP principles with management system elements for systematic food safety control (ISO, 2018b).

Food manufacturing plays a central role in ensuring the safety of products entering both domestic and international markets. Regulatory authorities and international organizations have therefore promoted preventive, system-based approaches such as HACCP and certification standards, to strengthen food safety governance within food manufacturing environments. The United States Foreign Supplier Verification Program (FSVP), established under the Food Safety Modernization Act, mandates importers to verify that foreign suppliers produce food following preventive controls equivalent to U.S. safety standards, thereby extending food safety accountability beyond national borders and placing additional compliance demands on export-oriented food businesses (ECFR, 2016; Nair et al., 2022).

The introduction of internationally recognized certification systems and regulatory verification programs has been shown to significantly improve hygiene performance, process control, and organizational accountability within manufacturing facilities. However, the magnitude of improvement varies depending on management commitment, resource availability, and the effectiveness of implementation strategies. Existing literature highlights challenges faced among small-scale and export-oriented enterprises in resource-constrained regions, but lacks empirical findings that could provide stronger solutions, indicating further research is necessary to evaluate FSMS effectiveness in real operational contexts and identify strategies for improving compliance across manufacturing environments.

2.2. Food Quality under a certified environment

Food safety remains a major concern despite continuous efforts by authorities and experts, as outbreaks still attract media attention due to their serious consequences. Food quality is a dynamic concept that has evolved over time and continues to change under the influence of both objective and subjective factors. By implementing a Food Safety Management System (FSMS), an organization can demonstrate its ability to produce safe food by identifying, assessing, and controlling food hazards, establishing monitoring and verification, addressing nonconformities, and continuously improving. Although food quality and food safety are closely interrelated, in many food companies, quality indicators (e.g., moisture content or lipid oxidation parameters) are frequently managed separately from FSMS audit results and nonconformity reports. This separation limits the use of an integrated evidence base for management decision-making (Muminov et al., 2026). As a

result, verification of FSMS effectiveness requires the joint consideration of audit results and product-level performance indicators.

The successful implementation of FSMS depends on several factors, including the size and type of the organization, the type of product, the type of links it has with suppliers and customers, the use of automation, the significance of quality assurance, and the level of support from top management. These factors also apply after implementation and can affect how well FSMS works in a company (Maiberger and Sunmola, 2023). Each food company develops its unique Food Safety Management System (FSMS) based on chosen quality assurance (QA) standards and how these guidelines are tailored to fit company-specific circumstances. The effectiveness of the FSMS is influenced not only by the performance of the system itself but also by the contextual characteristics it operates within. Therefore, FSMS needs to be adapted to these contextual characteristics to ensure optimal food safety outputs (Fathurrahman et al., 2021).

ISO 22000 is an international standard aimed at enhancing food safety and preventing foodborne outbreaks, necessitating measurable food safety objectives to assess the effectiveness of a food safety management system (FSMS) within an organization (Fathurrahman et al., 2021). Studies have examined the implementation of Food Safety Management Systems (FSMS) in food organisations across different national contexts (Rebouças et al., 2016; Rihawi, 2024; Teixeira and Sampaio, 2013). However, much of this research has focused primarily on the adoption and operationalisation of the HACCP component of international standards, with comparatively limited attention given to the evaluation of product quality within FSMS-certified facilities.

2.3. Food safety at the interface between producers and consumers.

Grocery retailers play an important role as intermediaries, sourcing from agricultural producers and manufacturers and supplying consumers through retail stores (ReFED, 2025). They provide various services to consumers, facilitating the distribution of food, either pre-packaged or prepared in retail stores. Basic processing tasks, such as cleaning, sorting, grading, and packaging, occur in retail working areas, which must adhere to food safety procedures tailored to the specific production conditions of different food categories (Mazzocchi et al., 2025).

Hazards may be introduced at this stage, compromising the integrity of the entire chain. Therefore, flexible, risk-based FSMS supported by scientific input are needed for the retail

sector. To meet basic food safety requirements, retail food facilities must follow general hygiene guidelines. The location of the premises should be in a safe environment and include suitable loading and unloading areas protected from pests. Separate areas should be provided for storage, processing, and packaging. Food handling and storage areas need to be easy to clean and should have proper drainage, ventilation, and temperature control. Equipment and containers used during food handling or preparation must be designed and positioned to allow effective cleaning and sanitation. In addition, food handlers must maintain high standards of personal hygiene, including proper hand washing, use of protective clothing, and regular health monitoring, to prevent foodborne illnesses (EFSA Panel on Biological Hazards et al., 2018; FAO and WHO, 2014).

Effective implementation of a Food Safety Management System (FSMS) is essential for ensuring food safety. However, notable differences exist between developed and developing countries. Developed countries typically benefit from more stable economic and social conditions, which support reliable food availability, encourage responsible and healthy purchasing and consumption behaviors, and allow for the enforcement of stringent food safety regulations. In contrast, developing countries often face economic and social constraints that place greater emphasis on food access and availability, while food safety considerations and related regulatory frameworks tend to receive less priority (Rincon-Ballesteros et al., 2024). Given the complexity of food safety governance and the central position of retailers within the food supply chain, there is a clear need for further empirical investigation in these settings.

2.4. Sustainable Food Safety Management System

The global food system is undergoing rapid transformation due to the complex interdependencies among suppliers, producers, manufacturers, and retailers. At the same time, food systems are facing increasing environmental, social, and economic pressures that require more adaptive and integrated approaches to food safety management. This transformation must address the growing demand for safe, nutritious, and affordable food while responding to challenges such as climate change, globalization, and resource constraints (FAO, 2022). In this context, the transformation of agrifood systems is vital for achieving the Sustainable Development Goals (SDGs) outlined in the 2030 Agenda, particularly those related to health, responsible consumption, and environmental protection (United Nations, 2015). Within this context, food safety is increasingly recognized as a

foundational element of sustainable food systems, as unsafe food undermines public health, contributes to food loss and waste, and weakens consumer trust in food supply chains.

Food safety practices and sustainability approaches vary considerably among different food system stakeholders, including food manufacturers, retailers, and hybrid food service-retail formats, commonly referred to as grocerants. Food manufacturing facilities primarily focus on upstream control measures such as process standardisation, raw material verification, hygienic design, and compliance with formal regulatory and certification requirements, where food safety management is typically embedded within structured FSMS frameworks (Codex Alimentarius Commission, 2024; ISO, 2018b). In contrast, food retail and grocerant settings operate at the consumer interface and occupy a strategic position between manufacturers and consumers, giving them substantial influence over food safety outcomes and sustainability performance.

These settings represent critical points where daily food handling, employee hygiene, temperature control, cross-contamination risks, and shelf-life management directly determine consumer exposure to food safety hazards (Bekele et al., 2012; FAO and WHO, 2014). From a sustainability perspective, retail and grocerant operations play a significant role due to their contribution to food loss and waste generation, energy use, packaging disposal, and short product life cycles, especially for ready-to-eat and freshly prepared foods (FAO, 2019; Gustavsson et al., 2011). In these formats, food safety failures and sustainability outcomes are interconnected, as inadequate hygiene practices, improper storage, or poor stock rotation can lead to public health risks, product spoilage, disposal, and unnecessary environmental burdens.

As societal awareness of sustainability continues to grow, there is an increasing need for empirical research that examines how food safety management practices interact with environmental and social sustainability objectives at the operational level. In particular, retail and hybrid food service formats remain underexplored despite their expanding role in modern food systems. Understanding how food businesses integrate food safety management with sustainable operational strategies is therefore essential for developing comprehensive, evidence-based approaches to sustainable food safety management across diverse food system contexts.

3. Purpose, Hypothesis, and Scope of the Research

Purpose of the research

The dissertation aimed to assess the implementation and functioning of food safety management practices across selected food system stakeholders and to examine the association of food safety objectives with sustainability-oriented practices. The specific objectives of the research were:

- (1) to assess Food Safety Management System (FSMS) in a small-scale food manufacturing company;
- (2) to evaluate post-certification food quality through microbiological and physicochemical product quality indicators; and
- (3) to analyse food safety management practices across selected stakeholders, including sustainability supporting approaches relevant to food safety.

Hypothesis of the research

- H1: The implementation of food safety management is associated with improved compliance with food safety regulatory requirements.
- H2. Certification-based food safety management implementation is associated with sustained post-certification food quality, as reflected by microbiological and physicochemical product quality indicators over time.
- H3. In operational settings where food safety and sustainability objectives intersect, higher food safety practice implementation is associated with stronger sustainability-related practices.

The scope of the research

1. Literature review and data collection related to food safety management and sustainability-oriented interventions.
2. Development of an integrated audit approach, followed by evaluation of FSMS compliance with respect to standard and regulatory implementation.
3. Investigation of post-certification FSMS performance through microbiological and physicochemical product quality evaluation over time.
4. Development of a checklist tool and assessment of FSMS compliance in food retail shops in different geographical contexts.

5. Development of a structured questionnaire and assessment of food safety practices and sustainability practices in grocerants, with comparative analysis across selected countries.

4. Materials and Methods

4.1. Research scheme

The research was conducted in the following phases (Table 1).

Table 1. Phases of the research dissertation

	Research Tasks	Tests	Publication
Phase I Assessment of the effectiveness of the food safety management against food safety standards and regulatory requirements	→ Evaluation of FSMS compliance and non-compliance before and after certification	→ Internal audit → Statistical analysis	P1, P2
Phase II Evaluation of post-certification food quality	→ Microbiological characteristic → Physicochemical characteristic	→ Total Plate count (TPC) → moisture%, pH, salt%, acid value → Statistical analysis	P3
Phase III Assessment of the degree of compliance with the food safety management requirements in food retail shops	→ Evaluation of FSMS practices across key operational food safety sections	→ Observational data collection → Statistical analysis	P4
Phase IV Assessment of the degree of compliance with the requirements of food safety and sustainability practices in grocerants	→ Evaluation of food safety practices → Evaluation of sustainability practices	→ Observational data collection → Statistical analysis	P5

4.1.1. Research Design

The study design was a descriptive and comparative cross-sectional observational design, using quantitative assessment techniques. Descriptive research enables systematic

documentation of observed conditions within defined study settings, while comparative analysis supports the evaluation of differences across study phases and contexts. Data were collected through structured audit (Phase I), laboratory-based product analysis (Phase II), and observational checklists (Phase III and IV). The cross-sectional approach involves direct observation of FSMS implementation and operational practices at specific points in time. This design enabled the quantitative assessment of FSMS compliance, food handling practices, hygiene and sanitation conditions, and related operational controls across various food-system settings.

4.1.2. Research areas selected for the research

The study was conducted in three countries: Ghana (Africa), Poland (Europe), and India (Asia), representing three continents. These countries were selected because they represent different food safety governance systems and sustainability approaches within transitional, developed, and developing economies. Ghana was chosen as a representative of the Sub-Saharan African context, Poland as a European Union member with harmonised food safety standards, and India as a rapidly developing Asian country with evolving retail and regulatory systems

4.2. Research materials

4.2.1. Stakeholders

The research material consisted of selected stakeholders of the food sector. A food manufacturer was selected as the stakeholder for Phases I and II of the research. These phases were conducted on a small scale (MSME, 2020)-food manufacturing company located in Kerala, India. With the company's consent, food safety and food quality assessments were carried out. The firm produces a variety of traditional South Indian fried snacks exclusively for export, intending to increase exports to developed countries. Figure 1 illustrates the characteristics of the company studied. In order to meet the standards of its importing nations, the chosen firm obtained two certifications: ISO 22000:2018 and the Foreign Supplier Verification Program (FSVP) certification (**P2, P3**).

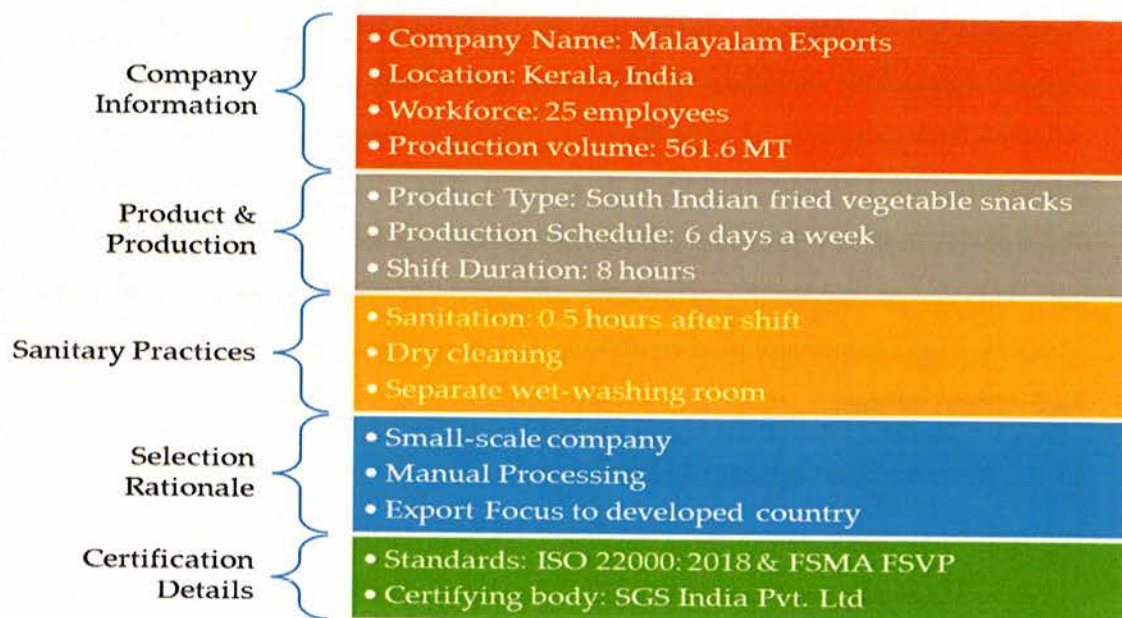


Figure 1. Schematic representation of the company selected for the studies.

Source: own study based on P2 publication. Adapted from (Sasikumar Nair et al., 2023), Applied Sciences, CC BY 4.0

Food retailers were selected as the stakeholders for Phase III of the research. The study was conducted from March 2024 to February 2025, covering a total of 1000 food retail shops- 500 each in Mazovia (Poland) and Kerala (India). These regions were deliberately chosen due to their extensive retail shop networks and significance in respective national food supply chains. A stratified purposive sampling approach was used to ensure representation of different retail environments. Retail shops were selected from urban, semi-urban, and rural settings, including big towns (e.g., Warsaw and Thiruvananthapuram), small-sized towns, and rural areas in both regions. Shops were further categorized by retail format, including hypermarkets, supermarkets, convenience stores, and local shops (Hino, 2014; Liese et al., 2007), to ensure coverage of different shop sizes, operational structures, and retail practices across the study regions.

Stakeholders operating hybrid outlets that combine grocery retail and food service activities- hereafter referred to as *Grocerants* (Kim et al., 2019) were selected for Phase IV of the research. The assessment was carried out across Ghana, Poland, and India in 150 randomly selected grocerants (50 from each country) between January and May 2024, primarily through direct on-site observations.

4.2.2. Sample collection and processing

Five traditional Indian fried snack products were selected for analysis based on consumer acceptance and the export market (Markets and Data, 2023; Saha et al., 2025): Kerala Murukku, Kerala Mixture, Banana Chips, Tapioca Chips, and Achappam. All samples were produced in an ISO 22000:2018-certified facility and packaged immediately after processing in metalised polyethylene terephthalate (PET) packaging material using modified atmosphere packaging (Nitrogen flushing) (Saurabh and Jyoti, 2013). Random sampling was performed once per year from 2020 to 2023, resulting in 20 finished product samples (one sealed packet per product per year). Each sample was analyzed in triplicate, and physicochemical and microbiological testing was conducted by the company following its internal procedures, with the data provided for this research. Ingredient portions for each sample are listed in publication **P3**.

4.3. Methods

4.3.1. **Phase I.** Assessment of the effectiveness of the food safety management system against food safety standards and regulatory requirements

This study seeks to assess the effectiveness of FSMS implementation in a selected small-scale food facility, identify the research gaps, and propose evidence-based improvements to enhance food safety. To evaluate the system improvement, the assessment was conducted during two periods: Stage 1 (2019), before ISO 22000 and Foreign Supplier Verification Program (FSVP) certification, and Stage 2 (2021), after certifications. A direct internal audit approach was applied, based on the principles outlined in ISO 19011 (ISO, 2018c) and the company's internal audit procedure. The audit checklist was developed using the requirements of the Foreign Supplier Verification Program (FSVP), ISO 22000:2018, and findings from earlier related studies (Fernández-Segovia et al., 2014; FSMA, 2024; Kotsanopoulos and Arvanitoyannis, 2017; Trafiałek and Kolanowski, 2017). In this manner, an integrated checklist combining both standards was established. The checklist was pilot-tested by the quality manager and two independent experts, and necessary revisions were made.

The final checklist consisted of 70 questions organized into 10 food safety sections: regulatory compliance, food safety plan, process and product control, sanitation, workers' hygiene practices, plant and grounds, food allergens, pest control, packaging and labelling, and employees and visitors (Table 2). The same checklist was used for both stages, and

each item was evaluated for conformity based on whether the specified requirement was met. Compliance was scored using a binary scale, where 1 indicated conformity and 0 indicated non-conformity. Conformity was determined using audit evidence such as documentation, factual statements, and other verifiable information relevant to the audit criteria (ISO, 2018c). The methodology and full checklist questions were presented in publication **P2**.

Table 2. The integrated audit checklist.

No.	Assessment Questions	Stage 1		Stage 2	
		C*	NC**	C	NC
1.	Regulatory Compliance				
2.	Food Safety Plan				
3.	Process and Product Control				
4.	Sanitation				
5.	Workers Hygiene Practices				
6.	Plant and Grounds				
7.	Food allergens				
8.	Pest control				
9.	Packaging and Labelling				
10.	Employees and Visitors				

*C- Compliance, **NC- Non-compliance

Source: own study based on **P2** publication. The complete audit checklist with its full set of indicators is provided in **P2**. Adapted from (Sasikumar Nair et al., 2023), Applied Sciences, CC BY 4.0.

4.3.2. **Phase II.** Evaluation of post-certification food quality

This study aimed to evaluate product quality by analyzing the physicochemical and microbiological quality of traditional Indian fried snacks produced in a Food Safety Management System (FSMS) certified facility over the period from 2020 to 2023.

Physicochemical Analysis: The analytical methods were performed by the company in accordance with IS 12711 (1989): Bakery products - Methods of analysis (BIS, 1989). Product samples were finely ground, and the ground powder was used for the estimation of physicochemical quality parameters, including moisture content, salt content, pH, and acid value of extracted fat. These parameters are the most frequently recommended tests to assess the quality of deep-fried snacks, and serve as essential indicators of product safety,

shelf life, and sensory quality (Jonnalagadda et al., 2001). Further details on these methodologies are provided in the **P3** publication.

Microbiological Analysis: Total Plate Count (TPC), also referred as Aerobic Plate Count (APC) was selected as the microbiological parameter in this study as it provides an overall measure of microbial load and serve as a general indicator of hygiene conditions in food products (Zhang et al., 2020). TPC is commonly applied in food safety assessments to monitor potential contamination during processing and storage. Microbiological analysis was conducted by the company in accordance with its internal procedures, which were based on the methods described in the FDA's Bacteriological Analytical Manual (BAM) (Maturin and Peeler, 2001) (**P3**).

4.3.3. **Phase III.** Assessment of the degree of compliance with the food safety management system requirements in food retail shops

This study aimed to evaluate the degree of compliance with food safety management systems practices in retail shops in Mazovia (Poland) and Kerala (India), through direct visual inspections. Direct observation can be an effective technique for assessing the food safety practices in grocery stores (Paulin et al., 2017). FSMS compliance in retail shops was assessed using a structured visual inspection method. A checklist-based tool consisting of 51 indicators was used, developed based on food safety requirements applicable in both countries (EFSA and ECDC, 2023; FSSAI, 2017a), and the indicators were organized into seven thematic sections: design and layout, general food safety, food handling and storage practices, display, personnel hygiene practices, sanitation and cleanliness, and pest control (Table 3).

Each indicator was rated using a four-point ordinal scale, where;

1 = Non-compliance: the requirement was not implemented at all;

2 = Low compliance: the requirement was only partially implemented, with major deficiencies identified;

3 = Moderate compliance: most requirements were implemented, although minor deficiencies remained; and

4 = Full compliance: the requirement was completely implemented in accordance with food safety guidelines (Djekic et al., 2014; Psomatakis et al., 2024).

Numerical scores were assigned accordingly, and higher values represented better compliance. All indicators were given equal weighting, and the overall compliance scores

for each retail shop were calculated as the mean of all indicator values. Contextual information on shop characteristics (country, location, retail format, and number of employees) was also recorded.

Table 3. List of indicators in the checklist

	Please mark ratings 1-4*
1. Design & layout	
2. Food Safety	
3. Food Handling and Storing Practices.	
4. Display	
5. Personnel Hygiene Practices	
6. Sanitation and Cleanliness	
7. Pest Control	

*Rating scale: 1- non-compliant, 2- partially compliant, 3- mostly compliant, and 4- fully compliant.

Source: own study based on P4 publication. The complete audit checklist with its full set of indicators is provided in P4. Adapted from (Nair et al., 2026), Applied Sciences, CC BY 4.0.

A pilot test was conducted in 10 retail shops per region to evaluate the clarity, applicability, and consistency of the inspection checklist prior to the main study. Based on the findings, minor revisions were made to improve wordings, sequence, and clarity, enhancing overall usability of the tool for full-scale assessment. Data collection was conducted by the first author, through unannounced on-site observations during routine operating hours to capture typical practices.

4.3.4. Phase IV. Assessment of the degree of compliance with the requirements of food safety and sustainability practices in groccrants

This study was conducted to assess and compare the prevailing Food Safety (FSP) and Sustainable Practices (SUST) implemented in groccrants across Ghana, Poland, and India. A direct observation approach was applied to systematically evaluate Food Safety Practices (FSP) and sustainable practices (SUST). A structured inspection checklist was developed and implemented as an on-site observation tool (Paulin et al., 2017), in groccrants across Ghana, Poland, and India, using Google Forms for data recording. The tool was designed to measure and compare compliance with food safety and sustainability practices across the three countries. To ensure an unbiased assessment, inspections were conducted by a trained inspector without prior notice. Observations were carried out during routine

operating hours while employees performed their regular tasks, thereby allowing documentation of practices under normal working conditions.

The checklist consisted of 28 indicators (Table 4). Prior to field application, the instrument was pilot-tested by the research team to confirm clarity, consistency, and suitability (D'Adamo et al., 2023; Nyarugwe et al., 2020). The indicators were organized into two main sections: (i) food safety practices, covering hygiene, handling procedures, and adherence to food safety management requirements, and (ii) sustainability practices, addressing environmental responsibility, waste management, and efficient resource use within the retail setting. Compliance with each indicator was evaluated using a four-point ordinal scoring system, adapted from Nyarugwe et al. (2020). A score of 4 represented full compliance with the assessed practices, 3 indicated minor deviations from full compliance, 2 reflected limited effort/partial compliance, and 1 indicated non-compliance.

Table 4. The checklist used in the study.

Q. No.	Scope	Abbreviation
Section: Food Safety Practices		FSP
Q1	Shop layout supports hygienic food handling.	Layout
Q2	Adequate ventilation and lighting to maintain safe food handling conditions.	Ventilation and Lighting
Q3	Food safety information (manuals, posters, signs, or icons) is clearly displayed in the shop.	Food safety information
Q4	Food preparation areas are maintained in a sanitary condition.	Sanitary area
Q5	Products are stored under correct conditions (e.g., refrigerated, frozen, or hot held).	Storage
Q6	High-risk items such as raw meat or seafood are kept separate from direct customer contact.	High-risk separation
Q7	Expired products are not displayed.	Expiry control
Q8	Displayed foods are protected from customer handling or contamination.	Display protection
Q9	Employees wear appropriate protective clothing while handling food.	Protective wear
Q10	Employees follow hygienic practices when serving or preparing food.	Hygiene behaviour
Q11	Food contact surfaces, equipment, and utensils are visibly clean.	Clean surface
Q12	Cleaning and sanitizing routines are carried out regularly.	Cleaning routine
Q13	There are no signs of pest infestation inside the shop.	Pest signs
Q14	Pest control devices are present and maintained in working order	Pest devices
Section: Sustainability Practices		SUST

Q15	Alternative sustainable packaging options	Alternative packaging
Q16	Energy-efficient appliances and equipment	Energy-efficient appliances
Q17	Eco-friendly cleaning products	Eco-clean
Q18	Discounts on surplus food/minimizing food waste	Discounts
Q19	Food donations to shelters/ charities	Food donation
Q20	Store charges for single-use bags	Bag charge
Q21	Waste segregation and recycling systems	Waste segregation
Q22	Prohibiting non-compostable labels on fruit or vegetables	Label prohibition
Q23	Sustainable refrigeration systems	Sustainable refrigeration
Q24	Use of natural light in design	Natural light
Q25	Organic fruits and vegetables are available	Organic products
Q26	Store accepts private food containers and bags	Private bag
Q27	Zero plastic packaging	Zero plastic
Q28	Local products are dominant in the store	Local products

Source: own study based on P5 publication

4.3.5. Statistical Analysis

The data obtained from Phase I-IV were subjected to statistical interpretation using STATISTICA version 13.3 (TIBCO Software Inc., Palo Alto, CA, USA). The descriptive statistics and the inferential statistics were computed. Significance was determined when $p < 0.05$.

- Cronbach's alpha was used to measure the internal consistency and reliability of the methods used for the research (**P2, P4, & P5**).
- Shapiro-Wilk test is used to check the normality of distribution (**P4 & P5**)
- Descriptive statistics includes mean, mode, standard deviation (**P2, P3, P4, & P5**).
- Student's t-test to compare the level of fulfilment of the audit criteria (**P2**).
- McNemar's test was applied to evaluate whether certification significantly influenced the compliance, by comparing the number of compliant items across the assessed sections before and after certification (H_0 : no impact; H_1 : significant impact) (**P2**).
- Cochran's Q test was used to examine the statistical differences in dichotomous compliance outcomes across multiple related measurements (**P2**).

- Analysis of Variance (ANOVA) and Tukey's HSD test were used to evaluate the potential differences in product quality metrics across years (P3).
- Principal Component Analysis (PCA) was carried out to evaluate the association patterns among quality parameters, ingredients load, and sampling years (P3), to evaluate the relationship between retail formats and FSMS compliance levels in Mazovia and Kerala (P4).
- Spearman's correlation was applied to determine the strength and direction of correlations between quality parameters and sampling years (P3), to determine the relationship between FSP and SUST practices in grocerants (P5).
- Mann-Whitney U test was used to compare FSMS compliance scores between Polish and Indian retail shops across the evaluated sections (P4).
- Multivariate cluster analysis to classify products based on microbial quality and identify similarity patterns across the study period (P3), to cluster food retail shops within each country based on FSMS compliance level (P4), to determine the grouping patterns of grocerants according to their compliance with FSP and SUST practices (P5).
- Kruskal-Wallis test with Dunn's post-hoc multiple comparisons with Bonferroni correction was used to analyse whether average total FSMS compliance scores differed significantly across variables like country, location, food sector, and number of employees (P4), to evaluate differences in mean FSP and SUST scores across countries (Ghana, Poland, India), across individual indicators (Q1-Q28), and across the clusters identified through cluster analysis (P5).

5. Results and Discussion

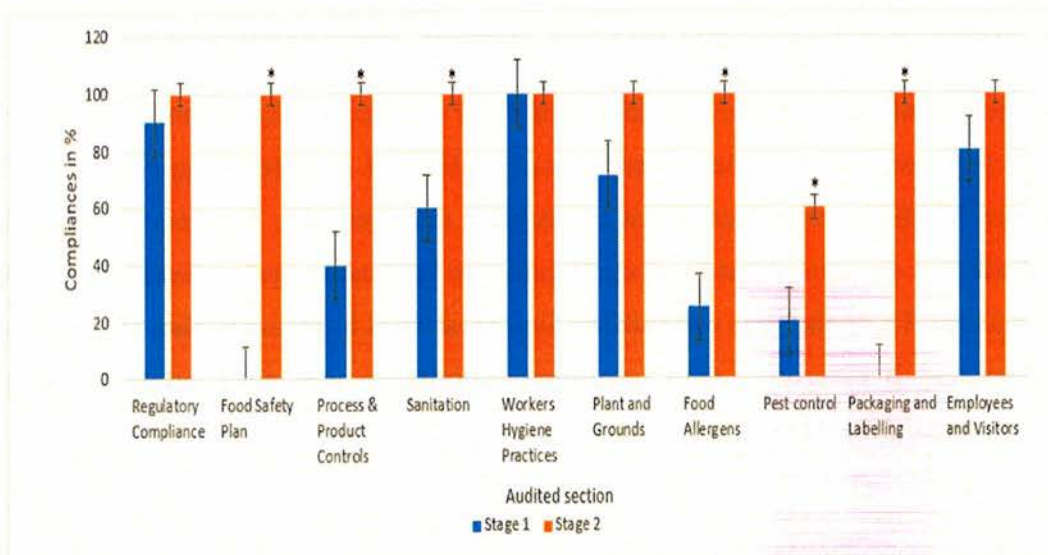
5.1. Phase I. Assessment of the effectiveness of the food safety management against food safety standards and regulatory requirements

The research results are presented in publication **P2** to demonstrate the effectiveness of implementing international food safety standards, as confirmed by certification of the evaluated small-sized food company. This evaluation is supported by the regulatory and operational context provided in Publication P1, which examines the Foreign Supplier Verification Program (FSVP) requirements and their implications for Indian food exporters. Publication P1 highlights key challenges, including documentation requirements, supplier verification, and resource limitations in small-scale food companies, highlighting structural gaps before certification. These insights help to better understand and interpret the improvements observed in publication P2, contributing to the overall assessment of FSMS effectiveness in Phase I.

Comparative assessments of food safety audit outcomes in developing country contexts remain limited in the existing research. In this phase, the effectiveness of implementing ISO 22000:2018 and the Foreign Supplier Verification Program (FSVP) requirements was evaluated using a two-stage audit approach that covered both FSMS documentation and the food safety system operating within the company. The pre-certification audit (Stage 1) revealed that the organisation's practices and documented controls were not aligned with ISO 22000 and FSVP requirements, indicating substantial gaps in system-based food safety management. These shortcomings were primarily associated with the limited availability of trained personnel and technical expertise, as well as the insufficient proactive engagement of senior management in establishing and maintaining preventive food safety controls (Lee et al., 2023).

The findings have shown that the degree of compliance with requirements was much improved by the use of the FSVP and ISO 22000 standards and the resulting certification. The overall degree of compliance increased significantly from 50% in Stage 1 (before certification) to 97.14% in Stage 2 (after certification) (Student's t-test $p = 0.0011$) (Figure 3). The analysis of individual sections demonstrated significant improvement in six out of ten sections, which includes Food Safety Plan (Student's t-test $p = 0.0000$), Process and Product Control (Student's t-test $p = 0.0017$), Sanitation (Student's t-test, $p = 0.0247$), Food

Allergens (Student's t-test, $p = 0.0240$), Pest control (Student's t-test, $p = 0.0241$), Packaging and Labelling (Student's t-test, $p = 0.0240$). The biggest differences were found in the Food Safety Plan and Packaging and Labelling sections, which were not implemented before certification, but reached full conformity after certification. Conformity before certification was observed only in the Workers' Hygiene Practices section. Non-compliance related to personnel hygiene has reported in previous studies by Al-Shabib et al (2016), Reboucas et al (2016), and Trafialek et al (2019).



* reflects the significant improvement.

Figure 3. Percentage of compliance with requirements, in particular the food safety sections, before and after certification (Stage 1 and 2, respectively). *Source: own study based on P2 publication.* Adapted from (Sasikumar Nair et al., 2023), Applied Sciences, CC BY 4.0

Before certification, the company fulfilled 35 of the 70 assessed parameters, whereas after certification, compliance increased to 68 parameters, with only two remaining non-compliant. McNemar's test confirmed that the change in compliance was statistically significant ($\chi^2(A/D) = 27.68$, $p < 0.0001$; $\chi^2(B/C) = 31.03$, $p < 0.0001$), indicating a clear improvement following certification (Publication P2). In addition, descriptive results showed that the compliance level increased from 50.00% before certification to 97.14% after certification, which was further supported by Cochran's Q test ($Q = 33.00$, $p < 0.0001$). This substantial increase is consistent with findings reported by Rihawi (2024), who reported that implementation of ISO 22000: 2018 significantly enhances operational

performance, including increased efficiency and a reduction in non-compliance incidents in food manufacturing facilities.

Non-conformities were identified in all assessed sections except workers' hygiene practices before certification, whereas after certification, non-conformities were observed only in the pest control section. Specifically, two issues remained: improper placement of flying insect traps and inadequate positioning of rodent control devices. Goyal et al. (2017) reported that Indian agricultural exporters are facing rejections and bans in major markets due to non-compliance with food safety and health standards, including pest infestations.

The results confirm that ISO 22000:2018 and FSVP certification significantly strengthened FSMS implementation in the assessed small-scale food manufacturing company. This evidence highlights the effectiveness of adopting internationally recognised food safety standards and supports the role of certification in improving system-based food safety performance. **These findings validate the hypothesis that implementation of food safety management is associated with improved compliance with food safety regulatory requirements (H1).**

5.2. Phase II. Evaluation of post-certification food quality

Managing product composition is crucial for food safety, helping to ensure microbial stability and shelf life. The main goal of the second phase of the research was to evaluate the physicochemical properties and microbiological quality trends of traditional fried snack products produced in an ISO 22000:2018 certified facility from 2020-2023. The research results are described in the publication **P3**.

5.2.1. Physicochemical analysis

Physicochemical parameters, including moisture content, acid value, pH, and salt content, were analysed to evaluate product stability and process consistency of five traditional Indian fried snack products in an FSMS-certified environment over the period 2020-2023 (Nawaz et al., 2021; Sivaranjani et al., 2024). Table 5 shows the mean \pm standard deviation values for moisture, acid value, pH, and salt content across these snacks from 2020 to 2023. Results from one-way ANOVA reveal statistically significant differences in all physicochemical parameters over the years.

Table 5. Physicochemical parameters of the five products from 2020 to 2023

Variable	Year	Mean± Standard Deviation				
		Kerala Murukku	Kerala Mixture	Banana Chips	Tapioca Chips	Achappam
Moisture %	2020	2.37±0.01 ^a	0.83± 0.01 ^a	1.48±0.01 ^b	1.64±0.01 ^a	1.68±0.01 ^a
	2021	2.37±0.06 ^a	0.55± 0.01 ^a	2.93±0.01 ^a	1.63±0.01 ^a	1.37±0.02 ^a
	2022	2.57±0.25 ^a	1.52± 0.53 ^b	1.30±0.60 ^b	2.20±0.45 ^a	1.96±1.18 ^a
	2023	1.97±0.01 ^b	0.97± 0.03 ^{ab}	0.79±0.33 ^b	1.62±0.55 ^a	0.78±0.30 ^a
Acid value	2020	0.32±0.01 ^a	0.30± 0.01 ^{ab}	0.38±0.01 ^a	0.49±0.01 ^a	0.28±0.01 ^a
	2021	0.33±0.01 ^a	0.49± 0.17 ^a	0.30±0.06 ^{ab}	0.50±0.01 ^a	0.81±0.46 ^a
	2022	0.97±1.03 ^a	0.15± 0.05 ^b	0.20±0.05 ^b	0.29±0.02 ^b	0.28±0.06 ^a
	2023	0.17±0.01 ^a	0.25± 0.04 ^b	0.23±0.01 ^b	0.28±0.01 ^b	0.25±0.08 ^a
pH	2020	5.96±0.00 ^a	6.35± 0.01 ^a	5.53±0.01 ^a	6.23±0.01 ^a	5.82±0.01 ^a
	2021	6.02±0.01 ^b	6.37± 0.00 ^a	5.84±0.01 ^a	5.97±0.00 ^a	5.97±0.00 ^a
	2022	6.02±0.02 ^b	6.34± 0.16 ^a	6.02±0.38 ^a	5.96±0.14 ^a	6.25±0.09 ^b
	2023	6.14±0.02 ^c	6.43± 0.05 ^a	5.77±0.08 ^a	6.19±0.15 ^a	6.15±0.07 ^b
Salt	2020	0.33±0.06 ^a	1.09± 0.01 ^a	0.42±0.01 ^a	0.36±0.01 ^a	0.18±0.01 ^{ab}
	2021	0.73±0.59 ^{ab}	1.10± 0.01 ^a	0.52±0.14 ^a	0.48±0.18 ^{ab}	0.19±0.03 ^b
	2022	1.33±0.06 ^b	1.19± 0.10 ^{ab}	0.96±0.14 ^b	0.87±0.16 ^b	0.10±0.00 ^a
	2023	1.37±0.12 ^b	1.26± 0.04 ^b	0.96±0.14 ^b	0.88±0.19 ^b	0.17±0.06 ^{ab}

Different superscript letters within each column indicate statistically significant differences between years for that product ($p < 0.05$), based on Tukey's HSD test. Values sharing the same superscript letters are not statistically significant. *Source: own study based on P3 publication.* Reproduced from (Sasikumar Nair et al., 2025), Applied Sciences, CC BY 4.0.

Significant year-wise variations in moisture content were observed for Kerala Murukku ($p = 0.0032$), Kerala Mixture ($p = 0.0126$), and Banana Chips ($p = 0.0003$), while no statistically significant differences were found for Tapioca Chips ($p = 0.2001$) and Achappam ($p = 0.1842$). However, moisture levels remained consistently below 2% across all products, indicating optimal moisture removal during frying and reducing susceptibility to microbial growth in low-moisture settings. The final oil uptake and moisture content are crucial quality parameters for fried products, ensuring a balance between water evaporation and diffusion (Basak et al., 2023).

Acid value, a marker of oil degradation (Garg et al., 2022), remained below 1.0 mg KOH/g for all products, suggesting maintained fat quality (Basak et al., 2023). Significant year-wise variations were observed in Kerala Mixture ($p = 0.0093$), Banana Chips ($p = 0.0022$),

and Tapioca Chips ($p < 0.0001$), while Kerala Murukku ($p = 0.308$) and Achappam ($p = 0.0588$) showed no significant changes over time.

Statistically significant year-wise pH variation was observed in Kerala Murukku ($p < 0.000001$), Tapioca Chips ($p = 0.0234$), and Achappam ($p = 0.00007$), though the overall pH range remained above 5 across all products. The pH values of Banana chips were found to be similar to those stated by Assanvo et al. (2023), who reported that the pH values of their ripe and unripe plantain chips range from 5.16 to 6.04, respectively.

Salt content showed significant variations across all products, with pronounced differences observed in Kerala Mixture ($p = 0.0167$), Kerala Murukku ($p = 0.0082$), and Banana Chips ($p = 0.0011$). The salt content observed in this study remained below the reported range for Indian packaged fried snacks (1.45%- 2.71%) as documented by Raj et al. (2015), indicating comparatively moderate sodium levels and potentially reduced dietary risk when consumed in typical amounts.

5.2.2. Microbiological analysis

The microbiological quality of food samples, based on TPC, is shown in Figure 4, which presents the mean values with standard deviations across products and years. Across the study period, all samples showed measurable aerobic bacterial counts, but remained below the accepted limit for ready-to-eat fried snacks (5.99 log CFU/g), indicating acceptable microbial quality. Significant year-wise variation in TPC was observed for Kerala Mixture ($p < 0.000001$) and Tapioca Chips ($p = 0.0074$), while Kerala Murukku, Banana Chips, or Achappam did not show significant changes over time ($p > 0.05$).

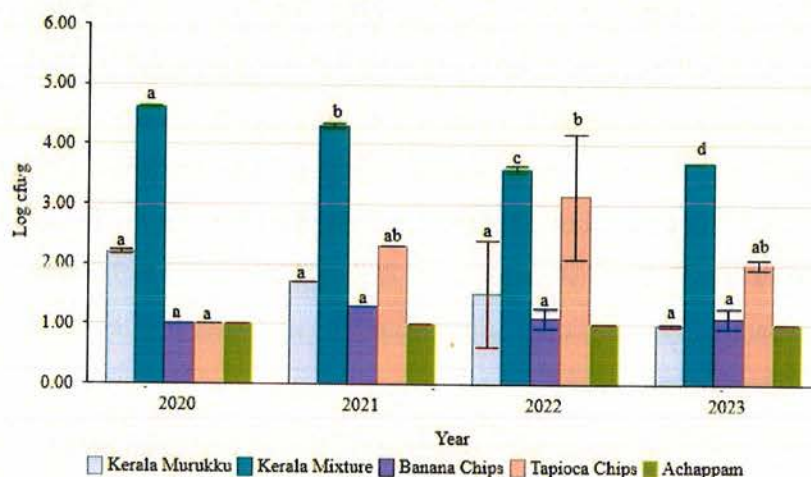


Figure 4. Total Plate Count (log CFU/g) in five traditional Indian fried snack products from 2020 to 2023. Bars indicate mean values \pm standard deviation. Superscript letters denote

statistically significant differences between years within each product ($p < 0.05$). Means sharing the same letter are not significantly different. *Source: own study based on P3 publication.* Adapted from (Sasikumar Nair et al., 2025), Applied Sciences, CC BY 4.0

Kerala Mixture consistently exhibited the highest TPC, with the peak mean value of 4.61 log cfu/g in 2020, suggesting greater susceptibility to contamination. Similar findings have shown that while low-moisture snacks are generally microbiologically stable, contamination risks persist, especially after frying, due to seasoning and handling during cooling and packaging (Kuehm and Casas, 2014). In contrast, Achappam consistently demonstrated the lowest TPC, indicating better microbiological stability. Comparable low counts (5.78×10^2 CFU/g) have been reported by Navarro et al. (2018), on banana chips, where effective frying and post-processing conditions limit contamination. The findings highlight that while frying ensures initial microbial reduction, post-processing stages remain as the critical control points. Therefore, better hygiene, equipment sanitation, and controlled handling are required, especially for complicated products like Kerala Mixture.

5.2.3. Correlation between physicochemical parameters and microbial counts across products

Principal Component Analysis (PCA) was applied to find the multivariate relationships among physicochemical properties, ingredient formulations, microbial quality, and sampling years across the five traditional fried snack products (Figure 5). The first two principal components explained 56.50% of the total variance (PC1: 38.15%, PC2: 18.35%), indicating major sources of variability of the dataset.

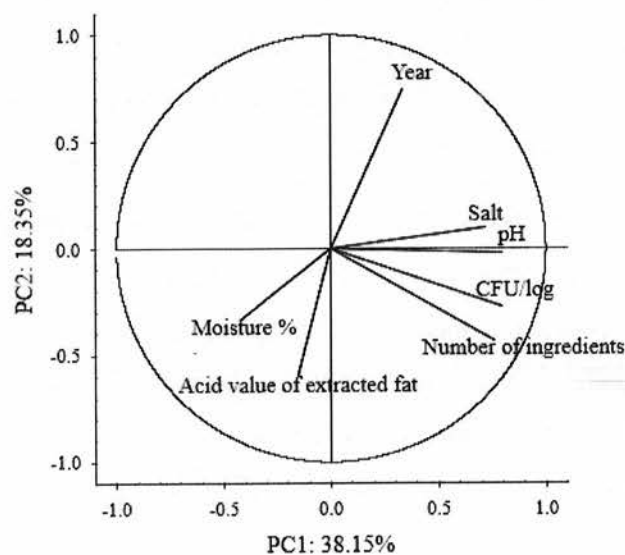


Figure 5. PCA biplot showing correlations between physicochemical and microbiological parameters, ingredient count, and sampling years across all analyzed products. *Source: own study based on P3 publication.* Adapted from (Sasikumar Nair et al., 2025), Applied Sciences, CC BY 4.0

The PC1 showed a positive correlation with the number of ingredients, CFU/log, pH, and salt content, suggesting product complexity and formulation characteristics are linked to microbial load and compositional attributes. PC2 was associated with moisture% and acid value, but with negative correlations with PC1, as explained in the **P4** publication. Similar observations have been reported in low-moisture food systems, where microbial presence is primarily influenced by handling practices rather than growth conditions (Beuchat et al., 2013).

The positive and negative correlations identified from PCA were further supported by Spearman's correlation analysis. A significant moderate negative correlation was observed between the acid value of extracted fat and year ($\rho = -0.56$, $p < 0.05$), reflecting a progressive reduction in acid value and suggesting improved oil stability in later production years.

5.2.4. Clustering of products based on microbial quality

Multivariate cluster analysis was applied to classify snack products based on microbial quality (CFU/log). Two distinct clusters were identified (Figure 6). Cluster 1 comprised Kerala Murukku, Banana Chips, Achappam, and Tapioca Chips, all of which consistently exhibited lower microbial counts over the years, reflecting effective food safety control measures. In contrast, Cluster 2 consisted only of Kerala Mixture, which displayed comparatively higher microbial loads (4.61 ± 0.01 in 2020 to 3.70 ± 0.00 in 2023), although still within acceptable limits. The separation of Kerala Mixture into a distinct cluster suggests a product-specific vulnerability to contamination.

Previous studies have demonstrated that effective FSMS implementation can enhance microbiological quality and operational control through better process control, monitoring, and hygiene practices (Chen et al., 2021; Yen et al., 2021). While this study did not directly assess FSMS implementation, the facility was ISO 22000:2018 certified, and the year-to-year variation in product quality indicators underscores the need for ongoing, practical application of these systems, especially in manual small-scale operations.

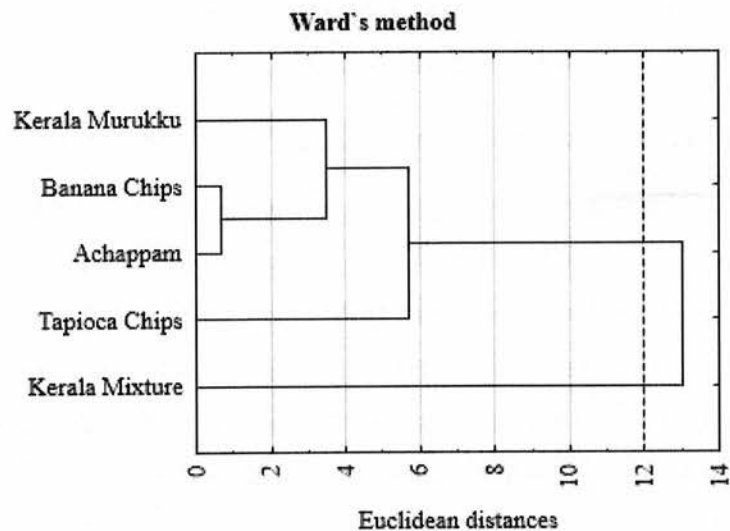


Figure 6. Hierarchical clustering dendrogram of five fried snack products based on their average Total Plate Count (log CFU/g) values from 2020 to 2023, using Ward's method and Euclidean distances. *Source: own study based on P3 publication.* Adapted from (Sasikumar Nair et al., 2025), Applied Sciences, CC BY 4.0.

Standardised processing is essential for ensuring product consistency, as the higher microbial load observed in Kerala Mixture is likely linked to manual, small-scale operations. Although the company is ISO 22000:2018 certified, certification alone reflects system presence rather than implementation effectiveness. The observed variability suggests inconsistencies in monitoring, verification, and corrective actions, indicating a gap between established procedures and their execution. Therefore, strengthened operator-level controls and standardised handling practices are required to improve product uniformity. Nevertheless, all products remained within acceptable limits, indicating sustained baseline food quality. **These results support the hypothesis that certification-based food safety management implementation is associated with sustained post-certification food quality, as reflected by microbiological and physicochemical product quality indicators over time (H2).**

5.3. Phase III. Assessment of the degree of compliance with the food safety management requirements in food retail shops

5.3.1. Influence of location, retail format, and staffing on FSMS compliance

Retail food establishments with inadequately implemented FSMS demonstrate higher rates of non-compliance, whereas those with comprehensive FSMS frameworks show markedly better conformity with food safety standards (U.S. FDA, 2024). This study assessed compliance with FSMS practices in retail shops across Mazovia and Kerala, revealing several areas requiring improvement to enhance FSMS performance in both countries. The inspection checklist demonstrated excellent internal consistency (Cronbach's $\alpha = 0.97$).

The Kruskal-Wallis test showed that the average total compliance scores were significantly influenced by country, location, food sector, and number of employees ($p < 0.001$). Dunn's post-hoc analysis indicated significantly higher compliance in Mazovia (Mean rank, $R = 559.67$) compared to Kerala ($R = 441.33$) ($p < 0.001$), with significant differences also observed within each country across all factors. Higher compliance was associated with hypermarkets and urban locations, while lower scores were observed in local shops, rural areas, and single-employee shops, with Polish shops showing less variation and higher compliance across all factors (Table 6).

Table 6. FSMS compliance scores of retail shops according to location, retail format, and number of employees in each region.

		FSMS Compliance score (Mazovia)		FSMS Compliance score (Kerala)	
		N	Mean \pm SD	N	Mean \pm SD
Location	Big towns	257	3.49 \pm 0.48 ^a	175	3.59 \pm 0.38 ^a
	Small towns	181	3.41 \pm 0.48 ^a	165	3.00 \pm 0.58 ^b
	Rural areas	62	3.00 \pm 0.60 ^b	160	2.88 \pm 0.48 ^b
Type of retail shop	Hypermarkets	33	3.70 \pm 0.40 ^a	106	3.67 \pm 0.48 ^a
	Supermarkets	206	3.51 \pm 0.41 ^b	221	3.18 \pm 0.48 ^b
	Convenience shops	138	3.66 \pm 0.29 ^a	84	3.16 \pm 0.48 ^b
	Local shops	123	2.84 \pm 0.50 ^c	89	2.54 \pm 0.35 ^c
Number of employees	>10	41	3.44 \pm 0.53 ^{ab}	81	3.75 \pm 0.32 ^a
	5-10	90	3.56 \pm 0.43 ^a	52	3.42 \pm 0.49 ^b

	4-5	72	3.58 ± 0.32^a	121	3.21 ± 0.54^b
	2-3	113	3.36 ± 0.55^b	179	3.02 ± 0.48^c
	1	184	3.26 ± 0.56^{ab}	67	2.59 ± 0.41^d

Different superscript letters within each column denote statistically significant differences between groups ($p < 0.05$), based on Dunn's post-hoc test comparisons. Values sharing the same letter are not statistically different. *Source: own study based on P4 publication.* Adapted from (Nair et al., 2026), Applied Sciences, CC BY 4.0.

This pattern was further supported by cluster analysis, which showed a clear separation between Mazovian and Kerala retail shops, indicating distinct FSMS compliance structures between the two regions (Figure 7). The separation of these clusters suggests a distinct compliance pattern between the two regions, with Kerala retail shops showing greater variability and generally lower FSMS performance compared to Mazovian shops. The results indicate a clear divergence in FSMS implementation across the two national contexts.

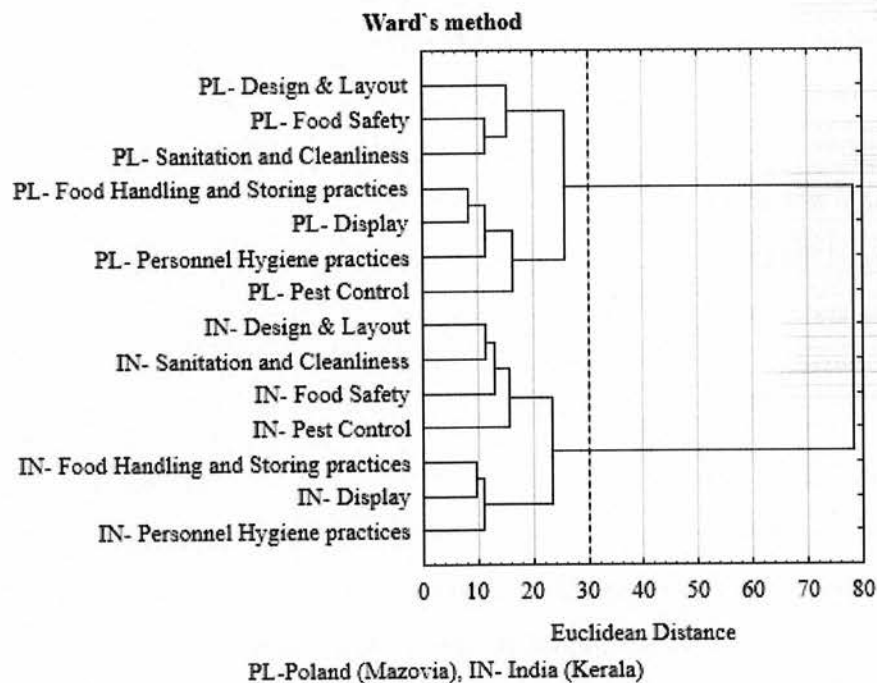


Figure 7. Dendrogram showing clusters extracted from Mazovia (Poland) and Kerala (India) retail shops based on section-wise FSMS compliance performance. *Source: own study based on P4 publication.* Adapted from (Nair et al., 2026), Applied Sciences, CC BY 4.0.

Inadequate FSMS implementation has been associated with food safety incidents and regulatory actions, including improper food handling, inadequate hygiene practices, and

poor temperature control in retail settings (Food and Drug Administration., 2023; Gibson et al., 2013; UDAF, 2022). Moreover, even where basic hygiene practices are in place, maintaining consistent implementation remains a challenge due to operational limitations and variability in staff practices. This underscores the need for clearer guidelines and stronger institutional support to improve FSMS adoption across retail environments (Zajac et al., 2021).

5.3.2. Management of FSMS in Retail Shops

Section-wise analysis revealed that differences in FSMS compliance between Mazovia and Kerala were primarily associated with behaviour-dependent FSMS components (Table 7). Significant differences ($p < 0.05$) were observed in six of the seven FSMS sections (2-7), with higher mean scores reported in Polish retail shops. No significant difference was found in the design & layout section ($p = 0.103$). The largest differences were identified in sections related to the requirements for display, personal hygiene practices, and pest control.

Table 7. Mean scores of food retail shops across Mazovia and Kerala.

Section number	Sections	Mazovia	Kerala	p*
		Mean score of FSMS compliance	Mean score of FSMS compliance	
Section 1	Design & Layout	3.146	3.108	0.103
Section 2	Food Safety	3.157	3.010	0.000
Section 3	Food Handling and Storing Practices	3.537	3.318	0.000
Section 4	Display	3.615	3.374	0.000
Section 5	Personnel Hygiene Practices	3.484	3.174	0.000
Section 6	Sanitation and Cleanliness	3.227	3.096	0.019
Section 7	Pest Control	3.346	2.815	0.000

*Mann-Whitney *U* test. Source: own study based on P4 publication. Reproduced from (Nair et al., 2026), Applied Sciences, CC BY 4.0.

Differences in hygiene culture and management practices may further influence FSMS outcomes. In this study, Polish retail stores more frequently displayed hygiene signage and food safety information, whereas such visual cues were less common in Indian retail stores, supporting previous findings that communication, training, and visible hygiene prompts are key factors in strengthening food safety culture (Wu et al., 2020).

Significant differences between regions were observed in product display, personnel hygiene, and pest control, likely reflecting differences in retail organization and management structures. Previous studies emphasize the importance of workforce training, managerial commitment, and supervision in maintaining hygienic practices, while infrastructural factors such as layout, maintenance, and pest prevention also affect compliance, particularly in small retail establishments (EFSA Panel on Biological Hazards et al., 2018; Neal et al., 2012; Soon-Sinclair et al., 2012).

No significant difference was identified in the design and layout dimension, with both regions showing moderate compliance (mean=3). This similarity may reflect the influence of baseline regulatory requirements (FSSAI, 2017b; Schirone et al., 2018), although optimal conditions were not consistently achieved. Broader organisational factors also influence FSMS compliance as structured retail systems tend to support standardisation, whereas mixed formal- informal sectors show greater variability (Gurav, 2015; Reardon et al., 2003; Soon-Sinclair et al., 2012).

Temperature control remains a key challenge in retail food safety, with inconsistent monitoring observed, particularly in Kerala. Issues such as inadequate maintenance and improper storage were observed in both regions, consistent with previous findings (Choi et al., 2016; Liggans and Kim, 2024; Psomatakis et al., 2024; Zajác et al., 2021). Pest control issues, including inadequate barriers, open access points, and the presence of animals, further indicate gaps in prerequisite programme implementation, despite established international guidelines (FAO and WHO, 2014; Food and Agriculture Organization of the United Nations., 2009). Field observations supported the quantitative findings by identifying both compliant and non-compliant practices across retail environments. Similar compliance patterns were observed within franchise-based shops, while greater variability occurred across independent shops. A detailed description of these observations is provided in publication **P4**.

5.3.3. Principal component analysis of FSMS compliance patterns

The PCA biplot (Figure 8) illustrates the projection of average FSMS compliance scores of eight retail formats (four from Mazovia and four from Kerala), along with a benchmark for full compliance. The first two principal components explained 80.23% of the total variance (PC1=53.97%; PC2=26.26%), indicating a strong representation of variability in compliance patterns. The full compliance reference was positioned at the positive axis of

PC1, representing optimal compliance. Hypermarkets from both regions were located closest to this benchmark, demonstrating the highest compliance levels, whereas supermarkets, convenience shops, and local shops were positioned further away, indicating lower compliance.

Higher FSMS compliance observed in hypermarkets can be attributed to structural advantages, including better infrastructure, systematic procedures, and greater staff availability. Small and medium-sized enterprises (SMEs) often face barriers such as limited resources and financial capacity, insufficient motivation for compliance, and challenges in maintaining inspection and auditing (Al-Busaidi et al., 2017; EFSA Panel on Biological Hazards et al., 2018; Psomatakis et al., 2024). These constraints were also evident among smaller retail shops in both Mazovia and Kerala. Previous studies in Poland have shown that although elements are implemented in small enterprises, they are often incomplete and not consistently integrated into daily operations due to resource constraints and perceived system complexity (Dzwolak, 2017, 2014).

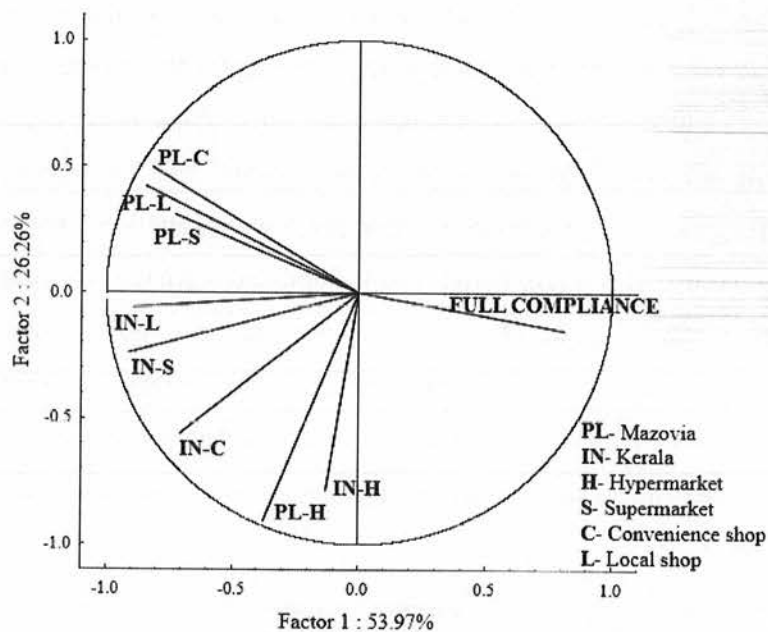


Figure 8. Principal component analysis (PCA) biplot showing the relationship between retail shop types and FSMS compliance levels in Mazovia and Kerala. *Source: own study based on P4 publication.* Adapted from (Nair et al., 2026), Applied Sciences, CC BY 4.0.

The current study reaffirms that implementing FSMS is challenging for small retail shops, including local shops and supermarkets, in both developing and developed contexts. The

findings highlight overall FSMS compliance levels and key areas requiring improvement to ensure food safety at the retail stage. Significant differences were observed between the two regions, with compliance influenced by shop-specific factors such as location, retail format, and workforce size. These findings suggest the need for targeted strategies, including enhanced monitoring and training in larger outlets and simplified guidelines with focused hygiene training for smaller retail shops. **These results validate the hypothesis that implementation of food safety management is associated with improved compliance with food safety regulatory requirements (H1).**

5.4. Phase IV. Assessment of the degree of compliance with the requirements of food safety and sustainability practices in grocerants.

This study offers a cross-sectional comparison of prevailing compliance levels in grocerants, examining both Food Safety Practices (FSP) and Sustainability Practices (SUST) across countries with different regulatory and governance frameworks. The reliability analysis demonstrated strong internal consistency for both sections of the observational checklist, with Cronbach's alpha values of 0.920 for FSP and SUST practices, confirming the robustness of the measurement tool for cross-country compliance assessment.

5.4.1. Cross-country variation in food safety and sustainability compliance.

Figure 9 shows mean compliance scores for FSP and SUST in three countries. Based on the Kruskal-Wallis test, significant differences were observed among Ghana, Poland, and India for both FSP ($\chi^2 = 30.1478$, $p < 0.05$) and SUST ($\chi^2 = 9.981$, $p = 0.0068$), demonstrating that compliance is strongly influenced by national environments and governance maturity. Post-hoc comparisons showed Polish grocerants scored higher in FSP than Ghana and India ($p < 0.05$), with no difference between Ghana and India (Figure 9a). Similarly, in the SUST section, Polish grocerants outperformed in Ghana ($p < 0.05$), but India did not differ significantly from either group (Figure 9b).

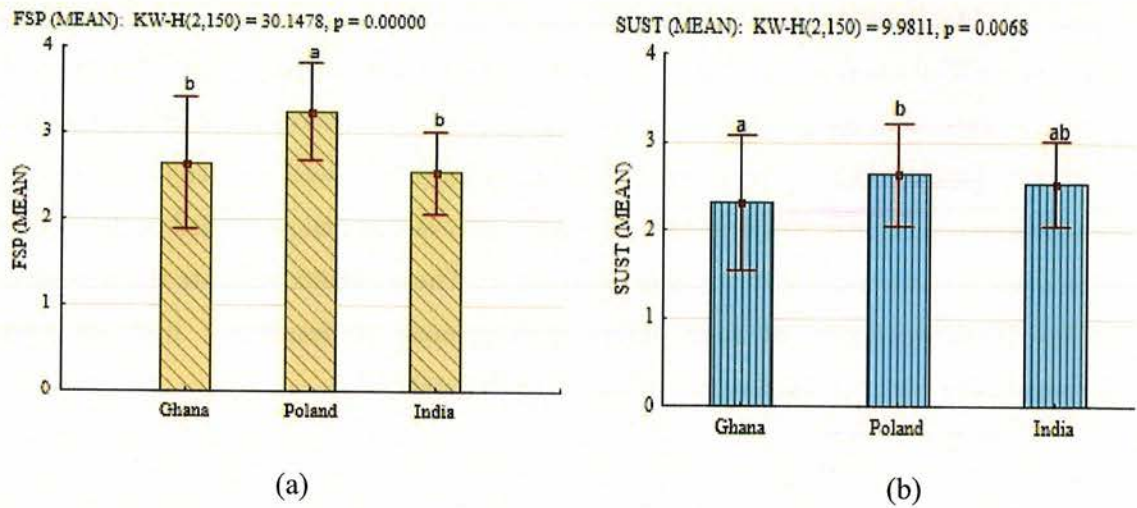


Figure 9. Box plots (\pm SD) showing differences in prevailing (a) Food Safety Practices (FSP) scores (Likert scale 1-4) and (b) Sustainability Practices (SUST) scores across Ghana, Poland, and India. Kruskal-Wallis tests indicated significant differences ($p < 0.001$). Different letters above the bars denote significant pairwise differences between countries based on post-hoc test multiple comparisons of mean ranks ($p < 0.05$). Source: own study based on P5 publication.

This pattern supports findings by Nyarugwe et al. (2020), who reported that stronger food safety governance systems are associated with proactive compliance behaviours and higher food safety culture maturity. Similarly, Rincon-Ballesteros et al. (2024) observed that enterprises operating within developed regulatory frameworks demonstrate more structured FSMS implementation.

5.4.2. Food Safety Practices

To provide an overview of the prevailing Food Safety Practices across each country, Table 8 depicts mean scores (\pm SD) for the assessed indicators used to determine the prevailing FSP of the grocerants.

Table 8. Mean \pm SD scores of Food Safety Practices (FSP) across Ghana, Poland, and India

Q.No.	Questions	Ghana	Poland	India	KW-H test*
Q1	Layout	3.1 \pm 0.93 ^a	2.8 \pm 0.99 ^a	2.2 \pm 0.82 ^b	18.00, $p < 0.001$
Q2	Ventilation and Lighting	3.0 \pm 1.05	3.0 \pm 0.90	2.6 \pm 0.93	5.57, $p = 0.061$
Q3	Food safety information	2.1 \pm 1.22 ^a	3.0 \pm 1.02 ^b	1.9 \pm 0.77 ^a	25.98, $p < 0.001$
Q4	Sanitary area	3.2 \pm 0.82 ^a	3.3 \pm 0.80 ^a	2.8 \pm 0.76 ^b	13.57, $p = 0.001$
Q5	Storage	2.6 \pm 1.05 ^a	3.6 \pm 0.70 ^b	2.6 \pm 0.88 ^a	32.43, $p < 0.001$
Q6	High-risk separation	2.5 \pm 1.07 ^a	3.7 \pm 0.61 ^b	3.0 \pm 0.70 ^a	39.19, $p < 0.001$

Q7	Expiry control	2.2±0.95 ^c	3.7±0.67 ^a	3.2±0.74 ^b	58.49 p<0.001
Q8	Display protection	2.5±0.97 ^b	3.7±0.54 ^a	3.0±0.80 ^b	42.04, p<0.001
Q9	Protective wear	2.3±1.23 ^b	3.0±1.12 ^a	2.0±0.92 ^b	19.43 p<0.001
Q10	Hygiene behaviour	3.2±0.78	3.2±0.77	3.1±0.97	0.34, p=0.84
Q11	Clean surface	2.8±0.93 ^b	3.6±0.70 ^a	2.8±0.62 ^b	32.41, p<0.001
Q12	Cleaning routine	2.9±0.84 ^a	3.0±0.99 ^a	2.4±0.85 ^b	14.36, p=0.001
Q13	Pest signs	2.4±0.99 ^b	3.4±0.76 ^a	2.2±0.81 ^b	43.00, p<0.001
Q14	Pest devices	2.2±1.27 ^{ab}	2.6±1.01 ^a	2.0±0.95 ^b	7.26, p= 0.027

*Kruskal-Wallis tests indicated significant differences (p<0.001). Different letters above the bars denote significant pairwise differences between countries based on post-hoc test multiple comparisons of mean ranks (p< 0.05). No letter denotes no significance. *Source: own study based on P5 publication.*

Polish grocerants demonstrated the highest overall compliance, with mean scores primarily ranging from 3.0 to 3.7, indicating partial to full compliance across most indicators. The highest scores were recorded for Q6 (High-risk items, such as raw meat or seafood, are kept separate from direct customer contact), Q7 (Expired products are not displayed), and Q8 (Displayed foods are protected from customer handling or contamination). These findings indicate strong implementation of preventive hygiene measures and systematic monitoring of product segregation and display conditions. However, comparatively lower adherence was observed for Q14 (Pest control devices are present and maintained in working order), implying that pest management systems may not be as diligently maintained or routinely inspected as other hygiene practices. Nyarugwe et al. (2020) corroborate these findings, noting that proactive food safety behaviors and enhanced compliance usually occur in well-organized food governance systems and among those participating in private standards.

Ghanaian and Indian grocerants generally demonstrated moderate compliance with food safety practices, with average scores ranging from 2.1 to 3.2, indicating partial fulfillment of most requirements with consistent effort. As shown in Table 8, Ghana's highest adherence was observed in maintaining sanitary food preparation areas (Q 4, 3. 2 ± 0.8), supporting hygienic shop layouts (Q1, 3.1 ± 0.9), and employees practicing hygiene during food preparation (Q10, 3.2 ± 0.8). These findings suggest Ghanaian establishments prioritize cleanliness and staff hygiene. However, lower compliance was noted in displaying food safety information (Q3, 2.1 ± 1.2) and managing expired products (Q7, 2.2 ± 0.9), indicating inconsistencies in documentation and monitoring. Although overall compliance in Ghana was moderate, the pattern of mean responses indicates that basic

hygiene behaviours are relatively well embedded in daily operations, while managerial and preventive control measures remain less developed (Monney et al., 2014). This finding suggests that grocerants have achieved functional cleanliness and acceptable staff hygiene standards but still lack systematic oversight through documentation, monitoring, and pest-management activities. Such partial implementation aligns with earlier findings from Ghana, where food-handlers exhibited adequate food safety knowledge but failed to consistently apply it in practice (Akabanda et al., 2017). Although Ghana's food safety regulations are largely well-established under the Public Health Act ("Public Health Act 851," 2012) and the Food and Drugs Authority's (FDA) mission, enforcement and implementation remain challenging due to capacity and resource limitations (Monney et al., 2014).

In India, grocerants scored higher on separating high-risk items from customer contact (Q6, 3.0 ± 0.8), avoiding display of expired products (Q7, 3.2 ± 0.7), and protecting displayed foods from contamination (Q 8, 3.0 ± 0.8), reflecting satisfactory implementation of basic preventive hygiene controls. These results indicate that key principles promoted under the Food Safety and Standards Authority of India (FSSAI) are increasingly implemented at the retail food service level. Nevertheless, lower compliance in the display of food safety information (Q3, 1.9 ± 0.9) and pest control (Q14, 2.0 ± 0.9) highlights weakness in communication systems and facility-level preventive management. This uneven adoption of food safety management practices reflects India's transitional regulatory context, where foundational hygiene behaviours are present, but systematic FSMS implementation remains inconsistent due to infrastructural and execution constraints (Jena, 2018; Sharma, 2022). Qualitative studies also highlight similar challenges, including limited managerial commitment, poor infrastructure, and reliance on longstanding informal practices that hinder consistent food safety standards (Kumari and Kapur, 2018).

The Kruskal-Wallis test (post-hoc: multiple comparisons of mean ranks) was conducted on the average scores of FSP variables for each country to determine whether the observed differences in Table 8 were statistically significant. The analysis revealed significant variations across countries in shop layout design, display of food safety information, separation of high-risk items, and food protection practices among Polish, Ghanaian, and Indian grocerants. Polish grocerants consistently attained higher mean ranks, whereas Ghanaian and Indian grocerants demonstrated moderate compliance. No significant

differences were identified in ventilation, lighting, hygienic food preparation, or pest control measures.

5.4.3. Sustainability Practices

Table 9 delineates the mean scores utilized to evaluate the sustainability approaches adopted by grocerants. A partial level of compliance was observed across the three countries, with Ghanaian grocerants exhibiting lower scores compared to those in India and Poland. Ghanaian grocerants demonstrated moderate adherence to sustainability practices, with mean scores ranging from 1.6 to 2.7, indicating that most requirements were only partially fulfilled with limited to minimal efforts. As evidenced in Table 9, relatively higher compliance was noted for energy-efficient appliances and equipment (Q16, 2.7 ± 0.9), the use of environmentally friendly cleaning products (Q17, 2.7 ± 1.0), and the promotion of local products (Q28, 2.7 ± 0.9), suggesting that Ghanaian grocerants exerted moderate efforts to integrate energy conservation and local sourcing into their daily operations. Conversely, lower mean scores were recorded for initiatives such as discounting surplus food to minimize waste (Q18, 2.1 ± 1.1), donating surplus food to shelters or charities (Q19, 2.1 ± 1.1), imposing charges for single-use bags (Q20, 1.6 ± 0.9), indicating limited or inconsistent waste reduction efforts, and waste segregation and recycling systems (Q21, 1.6 ± 0.9), reflecting underdeveloped practices in packaging sustainability and waste reduction practices. This pattern corresponds to the *initial phase* of sustainability maturity, where enterprises prioritise operational efficiency and cost-saving measures rather than structured environmental and social sustainability strategies (León Bravo et al., 2021). Similar tendencies have been observed in food retail settings where sustainability actions are driven primarily by immediate economic benefits rather than long-term environmental planning (Bekele et al., 2012). The limited adoption of formal waste management and food redistribution practices further suggests the absence of standardised sustainability assessment frameworks, which constrains systematic monitoring and improvement of sustainability performance in developing retail contexts

Polish grocerants demonstrated relatively high compliance with sustainability practices, with average scores ranging from 1.1 to 3.8, indicating levels from minimal to full compliance across various parameters. The highest compliance was seen in accepting private food containers and bags (Q26, 3.8 ± 0.7), store charges for single-use bags (Q20, 3.4 ± 1.0), and using eco-friendly cleaning products (Q17, 3.3 ± 1.0). Conversely, compliance was low for offering discounts on surplus food (Q18, 1.7 ± 0.9) and food

donation shelters (Q19, 1.1 ± 0.5), showing limited engagement with social sustainability initiatives. The overall strong sustainability performance of Polish grocerants reflects a mature operational environment shaped by regulatory pressure and environmentally conscious consumer behaviour within the European Union (European Commission, 2002; Havinga, 2013). These findings on compliance align with Rincon-Ballesteros et al. (2024), indicating that developed countries maintain stable economic and social conditions, facilitating food access, responsible procurement and consumption, and stringent safety legislation. This pattern aligns with the *committed stage* of sustainability maturity, in which organisations adopt structured environmental practices beyond operational efficiency while progressively integrating broader social responsibility (León Bravo et al., 2021). However, the weaker performance in food redistribution initiatives suggests that even in advanced regulatory contexts, social sustainability remains less institutionalised with environmental compliance.

Indian grocerants displayed moderate sustainability compliance, with mean scores between 1.5 and 3.7, reflecting partial to full compliance across most parameters. Higher compliance was observed for acceptance of private food containers and bags (Q26, 3.7 ± 0.6), adoption of alternative sustainable packaging (Q15, 2.6 ± 0.9), use of eco-friendly cleaning products (Q17, 2.6 ± 0.9), and implementation of energy-efficient appliances (Q16, 2.6 ± 0.9). These practices indicate increasing integration of visible environmental approaches within food-retail operations, aligning with the diffusion of national sustainability programmes such as the Eat Right India framework (“Eat Right India,” 2025) into everyday business practices. In contrast, lower compliance in prohibiting non-compostable labels (Q22, 2.5 ± 0.8), availability of organic produce (Q25, 2.5 ± 0.9), and waste segregation systems (Q21, 1.5 ± 0.9), indicating persistent weakness in material management and circular economy practices. This study aligns with Bălan (2021), who found that retailers often serve as key intermediaries in promoting sustainable consumption through marketing strategies, information cues, and product variety. The sustainability trends in Indian grocerants correspond to the *committed*, but transitional maturity level (León Bravo et al., 2021), where enterprises selectively implement externally promoted sustainability approaches rather than fully institutionalising comprehensive environmental and social responsibility frameworks.

The Kruskal-Wallis test revealed significant differences ($p < 0.05$) among Ghana, Poland, and India in certain sustainability indicators. Overall, the countries showed moderate

variation in their sustainability practices, with no single region consistently outperforming others across all measures. Notably, there was significant variation in indicators like alternative packaging (Q15), energy-efficient appliances (Q16), and eco-friendly cleaning products (Q17). Conversely, for indicators such as natural lighting use (Q24), zero plastic packaging (Q27), and promoting local products (Q28), no significant differences ($p > 0.05$) were observed, indicating similar levels of adoption in all three countries.

Table 9. Mean \pm SD scores of Sustainability Practices (SUST) across Ghana, Poland, and India.

Q.No.	Questions	Ghana	Poland	India	KW-H test
Q15	Alternative packaging	2.4 \pm 1.05 ^a	3.1 \pm 0.90 ^b	2.6 \pm 0.96 ^{ab}	12.41, $p=0.002$
Q16	Energy-efficient appliances	2.7 \pm 0.89 ^b	3.2 \pm 1.01 ^a	2.6 \pm 0.86 ^b	13.93, $p=0.0009$
Q17	Eco-clean	2.7 \pm 1.00 ^b	3.3 \pm 0.95 ^a	2.6 \pm 0.86 ^b	17.46, $p=0.0002$
Q18	Discounts	2.1 \pm 1.09 ^{ab}	1.7 \pm 0.95 ^b	2.4 \pm 0.91 ^a	14.84, $p=0.0006$
Q19	Food donation	2.1 \pm 1.15 ^a	1.1 \pm 0.48 ^b	1.9 \pm 0.81 ^a	35.83, $p<0.001$
Q20	Bag charge	1.6 \pm 0.97 ^b	3.4 \pm 1.05 ^a	3.0 \pm 0.94 ^a	57.86, $p<0.001$
Q21	Waste segregation	1.6 \pm 0.92 ^{ab}	2.1 \pm 1.20 ^a	1.5 \pm 0.91 ^b	8.13, $p=0.017$
Q22	Label prohibition	2.2 \pm 1.14 ^b	3.0 \pm 1.07 ^a	2.5 \pm 0.79 ^b	16.11, $p=0.0003$
Q23	Sustainable refrigeration	2.5 \pm 0.93	2.5 \pm 1.40	2.2 \pm 0.91	2.30, $p=0.317$
Q24	Natural light	2.7 \pm 1.00	2.7 \pm 1.00	2.7 \pm 0.96	0.32, $p=0.85$
Q25	Organic products	2.5 \pm 0.91 ^a	2.0 \pm 1.12 ^b	2.5 \pm 0.86 ^a	11.42, $p=0.003$
Q26	Private bag	2.0 \pm 1.02 ^b	3.8 \pm 0.71 ^a	3.7 \pm 0.61 ^a	79.40, $p<0.001$
Q27	Zero plastic	2.5 \pm 0.99	2.2 \pm 0.97	2.3 \pm 1.04	2.32, $p=0.31$
Q28	Local products	2.7 \pm 0.91	2.7 \pm 1.05	2.9 \pm 0.78	1.00, $p=0.607$

*Kruskal-Wallis tests indicated significant differences ($p<0.001$). Different letters above the values denote significant pairwise differences between countries based on post-hoc multiple comparisons of mean ranks ($p < 0.05$). No letter denotes no significance. *Source: own study based on P5 publication.*

5.4.4. Hierarchical cluster analysis

A hierarchical cluster analysis was conducted to classify grocerants based on their adherence to Food Safety Practices (FSP) and Sustainability Practices (SUST), utilising the scores of 28 individual variables. The analysis yielded three distinct clusters: Cluster A primarily consisted of grocerants from Ghana ($n=26$) with a few from Poland ($n=3$); Cluster B comprised a mixture of grocerants from Ghana ($n=13$), Poland ($n=17$), and predominantly from India ($n=48$); whereas Cluster C was mainly composed of Polish grocerants ($n=30$), along with Ghanaian ($n=11$) and Indian ($n=2$) grocerants. These three

clusters were subsequently compared using mean scores for FSP and SUST to assess statistically significant differences across countries (Table 10).

The Kruskal-Wallis test indicated that there were no statistically significant differences in food safety practice (FSP) scores among the countries within the respective clusters ($p > 0.05$), indicating that grocerants within the same cluster exhibit comparable hygiene performance regardless of national context. Conversely, the sustainability practice (SUST) scores demonstrated a marginally significant difference in Cluster B ($H = 5.99$, $p = 0.05$), and a statistically significant difference in Cluster C ($H = 6.28$, $p = 0.043$), where Indian grocerants exhibited higher sustainability compliance, although post-hoc comparisons did not confirm clear pairwise differences.

Table 10. Mode scores, mean scores, and the significant differences for the prevailing Food Safety Practices (FSP), Sustainability Practices (SUST) among countries within Clusters A, B, and C.

Section	Country	Cluster A (n=29)		KW-H test	Cluster B (n=78)		KW-H test	Cluster C (n=43)		KW-H test
		Mode	Mean		Mode	Mean		Mode	Mean	
FSP	Ghana	2	2.5	0.00	2	2.4	4.25	4	3.9	1.52
	Poland	3	2.7	$p = 1.00$	3	2.8	$p = 0.11$	4	3.8	$p = 0.46$
	India	-	-	(ns)	3	2.6	(ns)	4	4.0	(ns)
SUST	Ghana	2	1.7	0.00	3	2.9	5.99	3	3.1	6.27
	Poland	1	1.0	$p = 1.00$	2	2.5	$p = 0.05$	3	2.9	$p = 0.04$
	India	-	-	(ns)	2	2.5	(**)	4	4.0	(*)

Mode and Mean values represent each country's average compliance within clusters.

(*) symbolise significant differences between countries based on the Kruskal-Wallis non-parametric test ($p < 0.05$), where (**) and (ns) denote borderline and no significance, respectively. Source: own study based on P5 publication.

Cluster A exhibited low overall compliance with food safety and sustainability practices, with mean FSP and SUST scores of approximately 2.5 and 1.7, respectively, indicating minimal implementation of structured control measures. Most of these shops were based in Ghana, showing limited adherence to food safety and sustainability standards. This pattern is comparable to initial-stage or reactive compliance environments reported in food safety governance studies, where hygiene and sustainability practices remain inconsistently applied under weak regulatory enforcement (Nyarugwe et al., 2020; Rajic et al., 2022).

Cluster B demonstrated partial compliance across both FSP and SUST, with mean scores ranging from 2.6 to 2.8, reflecting transitional implementation of food safety and sustainability practices. Similar patterns have been observed in enterprises that adopt management systems primarily in response to market or regulatory pressure rather than through fully institutionalised operational frameworks (Rincon-Ballesteros et al., 2024). In contrast, Cluster C mainly consisted of Polish and Indian grocerants, showed near-full compliance with food safety practices (mean 3.9-4.0) alongside strong engagement with sustainability measures (mean 3.1-4.0), indicating a mature implementation across both domains. This level of integrated compliance is comparable to high-performing organisations operating within structured governance environments characterised by systematic preventive controls and continuous improvement (Nyarugwe et al., 2020; Rincon-Ballesteros et al., 2024; Spagnoli et al., 2024).

5.4.5. Association between food safety and sustainability practices in grocerants

Spearman correlation analysis (Table 11) demonstrated a strong and statistically significant positive association between food safety and sustainability practices in Poland grocerants ($\rho = 0.516$, $p < 0.001$), indicating that shops with higher food safety compliance also tend to implement sustainability practices more effectively.

Table 11. Country-wise association between food safety and sustainability practices in grocerants.

Country	Spearman's R (FSP / SUST)	p- value
Ghana	0.357	0.011
Poland	0.516	< 0.001
India	0.172	0.231

Source: own study based on P5 publication.

In Ghanaian grocerants, a moderate but significant positive association ($\rho = 0.357$, $p = 0.0109$) was observed, suggesting an emerging connection between these practices. In contrast, the association in Indian grocerants was weak, and not statistically significant ($\rho = 0.172$, $p > 0.05$), indicating that sustainability efforts are currently implemented mostly independent of food safety practices.

The significant positive associations observed in Poland and Ghana support the Green HACCP concept, which promotes the simultaneous integration of food safety control and environmental sustainability within food operations (Zarid, 2025). These findings indicate

that as food safety systems become more structured and consistently implemented, sustainability practices increasingly become embedded within routine operational management. Conversely, the absence of a significant relationship in India highlights the fragmentation that remains present in several developing retail food systems, where environmental initiatives are often externally driven rather than integrated into core management practices.

The observed association between food safety and sustainability practices directly contributes to achieving Sustainable Development Goal (SDG) 12.3, which targets substantial reductions in food waste through improved operational control. As emphasised by Adams et al. (2025), effective food management practices such as inventory control and process optimisation play a central role in reducing waste while improving sustainability performance. These results further support the principles of Green Retailing, where sustainability is incorporated into everyday operational activities rather than treated as an isolated or optional initiative (Sinha and Chaudhuri, 2014). From a broader Sustainable Development Goals (SDGs) perspective, this integrated approach contributes to SDG 3 (Good Health and Well-being), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) by promoting hygienic, safe, and environmentally responsible retail food environments. **These findings supported the hypothesis that in operational settings where food safety and sustainability objectives intersect, higher food safety practice implementation is associated with stronger sustainability-related practices (H3).**

6. Conclusions

This dissertation demonstrated the importance of Food Safety Management System (FSMS) in improving food safety across different stakeholders in the food system and explored their potential association with sustainability-oriented approaches. By combining regulatory and standard requirements, certification-linked auditing, multi-year product-quality assessment, and cross-country observations from retail and grocerant settings, the dissertation provides an integrated, multi-context assessment of FSMS as an operational control system.

1. The effective implementation of the food safety management practices contributes to improved food safety compliance, and stronger operational food safety practices.
2. The assessment of the Food Safety Management System (FSMS) implementation in a small-scale food manufacturing company confirmed that certification according to the integrated food safety standards significantly improved compliance with food safety regulatory requirements.
3. The evaluation of post-certification food quality demonstrated that products manufactured in a certified Food Safety Management System (FSMS) environment maintained stable physicochemical and microbiological quality within acceptable limits.
4. The assessment of food safety management practices in the retail environments revealed significant differences across retail formats and geographical contexts, with higher compliance observed in structured systems and larger retail formats.
5. Integrating food safety management with sustainability-oriented practices may support the development of more sustainable food systems.

7. References

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8. Copies of the articles making up the doctoral thesis and statements of co-authors

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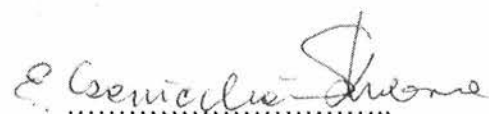
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AMERICAN FOREIGN SUPPLIER VERIFICATION PROGRAM (FSVP) – REQUIREMENTS, BENEFITS OR BURDENS FOR INDIAN FOOD COMPANIES, AND DIFFICULTIES IN THE IMPLEMENTATION®

Amerykański Program Weryfikacji Dostawców Zagranicznych (FSVP) – wymagania, korzyści lub obciążenia dla indyjskich firm spożywczych oraz trudności we wdrożeniu®

Key words: India, FSVP, food safety, importer.

The purpose of this article was to present the American Foreign Supplier Verification Program (FSVP). An importer of food is required to develop, maintain, and follow a Foreign Supplier Verification Program (FSVP) to ensure that each food product it imports meets FDA food safety standards. Specifically, an importer's FSVP must provide adequate assurances that: (a) the importer's foreign suppliers produce food with the same level of public health protection as those required by FDA for domestically produced food; and (b) the importer's foreign suppliers produce food that is not adulterated or misbranded. The FSVP regulations apply to all FDA-regulated food imported or offered for import into the United States.

Słowa kluczowe: Indie, FSVP, bezpieczeństwo żywności, importer.

Celem artykułu było przedstawienie Amerykańskiego Programu Weryfikacji Dostawców Zagranicznych (FSVP). Importer żywności jest zobowiązany do opracowania, utrzymywania i przestrzegania Programu Weryfikacji Dostawców Zagranicznych (FSVP) w celu zapewnienia, że każda importowana żywność spełnia normy bezpieczeństwa żywności FDA. W szczególności FSVP importera musi zapewnić odpowiednie gwarancje, że: (a) zagraniczni dostawcy importera produkują żywność o takim samym poziomie ochrony zdrowia publicznego, jak wymagany przez FDA dla żywności produkowanej w kraju; oraz b) zagraniczni dostawcy importera produkują żywność, która nie jest zafalszowana ani błędnie oznakowana. Przepisy FSVP mają zastosowanie do całej żywności podlegającej przepisom FDA, importowanej lub oferowanej do importu do Stanów Zjednoczonych.

INTRODUCTION TO THE FOREIGN SUPPLIER VERIFICATION PROGRAM (FSVP)

Food standards are increasingly impacting developing countries' trade balance and economic development. Over the past two decades, both public and private standards

have proliferated in global food supply chains. As the global food trade is increasing, the importance of uniform food standards for consumer protection is noticeable [29]. The most significant reform of food safety laws for developing countries in the history of the United States was the U.S. Food Safety Modernization Act (FSMA), which went into effect in September 2016 as it was signed into law by President Obama.

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Since then, the Food and Drug Administration (FDA) has been working to develop the rules that the act requires them to implement. The focus of this law is to prevent food safety issues in the U.S. food supply more effectively. The FSMA implementation is done through seven rules: (1) standards for produce safety; (2) preventive controls for human food; (3) preventive controls for food for animals; (4) a foreign supplier verification program; (5) accreditation of third-party auditors; (6) sanitary transportation of human and animal food; and (7) food protection against intentional adulteration [22, 23].

The Foreign Supplier Verification Program (FSVP) as a significant provision of FSMA [6]. The FSVP creates new requirements for importers of food for humans and animals into the United States. This regulation requires importers to perform risk-based activities to ensure that food imported into the United States was produced in accordance with applicable U.S. safety standards and that the food is not adulterated or allergen misbranded. The regulation includes standard requirements for larger importers as well as a modified set of procedures for importers who fall under the definition of "very small importer". Modified procedures can also be used when importing food products from certain small foreign suppliers. Importer refers to the owner or consignee of a food item offered for import into the United States. If that food does not have any U.S. owner or consignee at the time of entry, then the U.S. agent or representative of the foreign owner or consignee can be the importer, as confirmed in the signed statement of consent according to 21 CFR PART 1.500 [6]. The effectiveness of a food importer's FSVP is dependent on the calibre and knowledge of the Preventive Controls Qualified Individual (PCQI) it has chosen, the firm's hazard analysis, its food safety plans, the food safety programs of all its foreign suppliers, and the selection, implementation, and documentation of the appropriate levels of verification. For the last three years (2019–2022), the FDA has conducted 1645 FSVP inspections, of which 17 were found to comply with FSVP regulations equalling a compliance rate of 1% [1].

Regulations under the Foreign Supplier Verification Program are designed to ensure that imported food meets the same standards of quality as food made in the United States. Therefore, the process aims to enhance food safety by improving importers' responsibility for verifying foreign suppliers and compliance with GMPs. The FDA has released draft guidance for the Foreign Supplier Verification Program, which includes the most comprehensive set of requirements for importers to date [13]. The FSVP regulation applies to all food imported or offered into the United States. Apart from this, certain categories of imported food are not covered by the final rule which consists of certain juice, fish, and fishery products (because they are already subject to supplier verification requirements); food for research or evaluation; food for personal consumption; and alcoholic beverages and ingredients used in making alcoholic beverages, food that is transhipped through the U.S, food that is imported for processing and export, returned consignments, certain meat, poultry and egg products regulated by the FDA [7, 8].

THE FOREIGN SUPPLIER VERIFICATION PROGRAM (FSVP) – REQUIREMENTS

The FSVP rule is codified in 21 C.F.R.1, Subpart L, Sections 1.500–1.514 [6]. These regulations specify several requirements an importer must take when evaluating food and supplier for hazards and risks, including determining whom the FSVP importer is, conducting a hazard analysis of the food being imported, evaluating the foreign supplier, identifying and conducting verification activities on hazards requiring a preventive control, and re-evaluating food risks and the foreign supplier [4].

Suppliers play a significant role in the food industry sector. The quality of the final product is determined by many factors and one of them is raw materials and half-products used in the manufacturing process. Many authors emphasized the need to assess suppliers, including food importers [19, 30]. For the last 10 years, a considerable amount of research was carried out on supply chain management, especially: the selection of suppliers [5, 9, 31]. There is a similar requirement based on FSVP. The importers can only import foods from authorized foreign suppliers after assessing the risk the item poses and the supplier's track record. However, this does not preclude importers from temporarily importing food from unapproved suppliers as long as these products are subjected to sufficient verification procedures prior to importation. The FSVP mandates that importers develop, maintain, and follow an FSVP for each food imported into the United States from each foreign supplier of that food. This suggests that a separate FSVP would be necessary if an importer purchases a specific food from a different supplier. Similarly, if an importer purchases a variety of foods from a single supplier, a separate FSVP is required for each food [21]. If certain importers, who are also manufacturers or processors, comply with the supply-chain program requirements set forth in the preventive control rules, implement preventive controls for the hazards in the food in accordance with those rules or are exempt from those rules in certain specified situations, they are deemed to be in compliance with most FSVP requirements. Examples of such situations include those where the type of food (e.g. coffee beans) could not be consumed without the use of preventive control or when the customer will be significantly reducing or preventing identified hazards and they comply with disclosure and written assurance requirements. The risk must be re-evaluated at least every three years, or whenever new information about a potential hazard or the performance of a foreign supplier becomes available. If importers receive assurances that subsequent entities in the distribution chain are processing the food for food safety, they are not required to evaluate the food or conduct supplier verification activities. Importers must, however, disclose in the documents accompanying the food that the food has not been processed to control the identified hazard [21]. Importers will be required to document the hazards requiring controls of imported foods in order to proactively mitigate or eliminate them. An importer must also assess the vulnerability of the materials/products to food fraud and must produce documentation during a Food and Drug Administration inspection (FDA).

The frequent evaluation of the performance of importers' foreign suppliers is another important requirement of the FSVP rule. Foreign manufacturers' hazard analyses, entities in charge of hazard control (foreign manufacturers or their suppliers), food safety methods, processes, and practices, compliance with relevant regulations, and food safety history should all be included. Each facility would be required to implement a written food safety plan focused on hazard prevention. The regulation requires that certain activities must be completed by a "preventive controls qualified individual (PCQI)". Importers have an explicit responsibility to verify that their foreign suppliers have adequate preventive controls in place to ensure that the food they produce is safe. There are four types of preventive controls i.e., Process preventive controls, allergen preventive controls, sanitation preventive controls, supply chain preventive controls and other controls. An importer can rely on a third party to determine and perform appropriate supplier verification activities, so long as the importer reviews and assesses the relevant documentation. Annual on-site audits of the supplier's facility are required when there is a reasonable probability that exposure to a hazard controlled by the foreign supplier will result in serious adverse health consequences or death. An importer's verification activities may provide evidence that a foreign supplier has not provided the same level of public health protection as required under the Produce Safety and Preventive Controls rules. Taking appropriate corrective action by importers is the last requirement in meeting the FSVP requirements. The appropriate corrective measure will depend on the circumstances and may include discontinuing the use of the foreign supplier. According to the FSVP rule, importers must provide the name, email address, and unique facility identifier (UFI) for each line entry of food product offered for importation into the United States. The FDA has approved the data universal numbering system (DUNS) number as a valid UFI for the FSVP.

Although the FSVP proposed rule would not itself establish safety requirements for food manufacturing and processing, it would benefit the public health by helping to ensure that imported food is produced in a manner consistent with other applicable food safety regulations [6]. The research on the measurement of the effectiveness of FSMA FSVP implementation in food manufacturing companies is still very limited. Several authors have argued that increasing food standards, including FSVP, act as barriers to developing countries' integration in global markets and lead to the exclusion or reduced bargaining power of small farmers. On the other hand, there is evidence that standards can generate important benefits for poor rural households in developing countries, either in the form of contracts with processing or exporting companies, or as employees [29].

THE FOREIGN SUPPLIER VERIFICATION PROGRAM (FSVP) – BENEFIT OR BURDEN FOR INDIAN FOOD COMPANIES

Indian food regulatory model was a complex web of multiple ministries taking care of different food laws, standards setting and enforcement and even promotional bodies for different food commodities [29]. In 2006, the

Government of India consolidated food regulations into a single act known as the 'Food Safety and Standards Act' [10]. The FSSA covered the concept of food safety across the entire supply chain from manufacturing, storage, distribution. The FSSA consolidated the laws relating to food and established the Food Safety and Standards Authority of India (FSSAI) for laying down science-based standards for food regulating their manufacturing, storage, distribution, and sale to increase food safety [11, 28].

At the same time, the standards and conformity assessment are gaining increasing importance in relation to cross-border trade. Food safety and quality, a major agenda in international trade is, therefore, receiving increased attention in the Asia-Pacific region - especially in developing countries like India. Henson and Olale, 2011 analysed the E.U. and U.S. data for food products border rejections from 2002-2008 [17]. The study analysed four groups of products against some causes of rejections. From the data, in the United States, filthy/unsanitary conditions are the highest cause of rejections in fish and fishery products followed by microbial contaminants, while pesticide residues are a major cause of rejections in fruits and vegetables, labelling issues in nuts and seeds and microbial contaminants followed by labelling in herbs and spices. Some food manufacturing entities, especially exporting countries food governing bodies are not alert to producing healthy and safe food. Due to the lack of knowledge and awareness, it is very difficult for consumers to distinguish between healthy food and unhealthy food. A food production company may try to reduce production costs by mixing low-quality materials with the high-quality ones [24]. However, the expansion of food safety standards, including FSVP, has introduced new complexity in trade policy dialogues and efforts to expand global trade in agricultural products. A loss of competitiveness due to the significant costs required to comply with these standards has arisen concern among exporting firms, particularly those in developing countries [20].

In addition, for developing countries, it is difficult to comply with the food safety standards in developed countries as they are subject to change over time in response to emerging problems, advances in scientific knowledge, consumer concerns, political pressure, etc. The majority of food exporting industries show less interest in implementing these standards if the compliance comes at a large expense. However, a well-coordinated food safety management may generate international competitiveness and awareness in the global arena [24].

The implementation of food safety requirements in India has become a significant task in recent years. However, in comparison to other countries, such as the U.S., the U.K., the E.U., and Japan, food safety requirements and inspections in the Indian food chain are still not rigorous enough [2, 3, 15]. So, it is essential that all the importing countries have some kind of risk-based verification program/ activities to ensure that the food imported into their countries has been produced in a manner that meets their food safety requirements. FSMA applies to both domestic as well as imported food hence foreign food producers will have to adhere to the same safety standards as U.S. domestic farmers and food companies. Of these, three rules of significance to food exporters are the U.S.

are Preventive Controls for Human Foods (PCHF), Foreign Supplier Verification Program (FSVP) and Accredited Third-Party Certification [25]. Rejection of consignments of food exports from India to the U.S. in 2019 especially that of basmati rice, marine products, spices and fruits and vegetables, were mostly on grounds of contamination. The U.S. rejected a total of 1674 consignments compared to 1939 rejections the year before [27].

India is one of the largest producers of many crops and food grains such as rice, wheat, pulses, oilseeds, coffee, jute, sugarcane, tea, tobacco, groundnuts, dairy products, fruits, etc. Given these advantages, India is now exporting fresh and processed food products to a number of developed and developing country markets including the United States, the European Union, Vietnam and the Middle Eastern countries [14]. India's exports of fresh fruits and vegetables to the U.S. stood at 3,018 MT valuing 8.61 million USD in 2019–20 as against 2,541 MT valuing 7.97 million USD in 2018-19 [25]. During 2021–22, the U.S. was the largest importer of Indian agricultural products at US\$ 5.7 billion with a share of 11.5% of the total exports [18].

Multinational food corporations now account for a growing portion of the global food market. Food companies are keen to keep their reputation by offering safe and high quality food. Many of these companies have built food processing factories in developing countries where food safety regulations might be less stringent than in developed countries and where the ability of the government to conduct proper monitoring may be limited [12]. In India, the food industry is regulated by numerous legislatures which monitor the permits, licensing, and sanitation issues. The government also runs the Food Safety and Standards Authority of India (FSSAI) to monitor and regulate food processing, manufacturing, storage and market distribution. Despite a monitoring body to ensure safe food, public awareness must prevail.

Food standards do not necessarily lead to new barriers to trade but can also enhance developing countries' participation in high-value global food markets and generate benefits for the poor [29]. The benefit of FSMA FSVP is higher than the efforts, financial and time expenditures associated with the installation of inspection devices. The FSVP implementation can be viewed as both an opportunity to ensure food safety and defence against harm to a company's reputation that may emerge from recall efforts. We all know that prevention is better than cure, FSVP, one of the requirements as per FSMA rule is also focused on this by verifying that imported products comply with the same activity level of health protection concerning food safety as stated by FDA regulatory food requirements. Besides, the benefits will come back to consumers and the nation in general [24].

DIFFICULTIES IN THE IMPLEMENTATION OF FSVP

The number of border detentions is an explicit indicator of the ongoing difficulties that exporters in developing countries face in meeting food safety standards in industrialized countries. Indeed, the ultimate risk for exporters is that their consignments will be turned back at the border, necessitating the destruction of the implicated products or the incurring of

additional transportation costs to bring the products home or divert them to an alternative market [16]. Access to food export markets will be based on their ability to satisfy the regulatory requirements of importing nations [24]. Building the faith and confidence of importers and consumers in the integrity of their food systems is essential to creating and maintaining demand for their food goods in international markets. Such food safety measures are crucial because the agricultural output is the core of the economies of the majority of developing nations. In India, international standards, guidelines, and recommendations are increasingly used to guide domestic as well as international trade. If the FSVP importer obtains the foreign supplier's safety plan, unless the imported food is exempt or subject to modified requirements, a thorough evaluation of each imported food item (or type of food) is required. The FSVP also requires the importer to spend additional time analysing the food safety plan of its foreign supplier. Some importers lack the technical knowledge required for such analyses, as well as the time required for review which is very common in developing countries [24]. A Preventive Control Qualified Individual should perform the FSVP verification activities, as some importers are having difficulty finding qualified employees in an already competitive labor market. Hiring a Qualified Individual as a consultant imposes a financial burden on the importer and will most likely not encourage the degree of involvement between the importer and its FSVP that is desirable [26].

Sampling and testing of food samples is another FSVP difficulty facing the food exporters, especially small/ medium scale exporters, but this activity is already costing the food processor tens of thousands of dollars prior to the FSVP implementation. In addition, the HACCP system was created in large part due to the fact that sampling and testing are not reliable methods for guaranteeing the safety of food. Next difficulty is the implementation of food safety system based on HACCP principles. Food safety has been fervently discussed throughout the world. Priority for food safety addresses issues in enhancing food safety systems in terms of exporting countries, contribution to consumers' health and protection and advancement on food regulations and standards. Not all food industrial companies are able to follow demands presented by international bodies [24]. Next are the verification issues. An onsite audit, the recommended FSVP verification method, also comes at a high expense to the importer [26]. The FDA does not allow relying on foreign suppliers' own self-audit as an appropriate verification activity. The FDA accept third-party analyses, evaluations, and activities for meeting FSVP requirements. So if the importer doesn't have local auditing staff based in his manufacturing country, hiring a professional third party might be a good compliance solution [13].

CONCLUSIONS

The Foreign Supplier Verification Program (FSVP) regulations are intended to ensure imported foods meet the same quality levels of food produced in the U.S. The FSVP process aims to improve food safety by increasing the importers' responsibility for verifying foreign suppliers and their good manufacturing practice compliance. The U.S. Food and Drug Administration Food Safety Modernization Act (FSMA) on Foreign Supplier Verification Programs

(FSVP) for Importers of Food for Humans and Animals requires that importers perform certain risk-based activities to verify that food imported into the U.S. has been produced in a manner that meets applicable U.S. safety standards. The FSVP certification allows foreign (non-U.S.) suppliers to obtain certification following an audit. The FSVP program is mandatory and applicable to importers of food to the U.S. The compliance is equal to a passport for food products' entry into the U.S. market. Under the FSVP, U.S. importers are required to monitor their foreign suppliers' compliance with FDA requirements. There are difficulties in the implementation of FSVP in India. However, the benefit of FSMA FSVP is higher than the efforts, financial, and time expenditures.

WNIOSKI

Przepisy Programu Weryfikacji Dostawców Zagranicznych (FSVP) mają na celu zapewnienie, że importowana żywność spełnia ten sam poziom jakości, co żywność produkowana w USA. Proces FSVP ma na celu poprawę bezpieczeństwa

żywności poprzez zwiększenie odpowiedzialności importerów za weryfikację dostawców zagranicznych i przestrzeganie przez nich dobrych praktyk produkcyjnych. Amerykańska Ustawa o modernizacji bezpieczeństwa żywności (FSMA) Agencji ds. Żywności i Leków w sprawie Programów Weryfikacji Zagranicznych Dostawców (FSVP) dla importerów żywności dla ludzi i zwierząt wymaga, aby importerzy wykonywali określone działania oparte na ryzyku w celu sprawdzenia czy żywność importowana do USA została wyprodukowana w sposób, który spełnia obowiązujące amerykańskie standardy bezpieczeństwa. Certyfikacja FSVP umożliwi zagranicznym dostawcom (spoza USA) uzyskanie certyfikatu po audycie. Program FSVP jest obowiązkowy i dotyczy importerów żywności do USA. Zgodność jest równoznaczna z paszportem na wejście produktów spożywczych na rynek USA. W ramach FSVP importerzy amerykańscy są zobowiązani do monitorowania zgodności swoich zagranicznych dostawców z wymaganiami FDA. Istnieją trudności we wdrażaniu FSVP w Indiach. Jednak korzyści płynące z FSMA FSVP są większe niż wysiłki, koszty finansowe i czasowe.

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Signature

Article

Assessing Food Safety Compliance in a Small-Scale Indian Food Manufacturer: Before and after Certification of the Food Safety Management System and Foreign Supplier Verification Program

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Abstract: The implementation of food safety management systems has a great influence on global food safety and security, especially for developing nations. The principles of the Hazard Analysis and Critical Control Points are crucial for food safety and are the basis of food safety management systems. The purpose of this study was to assess the food safety management systems of a selected small-sized food company in India, both before and after certification of the International Organization for Standardization (ISO) 22000 and the Foreign Supplier Verification Program (FSVP). This company manufactured traditional fried vegetable snacks using manual processing. The effectiveness of these certifications was assessed through direct audit. The integrated FSVP and ISO 22000 audit checklist were elaborated and applied in this study. It was shown that the certification significantly improved (97.14%) food safety system conformity in the company in question. Before certification, many non-compliances were found, especially for HACCP implementation. After certification, the only non-conformity concerned pest control. The integrated FSVP and ISO 22000 audit checklist used for the assessment enabled an evaluation of several factors: the food quality and safety compliance level, the effectiveness of certification, and the readiness of the small-sized Indian snack producer to develop the export of their products to the U.S. and other developed countries. It was shown that certification enabled a small-sized Indian food producer to meet the requirements of ISO 22000 and FSVP, which are the prerequisites for exporting to the U.S. and other developed countries.

Keywords: audit; certification; traditional food; supplier; food safety; manual processing



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1. Introduction

India is the most populous country in the world and has become one of the World's largest food producers and exporters. This is of particular importance in the context of world population growth—now at over 8 billion—and increasing global food shortages, which are exacerbated by climate changes. Also, wars, such as in Ukraine, disrupt existing food supply channels. However, Indian food exports are often constrained by unverified food safety and the absence of certifications, which restricts the supply of Indian food to other countries [1,2]. Also, Indian food exporters regularly face challenges, such as foodborne illnesses and numerous recalls, bans, and rejections, which are mostly related to non-compliance with the stringent food safety and health standards and regulations set by developed importing countries. However, implementing and following these international food safety standards can result in certain difficulties, especially for small-scale food companies in developing countries [3].

Food safety incidents, such as the 2015 withdrawal of Maggie Noodles and government surveillance of foodborne diseases, have helped raise awareness of food safety in India [4]. The implementation of food safety requirements in India has become a significant task in recent years. Also, the Indian government is implementing policies and many schemes to promote sustainable agricultural practices [3]. However, in comparison to other countries, such as the United States (U.S.), the United Kingdom (U.K.), the European Union (E.U.), and Japan, food safety requirements and inspections in the Indian food chain are still not rigorous enough. In 2006, the Government of India consolidated food regulations into a single act known as the Food Safety and Standards Act (FSSA, 2006). The FSSA covered the concept of food safety across the entire supply chain—from manufacturing and storage to distribution. The FSSA consolidated the laws relating to food and established the Food Safety and Standards Authority of India (FSSAI) to lay down science-based standards for regulating food manufacturing, storage, distribution, and sale to increase food safety [5]. Under the FSSAI, in 2011, six regulations were implemented, covering the interests of food business operators and consumers, e.g., Food Safety Standards (FSS) (licensing and registration) and FSS (packaging and labelling) [6,7]. The FSSA laid down rules and regulations for running a food business and is also responsible for the registering and licensing of food business operators. Small operators, like street food vendors and local shops, are required to obtain registration with minimum Good Hygiene Practices (GHP) and Good Manufacturing Practices (GMP) requirements. However, medium and large operators are required to obtain a license under the Food Safety Regulations (2011) and need to be able to demonstrate the implementation of hazard control using the HACCP-based approach [8]. Consequently, India's presence in the global food market for both raw and processed foods is growing. Although the Indian food industry is attempting to meet food hygiene requirements, there is a level of uncertainty due to a lack of harmonisation of food standard regulations between India and other countries [9].

Currently, a triangulation of various methods is used all over the world to assess and analyse food safety culture [10,11]. However, in India, only the audit method seems feasible due to the different cultures of operation, data collection, and food safety. The audit covers an assessment of all processes in the plant and concerns both process documentation, their practical implementation, and the skills and qualifications of staff. In addition, in a small Indian plant that manufactures traditional snacks using manual processing and that has never used advanced assessment methods before, an audit is the only solution to assess the implemented system [12]. Therefore, the implementation and certification of a food safety management system would seem to be a reliable method to improve the level of food safety culture.

The successful implementation of food safety standards in food businesses is proved during the certification process. There are several internationally accepted private, voluntary standards, including the British Retail Consortium (BRC), International Featured Standards (IFS), Food Safety Management Systems 22000 (ISO 22000), and Quality management systems (ISO 9001) [13–18]. Private standards have stimulated exports from suppliers in developing countries [19]. Some local organizations, e.g., the Cashew Export Promotion Council of India (CEPCI), have supported the adoption of private food safety standards such as ISO and HACCP. Apart from offering training on quality certification, CEPCI covers up to a third of the costs stemming from food safety certification, including consultancies, audits, and the equipment required for quality control [20]. The certifications ensure that food businesses comply with the appropriate standards. Another example of voluntary standards is the U.S. Foreign Supplier Verification Program (FSVP), mandated by the Food and Drug Administration (FDA). FSVP mandates importers to verify that their foreign suppliers of food for both human and animal use comply with the applicable FDA safety requirements [21]. ISO 22000, also called Food Safety Management Systems 22000 is a globally recognised auditable standard. Developed countries have strong Food Safety Management Systems (FSMS) and well-established statutory frameworks, thereby effectively managing food safety hazards and reducing foodborne infections. In contrast,

developing nations, especially small-scale producers, face challenges when implementing FSMS because of limited financial resources, limited access to international markets, huge costs, weak regulations, and a lack of awareness about food safety and the benefits of FSMS [3,22]. But these challenges seem minor when compared to the costs associated with non-compliance [23].

International certification is necessary for food exporters who wish to enter the markets of developed countries [24]. However, there is a significant gap in the literature discussing the implementation of FSVP within the Indian food sector and its influence on the approval of quality management system standards in small food companies. While some research has been conducted on the impact of ISO 22000 certification on food quality, it is important to note that these studies were not performed in the Indian food sector [25–30]. There are only a few papers including authors from India discussing the role of food safety management systems in safe food production or ISO 22000 implementation methodology [31–33], and there is a lack of ready-to-implement tools, i.e., an integrated audit checklist, making it possible to check the requirements of both FSVP and ISO 22000 standards.

The Indian food processing industry is primarily export-oriented and also an exporter of processed vegetables to many countries. The research gap concerns the lack of knowledge about the readiness of small Indian food enterprises to meet the requirements of FSVP and ISO 22000 and their readiness to export to the U.S. or other developed countries. There are also no reports showing that FSVP and ISO 22000 certification are possible for small food producers in India. The next research gap concerns the impact of certification on the functioning of the quality and safety systems in small-sized Indian food companies. Furthermore, though India exports food products to many countries, including the U.S., the exporters are big companies. For these reasons, our hypothesis is that optimisation of food safety management in a small factory that manufactures traditional fried vegetable snacks using manual processing in India is possible by implementing non-mandatory food safety standards. Therefore, the aim of this study was to assess the food safety management system before and after certification of ISO 22000 and the Foreign Supplier Verification Program in a selected small-sized food producer in India using direct audit.

2. Materials and Methods

2.1. Materials

The company selected for this study was a small-sized company [34], Malayalam Exports. The company employed 25 workers and was located in Kerala State in India. The company manufactured a variety of South Indian fried vegetable snack products. Production was carried out six days a week and consisted of one eight-hour production shift, followed by half an hour for sanitation. The company was selected because of its small size and its production of traditional fried vegetable snacks using manual processing. A sanitary facility program was in place, with dry-cleaning procedures enforced in most production areas of the facility to minimise the establishment of environmental pathogens. A separate wet-washing room was used for washing, drying, and sanitising small equipment. The reason for the selection of this company for this study was because the enterprise was an exporting company, intending to expand exports to developed countries. The selected company achieved two certifications: ISO 22000:2018 and the Foreign Supplier Verification Program (FSVP) certification to fulfil their importing countries' standard requirements. Both certifications were conducted by third-party audits (SGS India Pvt. Ltd., Gurugram, India) (Figure 1). Prior to the implementation, no staff members had received specialised instruction in the fundamentals of food safety. The factory hired and trained an expert for this job in order to prepare for the implementation. The hiring and training of such a worker was one of the crucial responsibilities involved in the implementation process.



Figure 1. Schematic representation of sample company under study.

2.2. Assessment

The assessment was done in two periods: stage 1 in 2019, i.e., before the FSVP and ISO 22000 certification, and stage 2 in 2021, i.e., after FSVP and ISO 22000 certification. The assessment was carried out by an internal audit method. The audit methodology was based on the guidelines given in ISO 19011 [12] and the plant's own internal audit procedure. The assessment checklist was prepared based on the requirements of the Foreign Supplier Verification Program for Importers of Food for Humans and Animals (FDA, 2014), ISO 22000 (2018) and previous research on this subject [14,21,31,35]. An integrated audit checklist was developed to encompass the standard requirements of both the FSVP and ISO 22000. Before implementation, this comprehensive checklist was piloted by a quality manager and two independent experts. All shortcomings were improved. The checklist contained 70 questions grouped into 10 food safety sections: regulatory compliance, food safety plan, process and product control, sanitation, workers' hygiene practices, plant and grounds, food allergens, pest control, packaging and labelling, and employees and visitors (Figure 2 and Table 1). The questions applied to both stages (before and after certification) and were assessed according to conformity, i.e., whether the requirements of the evaluating criteria were fulfilled or not. The level of compliance with the audit criteria was assessed on a point scale. In the case of conformity, the item was marked with 1, and in the case of non-conformity—0. To determine conformity, audit evidence, such as records, statements of fact, or other verifiable information relevant to the audit criteria, were used [12].

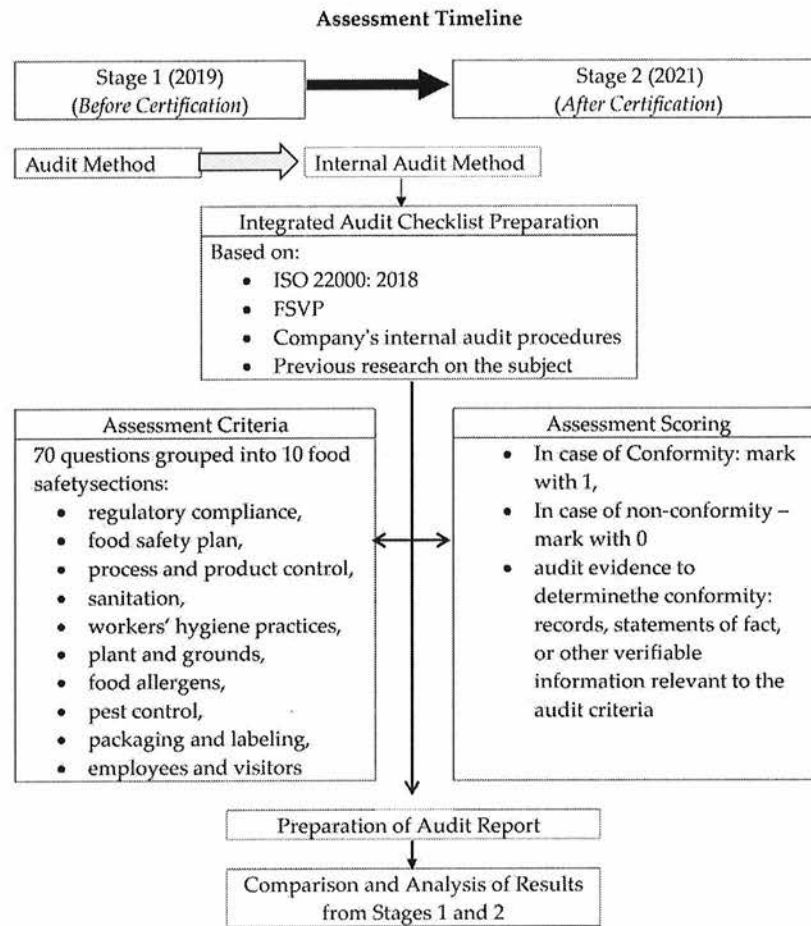


Figure 2. Schematic representation of the assessment methodology: before and after certification.

Table 1. The integrated audit checklist is according to the Foreign Supplier Verification Program (FSVP) and ISO 22000 requirements [17,21,36,37].

No	Assessment Questions	Stage 1		Audit Evidence	Stage 2		Audit Evidence
		C*	NC**		C	NC	
1.	Regulatory Compliance						
1.1	Does the company have a written Food Safety Policy? Is it readily available to relevant employees?						
1.2	Does the company have a documented training program on food safety and quality for all associates including upper management?						
1.3	Does the company have a current organizational chart that shows all individuals responsible for food safety and quality?						
1.4	Does the company have a responsible, designated Quality Assurance or Food Safety Manager?						
1.5	Does the company have a preventive control qualified individual (PCQI)?						
1.6	Does the company have a written and documented customer complaint program?						

Table 1. Cont.

No	Assessment Questions	Stage 1		Audit Evidence	Stage 2		Audit Evidence
		C *	NC **		C	NC	
1.7.	Does the company have documentation to track the effectiveness of policies?						
1.8	Does the company operate in accordance with the Quality and Safety policy?						
1.9	Does the company have a system in place to correct all violations noted in regulatory, in-house and third-party inspections?						
1.10	Are all required licenses present and current?						
2.	Food Safety Plan						
2.1	Has the company developed a food safety plan as per FSMA regulations?						
2.2	Does the food safety plan cover the HACCP plan for the company?						
2.3.	Does the company conduct hazard analyses based on experience, illness data, scientific reports, etc.?						
2.4	Does the food safety plan cover a written preventive inspection as required?						
2.5	Does the company document and implement food allergen preventive controls?						
2.6	Does the company maintain food safety plan-based records?						
2.7	Are the food safety plan-based records overseen by the PCQI in place?						
2.8	Does the food safety plan cover a recall plan as required?						
2.9	Does the company have a risk-based environmental monitoring plan?						
2.10	Have all critical control points (CCP), critical limits, monitoring procedures and corrective actions been correctly identified, documented and implemented?						
3.	Process and Product Control						
3.1	Does the company maintain product specifications for all raw materials, ingredients and packaging which is available to all relevant personnel?						
3.2	Is there a written and documented program in place to verify raw materials for compliance with specifications?						
3.3	Does the company require and maintain letters of guarantee on a yearly basis or certificates of analysis for incoming raw materials, ingredients and packaging?						
3.4	Has the company developed, documented and monitored a pre-requisite program?						
3.5	Does the company have procedures and systems in place to prevent cross-contamination between raw materials, packaging and finished products?						
3.6	Does the company conduct routine calibration of operational equipment and measuring devices?						
3.7	Does the company have a product traceability plan?						
3.8	Does the company have a metal detector or magnets in the packaging areas?						
3.9	Does the company conduct mock withdrawal?						
3.10	Does the company use proper identification labels for all stored ingredients?						

Table 1. Cont.

No	Assessment Questions	Stage 1		Audit Evidence	Stage 2		Audit Evidence
		C*	NC**		C	NC	
4.	Sanitation						
4.1	Does the company have a master cleaning schedule (MCS)?						
4.2	Do records and inspections indicate that the MCS is being properly executed?						
4.3	Are all food contact equipment and utensils clean and properly stored in a sanitary manner and re-sanitised prior to use?						
4.4	Are all non-food contact areas such as floors, walls, ceilings, fans, blowers, racks, etc. maintained and cleaned in an orderly manner?						
4.5	Are all garbage, trash and other waste materials disposed of in identifiable, covered containers?						
4.6	Are all pallets spaced at an adequate distance from walls to facilitate cleaning and monitoring for pests?						
4.7	Are waste containers clearly identified as to their intended purpose?						
4.8	Is waste removed from processing areas on a regular basis?						
4.9	Are all chemicals used in the company properly stored and secured?						
4.10	Does the company maintain a Material Safety Data Sheet (MSDS) for all the chemicals used?						
5.	Workers' Hygiene Practices						
5.1	Do plant employees wear clean uniforms, smocks or other protective clothing that is free of buttons and outer pockets above the waist?						
5.2	Are smocks, uniforms or other protective clothing removed prior to breaks or entering restrooms and stored in a sanitary manner?						
5.3	Are hand washing signs posted above all hand sinks in the company and in a language appropriate for employees?						
5.4	Do employees have hairnets and/or beard nets correctly in place when working around exposed products, packaging and ingredients?						
5.5	Are employee-support facilities physically separated from food processing areas and maintained in a sanitary condition?						
6.	Plant and Grounds						
6.1	Does company management perform a monthly audit of GMP and company conditions?						
6.2	Are there an adequate number of accessible hand sinks at the entrances of and in food-handling and food-processing areas?						
6.3	Are the walls properly designed, constructed, finished and maintained?						
6.4	Does the company have a documented metal detection or foreign material program?						
6.5	Does the company keep yards and parking areas free from external sources of contamination?						
6.6	Does the company implement an environmental monitoring plan?						
6.7	Is the design of the plant developed to facilitate maintenance and sanitary operations for food production purposes?						

Table 1. Cont.

No	Assessment Questions	Stage 1		Audit Evidence	Stage 2		Audit Evidence
		C *	NC **		C	NC	
7.	Food Allergens						
7.1	Are the food allergen and sensitising ingredients used in the company clearly identified?						
7.2	Is the production line tested for specific allergens during a changeover and post sanitation?						
7.3	Does the company have written allergen control procedures in place to prevent the cross-contamination of non-allergic ingredients with allergens?						
7.4	Is the potential for allergen cross-contamination adequately and properly controlled in the company?						
8	Pest Control						
8.1	Does the company maintain a documented pest control program that is either performed by in-house employees or contracted by an outside provider?						
8.2	Does the company have the current material safety data sheet (MSDS) and pest control operator (PCO) applicator license on file?						
8.3	Are flying insect traps properly located near exterior doors?						
8.4	Is there an adequate number of properly placed and adequately maintained rodent control devices in the company?						
8.5	Is the company provided with self-closing doors and proper ceilings to prevent the entry of pests?						
9.	Packaging and Labelling						
9.1	Are there label accuracy procedures in place that meet regulatory requirements?						
9.2	Is there a documented policy to ensure compliance with net-weight requirements?						
9.3	Is there a program in place to ensure package integrity?						
9.4	Is there a plan in place to prevent the use of unauthorised or incorrect labels?						
10.	Employees and Visitors						
10.1	Do employee applications contain full personal, employment, and legal history?						
10.2	Does the company check that personal items and/or containers are not brought into the operating areas by employees?						
10.3	Is there a designated plant employee to accompany visitors?						
10.4	Is there a documented process for managing all visitors which includes verification of ID and a sign-in process?						
10.5	Is there any documented evidence to verify that visitors have signed out?						

* C—conformity, ** NC—non-conformity.

2.3. The Auditor

The assessment was conducted by the first author of this paper. She had experience in the food industry as a Quality Assurance in Charge/Food Safety Team Leader person. She is qualified as a Preventive Control Qualified Individual. She had worked for many years in the food industry as an auditor of quality management systems. Throughout this period, she continued to develop and improve her competence and skills through a professional development program and periodic evaluations according to the criteria set out in ISO 19011 (2011). Additionally, she is an expert in the development and implementation

of HACCP and the food safety plan for ISO 22000: 2018 and FSMA FSVP certification. She also has experience in the chemical and microbiological analysis of food products.

2.4. Statistics

In order to determine the most common assessments from the audit, the sections included in the checklist were calculated using mean, mode, and standard deviation (SD). To assess the effectiveness of food safety certification, the total of the items in conformity (i.e., fulfilment of requirements) was taken for Stage 1 and Stage 2. To compare the level of fulfilment of the audit criteria, the Student's *t*-test was used. The null hypothesis (H0) and the alternative hypothesis (H1) were formulated as follows:

Hypothesis 0 (H0). *Certification has no impact on the number of items in the checklist that were compliant.*

Hypothesis 1 (H1). *Certification has a significant impact on the number of compliant items.*

McNemar's test was performed in order to verify the hypotheses [38,39]. It was examined whether the certification had a significant impact on the number of compliant items in the evaluated sections. McNemar's test was as follows:

$$x_1^2 = \frac{(B - C)^2}{B + C} \quad (1)$$

$$x_2^2 = \frac{(D - A)^2}{A + D} \quad (2)$$

where:

A—the number of compliant observations before and after certification;

B—the number of compliant observations before certification, which after certification were not compliant;

C—the number of not compliant observations before certification, which after certification were not compliant;

D—the number of non-compliant items before and after certification.

McNemar's test is used to compare two dependent samples when the results of individual measurements are defined by only two categories, that is, when the variable is a dichotomous variable taking only two values labelled 1 and 0 (for example, "yes" and "no"; "improvement", "no improvement"). Cochran's Q test is an extension of McNemar's test. Thus, these statistics fit perfectly with the research objective set, that is, to evaluate the food safety management system before and after ISO 22000 certification and the Foreign Supplier Verification Program.

In calculating McNemar's Chi-square statistic, the values of the chi-square statistic and the *p* were used to check if the numbers of *A* and *D* as well as *B* and *C* were the same. The *B/C* (x_1^2) corresponded to the Chi-square and *p* values, which were used to verify the hypothesis that the numbers of *B* and *C* were the same, whereas *A/D* (x_2^2) corresponded to the Chi-square and *p* values, which were used to verify the hypothesis that the numbers of *A* and *D* were the same [38,39]. The H0 hypothesis was rejected at $p < 0.05$.

In order to deepen the calculations of McNemar's test, Cochran's Q test was performed [40]. This tests two or more dependent groups ($k \geq 2$). Cochran's Q test was used to verify the hypothesis of symmetry between the results of multiple measurements. The tested feature could have only two values, to which (for the purposes of the analysis) numbers 0 and 1 were assigned. Cochran's Q test statistic calculation equation was as follows:

$$Q = \frac{(k - 1)(k.C - S)^2}{k.S - K} \quad (3)$$

where:

Q—Cochran’s Q test;
 k—the number of measurements;
 C, K, S—theoretical values.

McNemar’s test was used for the calculations because it is a non-parametric statistical test for comparing two related samples where the variables are nominal or dichotomous. The test was used to search for differences between groups in the conditions of the experiment before and after the certification. It was convenient for meeting food safety requirements before and after certification. Parametric statistical tests were not used because the sample was small and did not meet the condition of normal distribution. The Cochran Q test, on the other hand, is a non-parametric statistical test and an extension of the McNemar test. It was used to determine if numbers or paired items were significantly different from each other [40,41]. Cronbach’s alpha test was used to measure the internal consistency and reliability of the audit checklist used. In the case of this study, it was the internal consistency of the checklist, overall and divided into ten sections. The results of Cronbach’s alpha test showed that the reliability coefficient for the overall audit checklist was 0.75, and for each of the ten sections was above 0.72, which indicated acceptable internal consistency. All calculations were performed using Statistica 13.3 software (StatSoft, Inc., Krakow, Poland). Significance was identified when $p < 0.05$.

3. Results

3.1. Overall Assessments

The results obtained showed that the implementation of the FSVP and ISO 22000 standards and the resulting certification significantly improved the degree of compliance with the requirements (Table 2, Figure 3). There was 50% compliance in Stage 1 (before certification) and 97.14% in Stage 2 (after certification) (Student’s *t*-test $p = 0.0011$). The analysis of individual sections showed a significant improvement in 6 out of 10 sections. Significant improvement was achieved in the case of the following sections: food safety plan (Student’s *t*-test $p = 0.0000$), process and product control (Student’s *t*-test $p = 0.0017$), sanitation (Student’s *t*-test, $p = 0.0247$), food allergens (Student’s *t*-test, $p = 0.0240$), pest control (Student’s *t*-test, $p = 0.0241$), and packaging and labelling (Student’s *t*-test, $p = 0.0240$). The biggest differences before and after certification were found in the food safety plan and the packaging and labelling sections. These sections were not implemented at all before certification. In both sections, full compliance (conformity) was established after certification. Conformity before certification was found only in the workers’ hygiene practices section. Only small differences before and after certification were found in the regulatory compliance section, where there was only a 10% improvement, and in Employee and Visitors, where there was a 20% improvement. In other sections, the levels of improvement were more significant.

Table 2. Level of compliance with food safety requirements before and after certification—McNemar’s test.

Stage of Assessment	After Certification: Compliant		After Certification: Not-Compliant		Totally Before Certification
	Given from the Equations (1) and (2)	Number of Requirements	Given from the Equations (1) and (2)	Number of Requirements	
Before certification: compliant	A	35	B	0	35
Before certification: not compliant	C	33	D	2	35
Totally after certification	-	68		2	70

Equation (1): McNemar’s Chi-square B/C = 31.03; $p < 0.0001$; Equation (2): McNemar’s Chi-square A/D = 27.68; $p < 0.0001$.

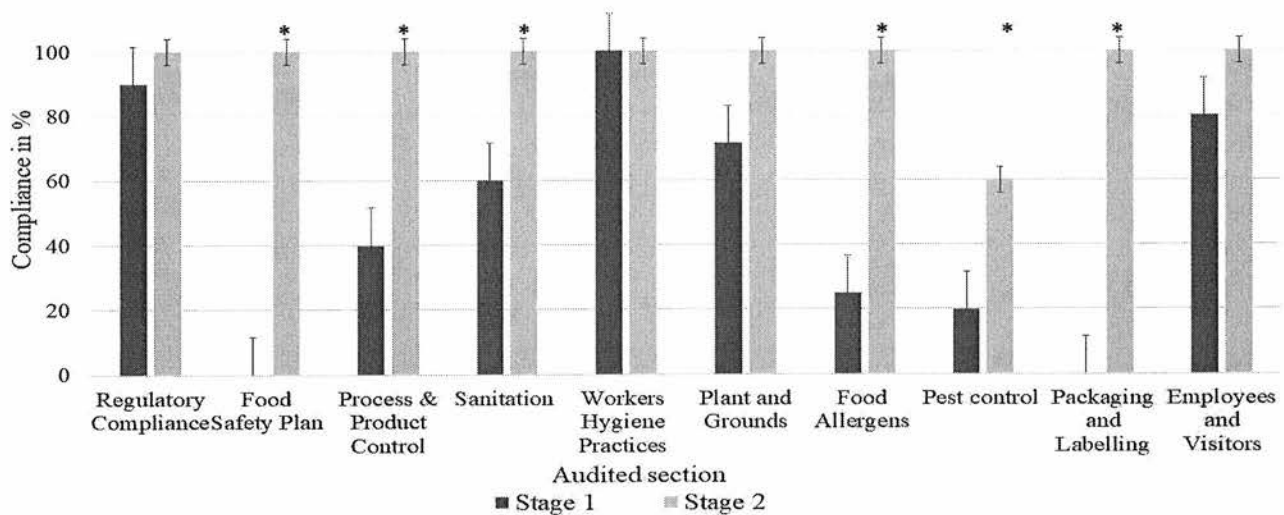


Figure 3. Percentage of compliance with requirements, in particular the food safety sections before and after certification (Stage 1 and 2, respectively). * reflects the significant improvement.

3.2. Analysis of Non-Compliances

Before certification, 35 of the 70 assessed parameters were compliant with requirements. However, after certification, 68 parameters were compliant, and only 2 remained not compliant, which were two requirements in the pest control section (Q 8.3 and 8.4).

The differences were significant, which is confirmed by McNemar’s Chi-square statistic $A/D = 27.68$, with $p < 0.001$. This indicated that the certification had a significant impact on meeting the food safety requirements. After certification, considerably more food safety parameters were compliant than before certification. The differences were significant, which is confirmed by McNemar’s Chi-square statistic $A/D = 31.03$, with $p < 0.001$. The null hypothesis was rejected in favour of an alternative hypothesis, which indicated that before certification there were significantly more not compliant parameters than after certification.

Cochran’s Q test showed that the overall level of compliance before certification was 50%, and after certification—97.14% (Figure 4). The $p < 0.0001$ was lower than α , which indicated that the certification had a positive and significant impact on the level of compliance.

Non-conformities before and after certification (Stages 1 and 2) are shown in Table 3. Before certification, non-conformities were observed in all sections except one—workers’ hygiene practices. Whereas after certification, non-conformity was found only in the pest control section. All individual non-conformities in each section were improved after certification except for two parameters in the pest control section. The flying insect traps were not properly located near exterior doors (Q. 8.3) and rodent control devices were not properly placed and maintained in the facility (Q. 8.4).

Table 3. Identified non-conformities before and after certification.

Section	Assessment Questions as per Table 1	Non-Conformities	
		Before Certification	After Certification
Regulatory Compliance	1.5	+	-
	1.10	+	-
Food Safety Plan	2.1	+	-
	2.2	+	-
	2.3	+	-
	2.4	+	-
	2.5	+	-
	2.6	+	-
	2.7	+	-

Table 3. Cont.

Section	Assessment Questions as per Table 1	Non-Conformities	
		Before Certification	After Certification
Food Safety Plan	2.8	+	-
	2.9	+	-
	2.10	+	-
Process and Product Controls	3.1	+	-
	3.3	+	-
	3.5	+	-
	3.6	+	-
	3.9	!	-
	3.10	+	-
Sanitation	4.5	+	-
	4.6	+	-
	4.8	+	-
	4.10	+	-
Workers' Hygiene Practices	all	-	-
Plant and Grounds	6.5	+	-
	6.6	+	-
Food Allergens	7.2	+	-
	7.3	+	-
	7.4	+	-
Pest Control	8.1	+	-
	8.3	+	+
	8.4	+	+
Packaging and Labelling	9.1	+	-
	9.2	+	-
	9.3	+	-
	9.4	+	-
Employees and Visitors	10.5	+	-

(-) shows conformities; (+) shows non-conformities.

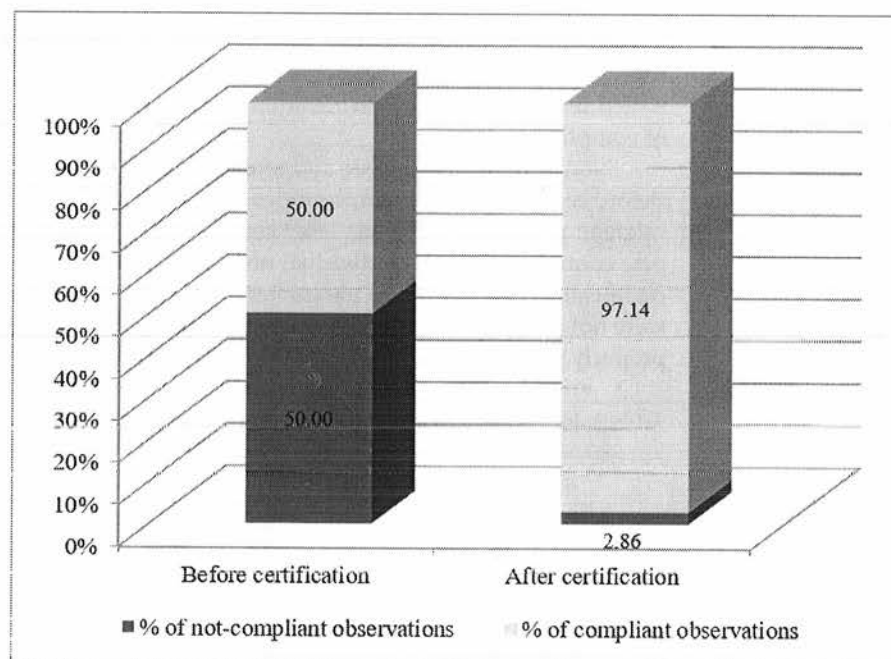


Figure 4. Percentage of fulfilment of food safety parameters before and after certification—Cochran's Q test, number of parameters: 70 Q = 33.00; df = 1; p < 0.0001.

The differences in compliance with the food safety section are presented in Figure 5. The largest differences resulting from certification were observed in the food safety plan and packaging and labelling sections, where none of the parameterisation conditions were met before certification but all improved afterwards. In second place was the food allergens section, where there was an improvement from 0.3 to 1. There was also a large improvement in the process and product control section, where the post-certification score improved from 0.4 to 1. No differences were observed in the workers' hygiene practices section, and slight differences were observed in the regulatory compliance section, where there was only a 0.1 improvement, and in the employees and visitors section, where there was a 0.2 improvement.

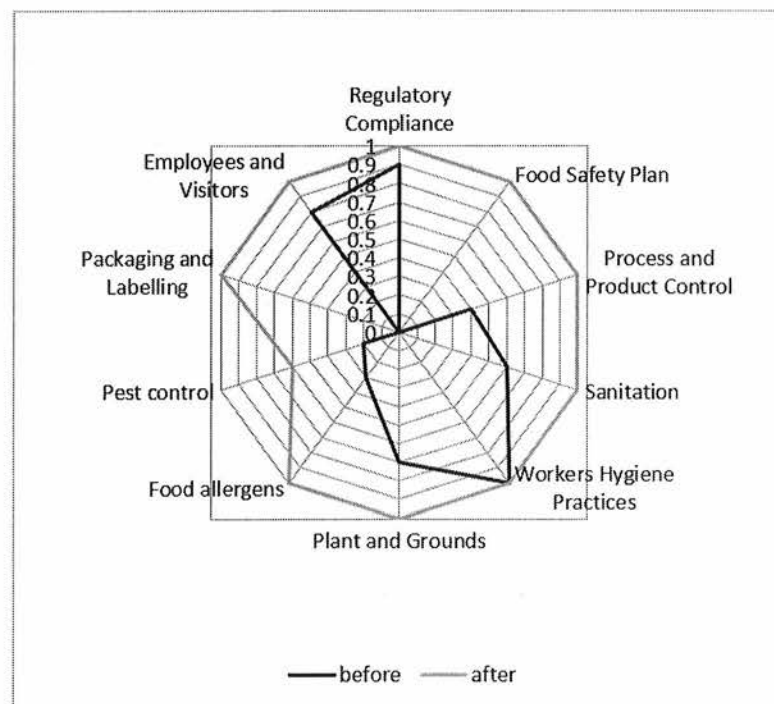


Figure 5. Nest diagram showing differences in compliance between food safety sections before and after certification, 1 means compliance, 0 non-compliance, $p < 0.00$.

4. Discussion

Rarely does a comparative assessment of the results of food safety audits in developing countries appear in the literature. The results presented in this study showed two stages of the implementation of ISO 22000 and FSVP requirements, both for the documentation and the food safety system in place at the company. An innovative ready-to-implement checklist was elaborated and used, which was a combination of the requirements of FSVP and ISO 22000: 2018 (Table 1). Such a combination has yet to be presented in the literature. Usually, the audit criteria or checklists of a single audited system are presented [42–44].

This approach helped us to provide an analysis of the company's readiness to export to developed countries. We assessed ten sections of the FSVP and ISO 22000: 2018 standards, beginning with regulatory compliances followed by requirements of the food safety plan, process and product control, sanitation, workers' hygiene practices, plant and grounds, food allergens, pest control, packaging and labelling, and employees and visitors. The initial assessment before certification of the company showed that the organization's functioning was far from the ISO 22000 and FSVP requirements. This was due to a lack of experts, trained employees, and proactive measures by senior management. Implementing food safety management reforms led to changes in management practices, staff education, and increased employee consciousness [3]. A high level of non-compliance was found in the

food safety plan, including the HACCP plan. The lack of a food safety plan or a labelling and packaging system was not in line with mandatory Indian regulations [6,45]. Many Indian food companies have implemented HACCP principles incorrectly, which was the main non-conformity reported by the official inspectorate in India [46]. This decreases food safety and makes exports very difficult or impossible. However, there are some food business operators in India that cover all HACCP principles like the extended dissemination of private standards in the Indian cashew industry where, previously, safety-related problems were noticed and overcome [20].

Food handling personnel are crucial for maintaining FSMS but may be hesitant to implement basic sanitary procedures due to time constraints. In this study, it was found that only personnel hygiene procedures of employees were found to be satisfactory both before and after the certification. All employees in the company were found to comply with good protective clothing (Q 5.1), its management (Q 5.2), hand washing signages (Q 5.3), proper usage of hairnets and/or beard nets (Q 5.4), and employee support facilities (Q 5.5). Non-compliance with personnel hygiene was noted in the works of Al-Shabib et al., Reboucas et al. and Trafiałek et al. [44,47,48]. In contrast, Jakubowska et al. and Tomašević et al. reported only a few discrepancies in this area [42,49].

Deviations from specific requirements are referred to as non-conformities. Many studies have pointed out the huge number of non-conformities in Indian food companies, e.g., lack of sufficient infrastructure and modern equipment [3], and detectable antimicrobial residues in the milk with most samples positive for neomycin and streptomycin [50]. For example, a major problem with the plant infrastructure was also reported in plants in Serbia [49]. In this study, the non-conformity concerned pests. Even though there were chances that pests and rodents could enter into the company's premises, adequate pest control activities based on risk assessment were not managed by the company, even after certification. Pests are a common problem among Indian food producers [51], and an in-place effective pest control system is required by ISO 22000: 2018, FSVP, and the FSSAI [5]. This problem has been pointed out by other authors in European countries [42], not only in food plants but in agriculture as well. Goyal et al. reported that Indian agricultural exporters faced rejections and bans in key markets due to non-compliance with food safety and health standards, including pest infestations [52].

Reddy et al. indicated poor hygiene practices in India, in particular, process control [53]. Poor plant hygiene was identified in previous studies [35,54]. There were also some studies that did not record such non-compliance, e.g., in meat plants [49]. Goyal et al. and Jakubowska et al. reported poor storage and transportation conditions and a lack of general cleanliness [42,52]. Those non-conformities were observed partly at the snack producer's plant before certification. After certification, the plant was totally clean—the waste and waste removal process as well as product control were managed correctly. The same observation concerned the packaging and managing allergens. There are results presenting non-compliance with the safety of food packaging [43], or managing allergens [49,55,56] which was observed before but not after the certification in the industry under study.

In the works of Jakubowska et al., Djekic et al., and Trafiałek et al., many non-conformities in food safety plans were found [14,42,57]. The same problems were identified by the snack producer before the certification. A higher degree of non-compliance in the food safety system and documentation of the company before the certification could have been caused by many factors, such as key personnel having insufficient knowledge, lack of monitoring, poor awareness of employees, costs, etc. [8]. Reddy et al. reported that approx. 60% of food industry employees in India were not aware of FSSAI food safety requirements [53]. This was the reason that the high level of non-conformity decreased. However, certification and the necessary training of the workers due to the requirements of ISO 22000 and FSVP increases food safety awareness [58]. Schuster et al. and Goyal et al. found problems with the traceability of food raw materials and products in India [24,52]. However, this non-compliance was not found in the company in question, neither before nor after certification as in other studies performed in Europe [42].

The results of this study show a continuous improvement in the functioning of the food safety system and the proper documentation in place at the company under review. The active management of non-compliance at this company was connected to having the license required by Indian food law. However, not all companies running food businesses have the license [53]. All food business operators in India are required to be registered or licensed [45,59]. In 2020, 58,538 licenses were issued by the Central Licensing Authorities, with an increased percentage compared to the previous year. Between 2019 and 2020 an increase of 25% in issued Central licenses and 24% and 28% in State licenses and registrations, respectively, were reported in comparison to the previous year [46].

During recent decades in India, many changes in lifestyle and eating patterns have been observed [60]. However, despite robust economic growth, in India, there are still cases of malnutrition [61,62]. Despite this, food companies that have implemented voluntary food safety standards like ISO 22000 and FSVP are prepared to deliver safe food and be good food suppliers for other countries. At this point, it is worth relying on proven methods of assessing the level of food safety, such as the audit method [42,63,64] when planning the use of currently supported triangulation methods [65,66]. The use of other methods in the audited company to compare the level of implementation of a food safety management system before and after certification would not be possible because the company did not collect any data on food safety before certification. Only after certification is it possible to include the audit method in the modern trend of assessing food safety culture by triangulation, as proposed by De Boeck et al. [67].

This study showed the effective implementation of international food safety standards, confirmed by certification in the evaluated small-size food company. However, certification is more often beneficial to large companies rather than small ones [68]. Our results showed that the standards associated with certification beneficially affect the food safety management system in small companies as well. Implementing international food safety standards and certification often necessitates significant effort and expense for the company. However, the benefits usually compensate for implementation costs [69]. Periodic inspections of compliance with food safety requirements are necessary, especially in the case of a food export company [52,56]. Because the assessment checklist we prepared was based on the ISO 22000 and FSVP requirements, it could be useful for food producers exporting their products to developed countries like the U.S. and the E.U. Lee et al. reported that the International FSMS application and certification increased significantly in Indian companies, greater than in African or Latin American companies and close to levels in developed countries [3].

This study has some limitations. It only included one small-sized fried snack producer from India, representing the low-risk food sector. Conclusions from this work may not be applicable to producers of higher food safety risks, such as dairy and meat companies, nor to plants located in other countries where food safety is not mandatory. However, despite these limitations, our results showed the need to check the readiness of Indian food companies to export their products to other countries. The results obtained also have certain implications for research and practice. The results after certification can be used for a comparative assessment of the results from developed countries. Through this study, it is clear that even small-scale enterprises can meet international food safety standards. A small-size producer of traditional fried vegetable snacks, after implementation of the requirements of ISO 22000 and FSVP and after certification of these standards, became ready to export to the U.S. and other developed countries.

5. Conclusions

Some food manufacturers in India are improving their food safety management system. The certification of the food safety management system can allow food export to countries, where food safety expectations are high, like in the U.S. and the E.U.

The results of this study showed that the certification of ISO 22000 and the Foreign Supplier Verification Program in a selected small-size food company in India significantly

improved the level of food safety management system implementation in the company in question. Before certification, many non-compliances were found, especially for HACCP implementation. The most satisfactory result, both before and after certification, was full compliance with the requirements in the workers' hygiene practices section. After certification, both the food safety system in place at the company and the documentation met the requirements. The highest increase in compliance was found in the food safety plan section as well as packaging and labelling section. The only non-conformity concerned pest control. Certification significantly improved food safety system conformity in the evaluated company. Certification gives credibility to the safety of traditional Indian fried vegetable snack products. The developed integrated audit checklist can be used by other food companies in India or other developing countries to check whether they meet the adequate level of fulfilment of food safety management requirements. However, more work is needed to confirm its reliability and validity, as well as its usefulness for other food sector companies. Further studies concerning the possibility of implementing ISO 22000 and FSVP requirements in other food companies using manual production as well as in other food sectors, especially with higher food safety risks, are needed.

Author Contributions: Conceptualization, Investigation, Data curation, Visualisation, Writing—original draft, Methodology, S.S.N. and J.T.; Formal analysis, A.K.M.-K.; Writing—review and editing, W.K. and J.T.; Validation, Writing—review and editing, Supervision, J.T. All authors have read and agreed to the published version of the manuscript.

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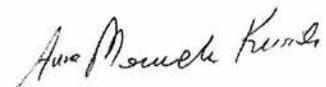
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Article

Post-Certification Quality Analysis of Traditional Indian Fried Snacks

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Abstract

Microbiological safety and quality consistency are critical challenges in the production of traditional Indian fried snacks, particularly in small-scale food enterprises. With growing export demand, maintaining strict quality control measures is essential. This study assessed the microbiological and physicochemical quality of five traditional Indian fried snacks—Kerala Murukku, Kerala Mixture, Banana Chips, Tapioca Chips, and Achappam—produced in a Food Safety Management System (FSMS)-certified facility over a four-year period (2020–2023). Products were evaluated for moisture, pH, salt content, acid value, and Total Plate Count (TPC). The number of ingredients for each product was recorded from standardized product formulation documents. TPC levels remained within acceptable limits (below 50,000 CFU/g) across all products. Among them, Kerala Mixture consistently showed the highest microbial counts (up to 4.61 log CFU/g) and Achappam the lowest, with no detectable variance (1.00 log CFU/g). Statistically significant year-wise differences ($p < 0.05$) were observed in all quality parameters. Kerala Mixture showed variation in salt and microbial load; Kerala Murukku varied in moisture, pH, and salt; while Tapioca Chips varied in moisture and salt. PCA identified that TPC, salt content, number of ingredients, and pH were key contributors to product variability. Cluster analysis confirmed Kerala Mixture as the most susceptible product to contamination risk. These findings provide valuable insights into the quality trends within an FSMS-certified environment and highlight the importance of strict post-processing controls.

Keywords: fried snacks; food safety; total plate count; physicochemical properties; post-processing contamination



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1. Introduction

Traditional foods, native to specific regions, serve as a dietary staple for people of all age groups. Among them, fried snacks, especially cereals and legume-based snacks, are particularly popular due to their distinctive taste, ability to satisfy hunger, and contribution to energy and nutrient intake, particularly through carbohydrates, fats, and proteins [1–4].

India's rich culinary diversity has led to the creation of a wide array of deep-fried and high-temperature processed foods. The Indian snacks product market reached USD 5347 million in 2024 and is expected to grow at an 8.26% compound annual growth rate by 2033 [5,6], which are categorized as chips, namkeen, extruded snacks, and others [7]. Several factors, including processing methods, starch–protein structure, and processing environments, influence the quality of these snacks [8]. Deep-fat frying is a common method used in the preparation of flour-based fried snacks [2]. However, microbial contamination poses a significant food safety concern in these products.

Microbial contamination in traditional snacks can be attributed to several sources, including raw ingredients, improper handling, and post-processing conditions. *Staphylococcus aureus* has been reported as one of the most frequently occurring pathogens in ready-to-eat (RTE) foods, primarily due to its ability to survive on human skin and environmental surfaces as an opportunistic microorganism. Thus, even if high-temperature frying effectively kills the *S. aureus* cells that are present in the ingredients, such as raw flours and grains, before cooking, inadequate post-processing practices can cross-contaminate the foods from equipment or workers. Several studies have reported that such practices can be the root cause of most foodborne diseases [9–14]. Moreover, *S. aureus* can produce heat-stable enterotoxins, so the consumption of contaminated products may lead to staphylococcal food poisoning even in the absence of viable cells [9]. *Bacillus* and *Serratia* species, which are spore-forming and environmentally persistent contaminants, have been frequently associated with RTE snacks and cereal products. A study on the microbiological safety of some Nigerian RTE fried snacks sold along the highways showed contamination with *Bacillus cereus*, *S. aureus*, *Escherichia coli*, and *Salmonella* spp. [15]. Spices such as pepper and curry paste often contain high concentrations of *Bacillus* spores. While these spices are not RTE foods, their use in seasoning poses a risk of indirect contamination. The presence of such microorganisms indicates potential contamination from raw ingredients and improper storage conditions [11]. As such, implementing an effective food safety management system (FSMS) is essential to mitigating potential hazards.

Moreover, India faces a significant challenge with foodborne diseases, particularly diarrheal infections, causing significant mortality and morbidity. Over 60% of emerging pathogens are from animals and the environment, transmitted through food and water. However, reported incidents are inaccurate due to their sporadic and self-limiting nature. The Integrated Disease Surveillance Programme (IDSP), a national initiative by the Ministry of Health and Family Welfare in India, is responsible for tracking and responding to epidemic-prone diseases. Surveillance data from the IDSP show a significant increase in outbreaks across India [16–19]. Moreover, a recent comprehensive review by Albert et al. 2024 has detailed the current situation of foodborne and waterborne disease outbreaks in India, highlighting risk factors, surveillance gaps, and control measures, emphasizing the need for improved regulatory frameworks and public awareness [20]. The Hazard Analysis and Critical Control Point (HACCP) and International Organization for Standardization (ISO) 22000 frameworks are widely used in food businesses to identify and control safety hazards. ISO 22000 integrates HACCP principles with good manufacturing practices to form a comprehensive Food Safety Management System (FSMS) [21–24]. As consumer expectations for safe and consistent food products grow, the verification of FSMS implementation, particularly HACCP, is crucial for real-world production effectiveness [25–27].

While several studies have explored ISO 22000:2018 implementation in food manufacturing [27–29], few have assessed FSMS performance through direct analysis of product quality in traditional South Indian fried snacks. The present study was conducted in a small-scale food exporting company in India operating under an ISO 22000:2018-certified environment. A previous study carried out in this same facility assessed FSMS imple-

mentation using a direct audit method [30], providing a complementary perspective on compliance with ISO 22000:2018 requirements. The current study aimed to evaluate product quality by analyzing the physicochemical and microbiological quality of traditional Indian fried snacks in the period from 2020 to 2023. The working hypothesis was that, within such a certified environment, the selected quality parameters, moisture%, acid value of extracted fat, pH, salt content, and total plate count (TPC), would remain within acceptable safety limits over the study period. These indicators were used to assess product quality and potential contamination risks, which in turn reflect the effectiveness of process control under the FSMS framework.

2. Materials and Methods

2.1. Characteristics of the Company

The present study was conducted in a small-scale food manufacturing and exporting firm located in Kerala, India. The company specializes in producing traditional South Indian fried snacks solely for export markets and operates under an internationally recognized food safety framework. To comply with global food safety requirements and meet importing country expectations, the company implemented the ISO 22000:2018 certification in 2020. The scope of FSMS ISO 22000:2018 implementation in this company covers all stages of production, from raw material procurement to final sales.

Although ISO 22000:2018 establishes well-structured food safety controls, this study does not evaluate the direct impact of certification. Instead, the research focuses on verifying product quality trends within the FSMS-certified environment, assessing physicochemical and microbiological parameters as indicators of process consistency and compliance with international safety standards.

2.2. Sample Collection and Processing

Five traditional Indian fried snacks were selected for analysis based on their popularity and demand in the export market [5,31]: Kerala Murukku, Kerala Mixture, Banana Chips, Tapioca Chips, and Achappam (Figure 1). These snacks are deep-fried, flour- or starch-based snacks commonly consumed across India. Kerala Murukku is a rice-flour and black gram-based, spiral-shaped snack; Kerala Mixture consists of deep-fried chickpea flour noodles mixed with nuts and spices; Banana Chips and Tapioca Chips are thinly sliced, deep-fried fruit and root vegetable chips, respectively; and Achappam is a crispy, flower-shaped fried snack or rose cookie made from rice flour.

All products were manufactured in an ISO 22000:2018-certified facility and packed in metalized polyethylene terephthalate (PET) packaging material, with modified-atmospheric packaging (nitrogen-flushed) immediately after processing. Packaging material was double-sealed and stored at ambient temperature [32]. Samples were collected randomly once per year from 2020 to 2023. A total of 20 samples were collected, comprising one finished product packet for each of the five products per year from 2020 to 2023. Each sample was analyzed in triplicate to ensure data reliability. The physicochemical and microbiological analysis was performed by the company according to the company's internal procedures, and the resulting data were made available for this study. The full ingredient composition for each product is shown in Table 1.

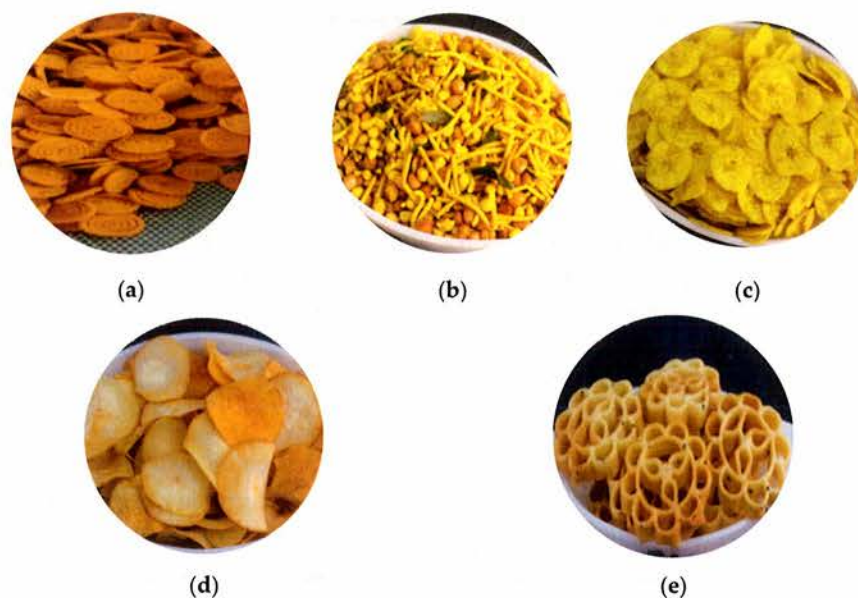


Figure 1. Images of the products used for this study: (a) Kerala Murukku, (b) Kerala Mixture, (c) Banana Chips, (d) Tapioca Chips, and (e) Achappam.

Table 1. Ingredients of sample products.

Samples	Ingredients
Kerala Murukku	Rice Flour, Refined Palmolein Oil, Black Gram flour (Urud Dal), Chili Powder, Salt, Small Onion, Garlic, Sesame Seeds, Fennel seeds, Ajwain
Kerala Mixture	Besan (Chickpea) Flour, Peanuts, Refined Palmolein Oil, Pea Flour, Rice Flour, Salt, Chili Powder, Curry Leaves, Turmeric, Garam Masala (Spices), Asafoetida
Banana chips	Plantain, Refined Palmolein Oil, Turmeric, Salt
Tapioca chips	Tapioca, Refined Palmolein Oil, Chili Powder, Salt
Achappam	Rice Flour, Sugar, Refined Palmolein Oil, Eggs, Corn flour, Sesame Seeds

2.3. Physicochemical Analysis

The analytical methods applied by the company followed the IS 12711 (1989): Bakery products—Methods of analysis [33]. Product samples were finely ground, and the ground powder was used for the estimation of physicochemical quality parameters, including moisture content, salt content, pH, and acid value of extracted fat. These parameters are the most frequently recommended tests to assess the quality of deep-fried snacks, and serve as essential indicators of product safety, shelf life, and sensory quality [34]. The moisture content of the samples was measured by the hot air oven method, where 10 g of the sample was dried in a 100 ± 2 °C oven until constant weight was achieved. The moisture content of finished products is usually less than 2% [35]. The salt content was analyzed by ashing 5.0 g of the sample, dissolving the chloride residues, and titrating with 0.1N silver nitrate (AgNO_3) using potassium chromate as an indicator until a permanent light brick red color was observed. The pH of the 10 g samples homogenized with 100 mL of distilled water was determined with a calibrated pH meter. The lower pH value (acidic) in food samples may result from the oxidation of fat content, resulting in the formation of fatty acids [36]. The acid value of extracted fat was determined by extracting fat using a Soxhlet apparatus and then dissolving it in a solvent (isopropyl alcohol/toluene) and titrating it with a standard alkali (potassium hydroxide/sodium hydroxide) solution after adding phenolphthalein as an indicator. A lower acid value indicates better fat quality in food [37], values exceeding one are generally considered an indication of rancidity and reduced product safety [38].

2.4. Microbiological Analysis

Total Plate Count (TPC) or Aerobic Plate Count (APC) was selected as the microbiological parameter in this study because it serves as a general hygiene indicator and reflects overall microbial load in food products [39]. TPC assessment is widely used in food safety evaluations to monitor contamination levels during processing and storage.

Microbiological analysis was performed by the company following procedures based on the FDA's Bacteriological Analytical Manual (BAM) methods [40]. Packed product samples were analyzed for the Total Plate Count (TPC) method. Samples (10 g) were aseptically weighed, homogenized in 90 mL 0.1% Butterfield's phosphate buffer, and serially diluted. The TPC was estimated by inoculating the samples into Plate Count Agar (PCA) (Himedia) and incubating them at 37 °C for 48 h. The colony-forming units per gram (cfu/g) were calculated using the following formula:

$$N = \frac{\sum C}{[(1 \times n1) + (0.1 \times n2)] \times (d)} \quad (1)$$

where

N = number of colonies per ml or gram of sample;

$\sum C$ = sum of all colonies of plates counted;

$n1$ = number of plates in the first dilution counted;

$n2$ = number of plates in the second dilution counted;

d = dilution from which the first counts were obtained [40].

According to the Food Safety and Standards Authority of India (FSSAI) [41], the maximum acceptable microbiological count is 50,000 CFU per gram. Other studies have adopted 5.99 log cfu/g as a microbial safety threshold for similar products [26,42,43]. Samples exceeding this limit were considered microbiologically unsafe.

2.5. Statistical Analysis

The statistical analysis of the physicochemical and microbiological data was performed using Statistica software version 13.3 PL. Each test was performed in triplicate, and all values were shown as mean \pm standard deviation. The Analysis of Variance (ANOVA) test, Tukey's HSD test, Principal Component Analysis (PCA) [44], Spearman's correlation, and multivariate cluster analysis were used. Significance was determined when $p < 0.05$.

The ANOVA and Tukey's HSD test were conducted to evaluate the potential differences in product quality metrics across years. The Principal Component Analysis (PCA) and Spearman's correlation were conducted to evaluate the relationship between quality parameters, ingredient load, and years across the fried snack products. Cluster analysis was used to develop dendrograms, clustering products based on microbial quality (CFU/log), as this method helps identify patterns in microbial contamination and assess similarities in food safety performance across different products. Ward's method was applied to minimize the variance within the groups, and the Euclidean distance was calculated during the grouping of products [45].

3. Results

3.1. Physicochemical Analysis

Table 2 presents the mean \pm standard deviation values for moisture content, acid value, pH, and salt content in the five fried snack products from 2020 to 2023. One-way ANOVA results indicated statistically significant differences over the years for all the physicochemical parameters.

Table 2. Physicochemical parameters of the five products from 2020 to 2023.

Variable	Year	Mean \pm Standard Deviation				
		Kerala Murukku	Kerala Mixture	Banana Chips	Tapioca Chips	Achappam
Moisture%	2020	2.37 \pm 0.01 ^a	0.83 \pm 0.01 ^a	1.48 \pm 0.01 ^b	1.64 \pm 0.01 ^a	1.68 \pm 0.01 ^a
	2021	2.37 \pm 0.06 ^a	0.55 \pm 0.01 ^a	2.93 \pm 0.01 ^a	1.63 \pm 0.01 ^a	1.37 \pm 0.02 ^a
	2022	2.57 \pm 0.25 ^a	1.52 \pm 0.53 ^b	1.30 \pm 0.60 ^b	2.20 \pm 0.45 ^a	1.96 \pm 1.18 ^a
	2023	1.97 \pm 0.01 ^b	0.97 \pm 0.03 ^{ab}	0.79 \pm 0.33 ^b	1.62 \pm 0.55 ^a	0.78 \pm 0.30 ^a
Acid value	2020	0.32 \pm 0.01 ^a	0.30 \pm 0.01 ^{ab}	0.38 \pm 0.01 ^a	0.49 \pm 0.01 ^a	0.28 \pm 0.01 ^a
	2021	0.33 \pm 0.01 ^a	0.49 \pm 0.17 ^a	0.30 \pm 0.06 ^{ab}	0.50 \pm 0.01 ^a	0.81 \pm 0.46 ^a
	2022	0.97 \pm 1.03 ^a	0.15 \pm 0.05 ^b	0.20 \pm 0.05 ^b	0.29 \pm 0.02 ^b	0.28 \pm 0.06 ^a
	2023	0.17 \pm 0.01 ^a	0.25 \pm 0.04 ^b	0.23 \pm 0.01 ^b	0.28 \pm 0.01 ^b	0.25 \pm 0.08 ^a
pH	2020	5.96 \pm 0.00 ^a	6.35 \pm 0.01 ^a	5.53 \pm 0.01 ^a	6.23 \pm 0.01 ^a	5.82 \pm 0.01 ^a
	2021	6.02 \pm 0.01 ^b	6.37 \pm 0.00 ^a	5.84 \pm 0.01 ^a	5.97 \pm 0.00 ^a	5.97 \pm 0.00 ^a
	2022	6.02 \pm 0.02 ^b	6.34 \pm 0.16 ^a	6.02 \pm 0.38 ^a	5.96 \pm 0.14 ^a	6.25 \pm 0.09 ^b
	2023	6.14 \pm 0.02 ^c	6.43 \pm 0.05 ^a	5.77 \pm 0.08 ^a	6.19 \pm 0.15 ^a	6.15 \pm 0.07 ^b
Salt	2020	0.33 \pm 0.06 ^a	1.09 \pm 0.01 ^a	0.42 \pm 0.01 ^a	0.36 \pm 0.01 ^a	0.18 \pm 0.01 ^{ab}
	2021	0.73 \pm 0.59 ^{ab}	1.10 \pm 0.01 ^a	0.52 \pm 0.14 ^a	0.48 \pm 0.18 ^{ab}	0.19 \pm 0.03 ^b
	2022	1.33 \pm 0.06 ^b	1.19 \pm 0.10 ^{ab}	0.96 \pm 0.14 ^b	0.87 \pm 0.16 ^b	0.10 \pm 0.00 ^a
	2023	1.37 \pm 0.12 ^b	1.26 \pm 0.04 ^b	0.96 \pm 0.14 ^b	0.88 \pm 0.19 ^b	0.17 \pm 0.06 ^{ab}

Different superscript letters within each column indicate statistically significant differences between years for that product ($p < 0.05$), based on Tukey's HSD test. Values sharing the same superscript letters are not statistically significant.

Moisture content varied significantly by year for Kerala Murukku ($p = 0.0032$), Kerala Mixture ($p = 0.0126$), and Banana Chips ($p = 0.0003$), but no significant differences were found in Tapioca Chips ($p = 0.2001$) and Achappam ($p = 0.1842$). Post hoc comparisons of Tukey's HSD test indicated that moisture content in Kerala Murukku in 2023 was significantly lower than in 2020 ($p = 0.0222$), 2021 ($p = 0.0242$), and 2022 ($p = 0.0024$). For Kerala Mixture, the moisture content had a significantly higher value from 2021 to 2022 ($p = 0.0093$), with a near-significant difference compared to 2020 ($p = 0.0523$). Regarding Banana Chips, the 2021 moisture content was significantly higher than in 2020 ($p = 0.0037$), 2022 ($p = 0.0019$), and 2023 ($p = 0.0004$).

The acid value of the fat extracted from the snack samples remained below 1.0 mg KOH/g across all years, indicating acceptable fat quality, and showed significant differences in Kerala Mixture ($p = 0.0093$), Banana Chips ($p = 0.0022$), and Tapioca Chips ($p < 0.0001$), but remained statistically unchanged in Kerala Murukku ($p = 0.308$) and Achappam ($p = 0.0588$). Tukey's HSD test revealed that the acid value of Kerala Mixture in 2021 was significantly higher than in both 2022 ($p = 0.0070$) and 2023 ($p = 0.0384$). For Banana Chips, acid values in 2020 were significantly higher than in 2022 ($p = 0.0026$) and 2023 ($p = 0.0068$). In Tapioca Chips, the acid values in 2022 and 2023 were significantly lower than in 2020 and 2021 (all $p < 0.0003$), with no statistically significant difference observed between 2022 and 2023 ($p = 0.8453$).

pH values remained above 5 in all products, indicating mild acidity or neutral profiles. However, statistically significant differences were identified in Kerala Murukku ($p < 0.000001$), Tapioca Chips ($p = 0.0234$), and Achappam ($p = 0.00007$). Kerala Mixture (0.5806) and Banana Chips ($p = 0.0786$) did not show significant year-over-year changes in pH. The pH of Kerala Murukku shows gradually higher values from 5.96 in 2020 to 6.14 in 2023. The post hoc Tukey's HSD test confirmed that the pH in 2023 was significantly higher than that in 2020 ($p = 0.0002$), 2021 ($p = 0.0030$), and 2022 ($p = 0.0021$), while no significant difference was found between 2021 and 2022 ($p = 0.9882$). In Tapioca Chips, although ANOVA indicated overall significance, Tukey's HSD did not identify statistically significant pairwise differences at the 0.05 level. Nonetheless, a borderline difference was

noted between 2020 and 2022 ($p = 0.0522$). For Achappam, the Tukey's HSD test showed that pH values in 2022 and 2023 were significantly higher than in 2020 and 2021 (all $p < 0.01$), while no significant difference was found between 2022 and 2023 ($p = 0.2221$).

The salt content varied significantly by year across all products: Kerala Murukku ($p = 0.0082$), Kerala Mixture ($p = 0.0167$), Banana Chips ($p = 0.0011$), Tapioca Chips ($p = 0.0055$), and Achappam ($p = 0.0379$). A post hoc analysis using Tukey's HSD test provided further insight into these differences. In Kerala Murukku, the salt content in both 2022 and 2023 was significantly higher than in 2020 ($p = 0.0161$ and $p = 0.0130$, respectively), although no significant differences were found between 2021 and the other years. For Kerala Mixture, the salt level in 2023 was significantly higher compared to both 2020 ($p = 0.0256$) and 2021 ($p = 0.0283$), indicating a trend of increasing salt incorporation in recent years. In Banana Chips, the salt levels in 2022 and 2023 were significantly greater than those in 2020, with p -values of 0.0035 and 0.0111, respectively. However, no statistically significant difference was detected between 2022 and 2023, suggesting stabilization in formulation practices during this period. Similarly, for Tapioca Chips, the salt content in 2022 and 2023 was significantly higher than in 2020 ($p = 0.0145$ and $p = 0.0126$, respectively), and 2023 levels were also elevated compared to those in 2021 ($p = 0.0481$), further indicating a progressive increase in seasoning levels. Regarding Achappam, a significant reduction in salt content was noted in 2022 compared to 2021 ($p = 0.0430$), although other pairwise comparisons were not statistically significant.

These observed variations in moisture, acid value, pH, and salt are likely influenced by the manual production process, where inconsistencies in the duration for frying, cooling, and mixing ingredients may affect the quality of the final product.

3.2. Microbiological Quality of Fried Products

The microbiological quality of food samples based on the total plate count is shown in Figure 2, presenting the mean values with standard deviations across products and years. The total plate count (TPC), expressed in log CFU/g, varied across years for certain products. One-way ANOVA revealed statistically significant differences in TPC over time for Kerala Mixture ($p < 0.000001$) and Tapioca Chips ($p = 0.0074$), while no significant variation was detected for Kerala Murukku ($p > 0.05$), Banana Chips ($p > 0.05$), and Achappam. All samples exhibited measurable aerobic bacterial counts, though none exceeded the regulatory threshold for acceptable microbial limits in ready-to-eat fried snacks (5.99 log CFU/g). Among the five products, Kerala Mixture consistently demonstrated the highest mean TPC values throughout the study period, with 4.61 log CFU/g recorded in 2020 and 3.70 log CFU/g in 2023. Tukey's HSD post hoc test indicated that the 2023 TPC was significantly lower than that of 2020 ($p = 0.0002$), 2021 ($p = 0.0002$), and 2022 ($p = 0.0178$), suggesting a statistically supported variation between these time points. In Kerala Murukku, TPC values ranged from 2.19 log CFU/g in 2020 to 0.98 log CFU/g in 2023. Despite numerical differences, ANOVA did not detect statistically significant changes over time ($p = 0.0667$). Tapioca Chips showed notable variation in 2022. According to Tukey's test, the TPC of Tapioca chips in 2022 was significantly different from 2020 ($p = 0.0049$), but no other yearly comparisons reached statistical significance. For Banana Chips, TPC values remained within a narrow range, and ANOVA confirmed the absence of statistically significant year-wise variation ($p = 0.8764$). Achappam presented uniform microbial results across all years, with TPC values remaining constant at 1.00 log CFU/g.

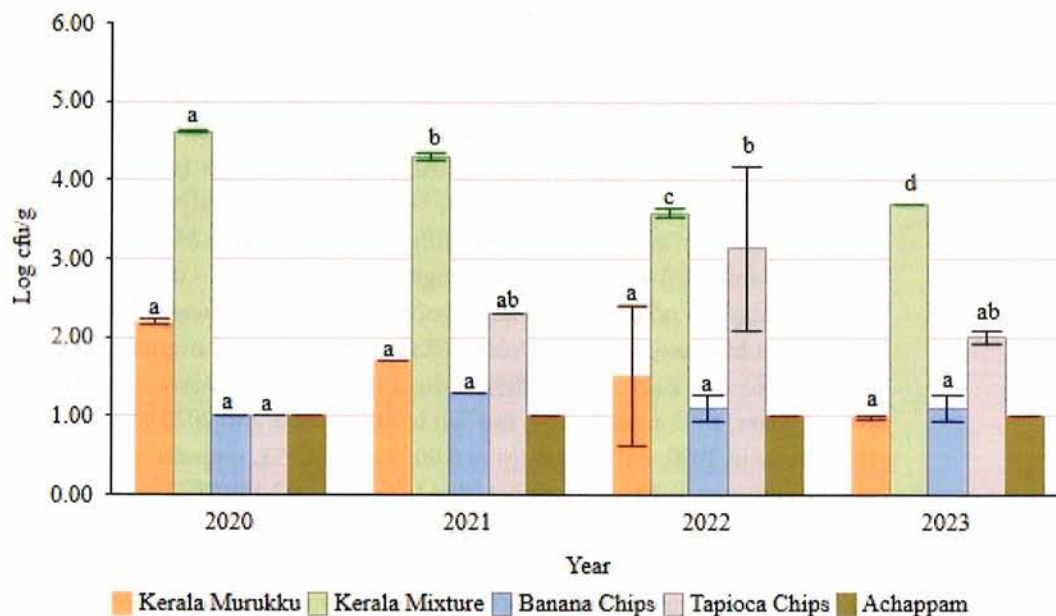


Figure 2. Total Plate Count (log CFU/g) in five traditional Indian fried snack products from 2020 to 2023. Bars indicate mean values \pm standard deviation. The x-axis groups products by year. Superscript letters denote statistically significant differences between years within each product ($p < 0.05$). Means sharing the same letter are not significantly different. Superscripts are only shown for products with significant ANOVA results.

3.3. Correlation Between Physicochemical Parameters and Microbial Counts Across Products

Principal Component Analysis (PCA) grouped the samples based on their physicochemical and microbiological characteristics. The PCA biplot (Figure 3) illustrates the projection of variables on the factor plane defined by the first two principal components (PC1 and PC2). Together, these components accounted for 56.50% of the total variance, with PC1 and PC2 explaining 38.15% and 18.35% of the variance, respectively. These components were selected because they capture the most significant factors contributing to variability in the data, particularly in relation to the microbial counts and physicochemical parameters across different snack products [46]. The PC1 is positively correlated with the number of ingredients, CFU/log, pH, and salt content, and forms a group, acting as major contributors to the variance across time. PC2 is influenced by moisture% and acid value, but with negative correlations with PC1.

The correlation analysis further reveals that CFU/log moderately correlates with pH ($r = 0.52$) and salt content ($r = 0.50$), suggesting microbial activity is influenced by these parameters. The number of ingredients also positively correlates with CFU/log ($r = 0.57$) and pH ($r = 0.57$), indicating that more complex formulations may impact microbial stability. Moisture content is negatively correlated with pH ($r = -0.35$) and CFU/log ($r = -0.28$), suggesting that drier products may exhibit lower microbial counts and different pH characteristics. The acid value of extracted fat showed weak correlations with other variables, except for moisture ($r = 0.14$). In addition, the positive and negative correlations obtained from PCA were further confirmed by Spearman's correlation method. In addition, Spearman's test shows a strong negative relationship of acid value of extracted fat with years ($p = -0.56$, $r = -0.18$), indicating improved oil stability over time, likely due to enhanced filtration practices and reduced re-use of frying oil post-certification.

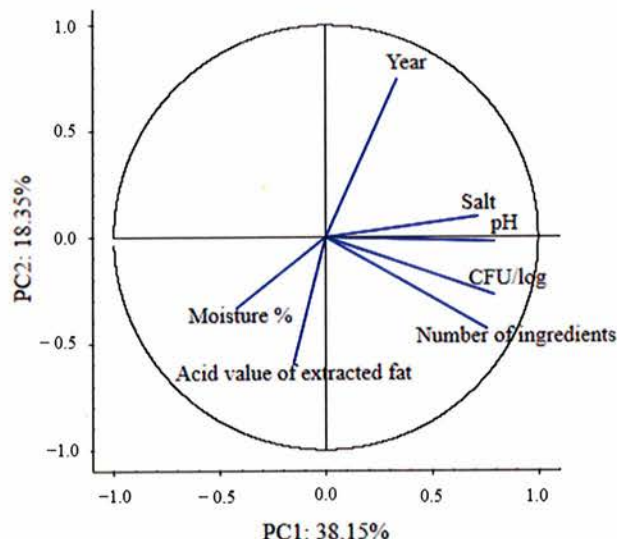


Figure 3. The principal component analysis biplot for correlations among physicochemical and microbiological parameters, ingredient count, and sampling years across all products.

3.4. Clustering of Products Based on Microbial Quality

Multivariate cluster analysis was conducted to classify the products based on their microbial quality over the study period. Products grouped with high microbial count were indicated as areas needing improvement. Two clusters were identified according to the similarities in microbial quality (CFU/log) (Figure 4). Cluster 1 included four products (Kerala Murukku, Banana chips, Achappam, and Tapioca chips), indicating a consistently low microbial count in these years and highlighting effective food safety measures. Cluster 2 included one product (Kerala Mixture), indicating a higher microbial count than the other products. Kerala mixture shows a comparatively higher microbial count (CFU/log: 4.61 ± 0.01 in 2020, 3.70 ± 0.00 in 2023) compared to other products. However, although microbial counts fluctuated slightly over the years, they remained within acceptable safety limits for all products.

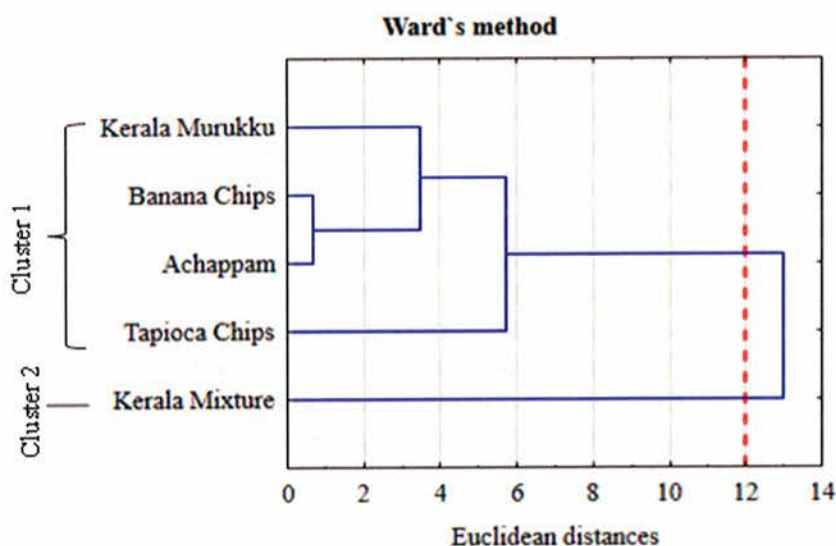


Figure 4. Dendrogram illustrating the hierarchical clustering of the five fried snack products based on their mean Total Plate Count (log CFU/g) values from 2020 to 2023, using Ward's method with Euclidean distances. The red dotted line represents the cut-off point (Euclidean distance ≈ 12) used to determine the clusters.

4. Discussion

This study was carried out to assess the physicochemical properties and microbiological quality trends in traditional fried snack products manufactured in an ISO 22000:2018-certified company. A fundamental aspect of food safety management is regulating the product composition to maintain microbial stability and shelf life. In food processing, variations in parameters such as moisture content, acid value, pH, and salt content can indicate shifts in manufacturing consistency, ingredient control, and storage conditions [2,8]. The physicochemical parameters of five traditional Indian fried snacks show variations due to differences in ingredient composition, manual processing, thermal behavior during frying, and shape of the product [47].

The moisture level in fried snacks is crucial in determining the shelf life of snack products [2,38]. Year-wise fluctuations in moisture content were statistically significant in Kerala Murukku, Kerala Mixture, and Banana Chips. Despite these fluctuations, all recorded moisture values remained below the 2% threshold commonly associated with microbial spoilage in low-moisture products. Excess moisture in salty snack products can occasionally lead to localized areas of high-water activity, which can enable mold development; however, such occurrences are uncommon and not typically expected in properly processed and packaged products [35]. These fluctuations can be due to variations in slice thickness, frying duration, and ambient cooling. This variability can be attributed to differences in mass and heat transfer properties during frying. The final oil uptake and moisture content are crucial quality parameters for fried products, ensuring a balance between water evaporation and diffusion [48]. Salt has several functions within the human body, as well as in influencing and balancing the qualities of food [49]. Salt content showed significant variations across all products, with pronounced differences observed in Kerala Mixture, Kerala Murukku, and Banana Chips. These changes may be attributed to unstandardized mixing and variation in component surface area. Increased surface area from finer particle sizes promotes salt and spice absorption, especially in dry spice coatings [48]. The salt content observed in this study remained below the reported range for Indian packaged fried snacks (1.45–2.71%) as documented by Raj et al. (2015), indicating comparatively moderate sodium levels and potentially reduced dietary risk when consumed in typical amounts [49]. The estimated average daily salt intake in India stands at 8.0 g/day, which far exceeds the World Health Organization (WHO) recommended limit (<5.0 g of salt per day) [49–51]. Concerning this, the measured salt content in Kerala Mixture and Kerala Murukku might raise concerns if consumed regularly, as they could further elevate sodium intake in the targeted population. Auto-oxidation of lipids and fats produces free fatty acids, which break down into smaller molecules, causing food quality degradation. The acid value measures the amount of free fatty acids in fat [52]. Acid value, a marker of oil degradation, showed statistically significant reductions over time in Tapioca Chips, Kerala Mixture, and Banana Chips, suggesting improved oil handling or turnover practices [48]. For example, the consistently lower acid values in 2023 across several products suggest that routine monitoring or adjustments in oil reuse practices may have been implemented. Kerala Murukku and Achappam showed no statistically significant change; however, all values stayed below the value that is considered unfavorable to safety or sensory quality. pH plays a role in microbial growth control [42]. Statistically significant year-wise pH variation was observed in Kerala Murukku, Tapioca Chips, and Achappam, though the overall pH range remained above 5 across all products. pH, an effective indicator of food stability, has been associated with microbiological and chemical reactions that cause food deterioration [53]. The pH values of Banana chips were found similar to those stated by Assanvo et al. (2023), who reported that the pH values of their ripe and unripe plantain chips range from 5.16 to 6.04, respectively [42].

Microbial analysis can predict the safety and stability of products [8]. Food microbiological quality may be generally determined by TPC; a high TPC count could suggest that the items were not produced hygienically or kept properly. Studies have reported that foods with a TPC level of more than 10^6 CFU/g may pose a risk of food poisoning pathogens such as *Salmonella*, *E. coli*, and *Staphylococci* [26]. In this study, all products are manufactured following standard operating procedures, indicating that when products are produced under hygienic conditions, the risk of food safety hazards is minimized. The consistently acceptable range of microbial count and physicochemical properties observed throughout the study period may be attributed to the modified air packaging, which effectively reduced environmental contamination.

Most international guidelines recommend Mesophilic aerobic bacteria (MAB) analysis as an indicator of microbiological status in ready-to-eat (RTE) foods. In this regard, MAB counts exceeding 5 log cfu/g are considered a potential risk for the presence of pathogens [54]. The findings of this study align with these guidelines, reinforcing that the products analyzed meet internationally recognized microbiological safety standards. Based on the results obtained, it has been found that the microbiological safety of all the samples examined indicated low levels of TPC (<5 log CFU/g). The study found an average count of 4.61 log cfu/g in Kerala Mixture in 2020, which was the highest TPC count across all products, while in the subsequent year, the average TPC level remained below this value. These results suggest possible post-frying and process environment contamination, likely caused by stages in seasoning, mixing, cooling, and packaging processes. Previous study indicates that while low-moisture snacks are generally microbiologically stable, contamination hazards remain, especially after frying, due to the application of seasonings and handling during cooling and packaging [35]. Seasonings that are added after frying without a kill-step provide a risk of contamination and necessitate strict hygiene measures. As outlined in ISO 22000, risk reduction should incorporate hazard-based control methods, environmental monitoring, and sanitation verification [21]. A similar study on the traditional snack "Chanachur" reported unsatisfactory microbial quality in both branded and unbranded samples, attributing contamination to improper handling, unclean mixing machines, and poor personal hygiene among food handlers [55]. High microbial counts in ready-to-eat (RTE) snacks are usually associated with poor hygiene and storage conditions, especially in unregulated or street-vendor settings. For example, a study in Nigeria reported the presence of total aerobic bacteria, coliforms, and foodborne pathogens such as *S. aureus* and *E. coli* in snack products sold in unsanitary conditions [11]. Despite this, unseasoned finished fried products typically have aerobic plate counts of less than 100–1000 CFU/g. The results also found that the product Achappam has consistently had the lowest microbial count among all products.

The results obtained in this study are like to the data reported for Banana chips by Navarro et al. (2018), who evaluated the microbiological quality of plantain banana snacks in Venezuela, revealing a load of 5.78×10^2 CFU/g for aerobic mesophilic germs, indicating the product is safe for consumption without any harmful health effects [56]. The authors emphasize the importance of a sanitized production line and immediate packaging of products to minimize outdoor exposure and contamination. These findings reinforce the importance of maintaining strict post-processing controls, especially for the Kerala Mixture, which showed a higher TPC count across all years. If food products have been put out in areas where airborne contamination occurs for an extended time, recontamination by air should be taken into account. The settling velocity of microorganisms, their concentration in the air, the product's exposure time, and the area within it all affect the entrance of microbial load to food through the air [54]. Food deterioration can occur due to factors like oil oxidation, carbohydrate-rich browning, and protein changes. Polymeric films with inert

gas with effective barrier properties are crucial to prevent the fried snacks from oxygen and moisture damage. Metalized polyethylene terephthalate (PET)/low-density polyethylene terephthalate (LDPE) or PET/Aluminum laminates are effective packaging materials that maintain food's microbial and physicochemical stability during storage [57]. In this study, all the products are packaged in metalized PET laminated packages to avoid oxidation, protect the product's safety and quality, and prevent premature staling.

Furthermore, a study examined the microbiological quality of various popular dried foods and reported the potential for fungus (10^5 – 10^7 cfu/g) and bacteria (10^4 – 10^7 cfu/g) contamination of dried foods, highlighting the need for regular microbiological examination to safeguard public health and prevent food-borne illnesses [13]. Previous studies proved that successful implementations of food safety management systems (FSMS), such as ISO 22000:2018, can help to improve microbiological quality and operational control. For example, a case study of a chaga mushroom processor in Vietnam found that implementing FSMS resulted in lower coliform levels and improved supplier oversight [27]. Similarly, food manufacturers working under ISO 22000 achieved better microbiological results than those using less stringent systems such as Makanan Selamat Tanggungjawab Industri (MeSTI) [58]. While this study did not directly evaluate FSMS implementation, the facility involved was ISO 22000:2018 certified, and the observed year-to-year variation in product quality parameters emphasizes the importance of continuous and practical application of such systems, particularly in manual small-scale settings.

This study reveals that standardized processing measures are crucial for maintaining quality consistency across products, with variations in parameters and higher microbial load in Kerala Mixture likely due to manual small-scale operations. Even if the company has ISO 22000:2018 certification, this certification basically verifies that adequate system structures and documentation for food safety are in place. However, previous research has emphasized that FSMS effectiveness depends not only on certification status but on how well the system is implemented in daily practice [26,59]. The observed variation emphasizes the possibility that regular monitoring, verification, or corrective actions might not be carried out adequately or systematically. This indicates an ongoing gap between established procedures and their actual implementation, particularly in environments with limited resources. The study emphasizes the need for robust operator-level controls and standard operating procedures to maintain product quality uniformity. It calls for transparent, unannounced food safety inspections by regulatory bodies. Advanced imaging technologies, like high-speed computed tomography, have improved scientific understanding of how frying parameters affect oil absorption and moisture migration, even though they are not yet applicable at the small-scale enterprise level. This has indirectly helped to refine fundamental quality control techniques in conventional settings [60]. This study also suggests that fully automated systems are largely unaffordable for small enterprises due to high capital and skill requirements. Therefore, in addition to regulatory control, governmental support through schemes that fund modernization, equipment upgrades, and technical training (such as India's Pradhan Mantri Formalisation of Micro Food Processing Enterprises Scheme (PM-FME) program) is essential [61,62].

Limitations and Future Perspective

This study contributes to the existing literature by assessing the microbiological and physicochemical quality of traditional South Indian fried snacks produced within an ISO 22000:2018-certified company. Rather than evaluating the direct impact of certification, the findings highlight how quality parameters evolved over time within a structured FSMS environment. Since this study focused on a single manufacturing firm, future research should examine multiple small- and medium-scale enterprises to enable a broader

comparison of FSMS implementation and its effectiveness across different operational settings. Moreover, incorporating pathogen-specific testing alongside TPC evaluations could provide deeper insights into microbiological safety in fried snack products. Moreover, future studies could explore the impact of seasonal variations on product quality, as changes in raw material availability and environmental factors may affect the microbiological and physicochemical properties of fried snacks. Despite this, future studies should explore the feasibility of incorporating edible coatings as an additional protective barrier, particularly for moisture and acid value control. The safety and quality of deep-fried foods can be enhanced by edible coatings, particularly those derived from chitosan and cellulose. By sustaining moisture, these coatings improve texture without overdrying. Likewise, they reduce oil absorption, which lowers oil content and retains moisture stability [63,64].

5. Conclusions

This study provides valuable insights into the physicochemical and microbiological quality trends of traditional fried snacks in a small-scale Indian food manufacturing company operating under an ISO 22000:2018-certified Food Safety Management System (FSMS). Based on four years of data (2020–2023), the results demonstrate that physicochemical parameters have remained within ranges not associated with food safety risks, and total plate count (TPC) values for all products remained below the acceptable limit of 5.99 log CFU/g. Statistically significant year-wise differences were identified in most products, particularly in Kerala Mixture, which showed the most pronounced variation in microbial load and salt content. These results emphasize the importance of more frequent monitoring and tighter control of post-processing operations, including stages in seasoning, mixing, cooling, and packaging processes. Although pre-certification baseline data were unavailable, preventing a direct assessment of the impact of ISO 22000 implementation, the consistent product quality monitoring observed during the study reflects a structured approach aligned with ISO 22000 verification principles, particularly Clause 8.8, which emphasizes product monitoring and analysis of results. This study does not claim full verification of ISO 22000:2018 compliance. Rather, it demonstrates how regular analysis of key safety parameters can support the internal evaluations of FSMS performance. These findings can serve as a reference for other small-scale food enterprises aiming to strengthen FSMS implementation by targeting product-specific risks and optimizing monitoring schedules. Ultimately, the study affirms that adopting structured food safety practices enables small-scale manufacturers to maintain consistent product safety and quality, despite the variability inherent in traditional manual production processes.

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Article

Food Safety Management System Compliance of Food Retail Shops: A Comparative Study Between Mazovia and Kerala

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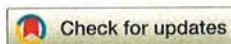
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Abstract

This study investigates and compares Food Safety Management System (FSMS) compliance in retail shops across Mazovia (Poland) and Kerala (India). A structured visual inspection checklist with 51 indicators across seven FSMS sections was used in 500 shops per country: design and layout, general food safety, food handling and storing practices, display, personnel hygiene practices, sanitation and cleanliness, and pest control. Each section was scored using a four-point ordinal scale. Compliance scores were analyzed using the Mann-Whitney U test, Kruskal–Wallis test, Principal Component Analysis (PCA), and Cluster analysis to identify influencing factors and compliance patterns. The results demonstrate significant differences between the two countries, with Polish retail shops showing notably higher compliance ($p < 0.001$). No significant difference was observed in the design and layout section ($p = 0.103$). None of the assessed shop categories in either country achieved full compliance with all food safety requirements. Retail format, location, and number of employees were significantly associated with compliance levels. This is the first comparative study to examine FSMS compliance in retail shops in Mazovia, Poland, and Kerala, India, using a standardized visual inspection method. The findings contribute to a better understanding of FSMS performance in retail environments under different economic and regulatory conditions. Identifying how variations in retail format, staffing, and operational practices influence FSMS compliance can support the development of context-specific strategies to improve food safety performance.

Keywords: food safety; food retail formats; degree of compliance; Poland; India



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1. Introduction

Despite advancements in food safety measures, foodborne illness outbreaks and recalls continue to be reported, many of which are associated with the retail level [1], which has prompted regulatory reforms and stringent enforcement worldwide [2]. To ensure consumer safety, food business operators are required to implement an integrated Food Safety Management System (FSMS) that includes Good Hygiene Practices (GHP), Good Manufacturing Practices (GMP), Traceability provisions as Prerequisite Programmes (PRPs), and

HACCP principles-based procedures. FSMS aims to proactively control foodborne illness risk factors through industry-specific procedures integrated into business operations [3].

However, the implementation of FSMS in retail environments differs considerably from its application in food manufacturing or processing sectors. Retail establishments operate at the final stage of the food supply chain and involve direct interaction with consumers, multiple food handling activities, and diverse storage and display conditions. Unlike manufacturing facilities that operate under standardized production processes, food retail outlets manage a wide variety of products, including fresh, frozen, and ready-to-eat foods, often handled under different temperature and hygiene requirements [4]. Retail operations also involve frequent product turnover and multiple potential contamination points during storage, display, and consumer interaction. Inadequate handling, poor stock management, or storage can lead to food losses and waste, even when products are still safe for consumption [5]. These characteristics make the implementation and monitoring of FSMS in retail environments particularly challenging and highlight the need for food safety practices tailored specifically to retail operations. Nevertheless, implementing FSMS requires significant technical knowledge, managerial commitment, and financial resources, which can be challenging for small food enterprises, including many retail businesses [6]. According to Regulation (EC) No 178/2002, retail is defined as 'the handling and/or processing of food and its storage at the point of sale or delivery to the final consumer, and includes distribution terminals, catering operations, factory canteens, institutional catering, restaurants and other similar food service operations, shops, supermarket distribution centers and wholesale outlets' [7].

Grocery retailers play a crucial role in connecting all stages of the food supply chain, sourcing directly from farms and manufacturers, to supply food to consumers through their stores [8]. Retail practices have a considerable impact on food safety, as mishandling or poor storage at the final stage can compromise the integrity of the entire supply chain. Therefore, flexibility in regulations as well as scientific input to apply a risk-based FSMS is very much needed for the unique operational settings of the retail sector. A retail business's FSMS should focus on identifying hazards and implementing specific activities to manage risk factors that contribute to foodborne illness [6]. Moreover, retailers play a crucial role in encouraging producers to shift from input-driven agricultural decision-making, issuing production mandates that can lead to significant changes in farming practices [9]. Although elements of FSMS may vary between food service and retail sectors, core elements such as training, monitoring, and systematic implementation are all consistent [3]. International systems such as Food Safety System Certification (FSSC) 22000, the International Featured Standard (IFS), the British Retail Consortium Global Standard (BRCCS), and the International Organization for Standardization (ISO) 22000 provide tools to achieve standardized food safety practices across diverse retail operations [2,10].

Inadequate compliance with FSMS requirements in retail establishments remains a persistent public health concern, with reports highlighting issues such as inadequate personal hygiene, contaminated surfaces and equipment, and improper time and temperature control as the most common causes of food safety failures [3]. Although the European Union has established harmonized hygiene regulations, such as Regulation (EC) No. 852/2004 and Regulation (EC) No. 178/2002 [7,11] to promote a unified food safety framework, numerous obstacles impede the successful implementation of FSMS (PRP and HACCP) in the retail sector. These include inconsistencies and insufficient awareness of safety protocols, inadequate training, irregular inspections/audits, lack of resources among small and micro retailers, and inflexibility [6]. The European Union One Health Zoonoses Report (2023) highlighted the retail sector as a frequent source of contamination for foodborne pathogens such as *Salmonella* and *Listeria* [12]. More importantly, a strong

internal food safety culture in the retail sector will be key to the successful implementation of FSMS [13]. A food company's culture can be defined as the perceptions and behaviours of its employees regarding food safety, as well as the actions they consistently engage in and demonstrate [14].

Ensuring food safety across the retail sector requires compliance with comprehensive hygiene and operational standards. These include the proper design, construction, and maintenance of premises to allow effective cleaning, prevent contamination, and limit pest entry. Surfaces that come into contact with food must be easy to clean and made of non-toxic, non-absorbent materials. Regular maintenance of the premises and facilities is essential to prevent deterioration that could compromise food safety. Equipment and utensils used in food storage, preparation, and display must be appropriate for their intended purpose, kept in good condition, and cleaned and sanitized frequently. Retailers must implement proper waste management systems, ensuring that waste is collected, stored, and disposed of hygienically to avoid contamination risks. Pest control measures must be actively maintained, including structural barriers and regular inspections, to prevent pest infestations. Temperature control must be rigorously applied during storage and display to ensure that perishable foods are maintained within safe temperature ranges. Moreover, food handlers must maintain high standards of personal hygiene, including proper hand washing, use of protective clothing, and regular health monitoring, to prevent foodborne illnesses. Together, these requirements establish a foundation for food retailers to manage food safety risks effectively and align with the implementation of FSMS [15].

Food safety priorities and enforcement mechanisms differ between developed and developing countries. Developed countries benefit from more stable economic and social environments, responsible procurement and consumer habits, and strict legislation for food safety, ensuring safe food access and availability [16]. Poland operates within the European Union (EU) food safety regulatory framework, where food safety enforcement is coordinated through EU legislation and implemented by national inspection bodies. Retail food establishments are subject to official inspections conducted by competent authorities to verify compliance with food safety legislation, and enforcement measures may be applied in cases of non-compliance [17]. Poland's retail sector is well-networked, highly structured, and increasingly aligned with the European food retail model. Specialized shops that provide basic food needs, such as housing estate stores, gas stations, and minimarkets, dominate the number of small food retail businesses in urban areas. In addition to private firms and cooperative retail chains, small and medium-sized enterprises with national or foreign capital are often organized into franchising networks, with the franchisor controlling their operations. A franchise network organization is a group of separate businesses that form a contractual network without any financial connections [18].

Food safety regulation in India is supervised by the Food Safety and Standards Authority of India (FSSAI), which oversees licensing, inspections, and enforcement activities across the country. Although FSSAI has strengthened regulatory frameworks and introduced training initiatives such as the Food Safety Training and Certification (FoSTaC) program, differences in inspection frequency, enforcement capacity, and regulatory implementation efficiency may occur due to regional administrative variations and the large number of small-scale and informal retail establishments. These institutional differences may influence the effectiveness of food safety management practices in retail environments. India's food retail sector is diverse, where traditional unorganized grocery stores and government-supported food distribution outlets supplying essential commodities remain dominant, while organized retail and e-commerce platforms, such as convenience stores, supermarkets, and hypermarkets, are growing [19].

The Food Safety and Standards Authority of India (FSSAI) registration is mandatory for all food businesses in India, including manufacturers, distributors, and retailers, to ensure the safety and quality of food products, with non-compliance resulting in penalties and fines [20]. According to the Food Safety and Standards Act of 2006, the FSSAI has established fundamental food safety and hygiene standards that are applicable to both organized and unorganized food retailers, with specific requirements concerning the size and complexity of operations [21]. To strengthen food safety and promote transparency at the retail level, FSSAI established Food Safety Display Boards (FSDBs), which are colour-coded informative boards that convey hygiene and food safety practices required at food business premises. In addition to the legal requirement for displaying the FSSAI license or registration number, these boards are being implemented gradually across several food company categories to increase consumer awareness and regulatory visibility [22,23].

There is limited research on FSMS practices and compliance levels in food retail shops in Poland, and such studies are even rarer in the Indian context. Given these considerations of the central role of retailers and the complexity of food safety governance, this study aimed to evaluate the degree of compliance with food safety management systems practices in retail shops in Mazovia, Poland, and Kerala, India, through direct visual inspections. By comparing two distinct regulatory and operational environments, the study seeks to identify key challenges and opportunities for strengthening food safety performance in the retail sectors in both nations. This study hypothesizes that FSMS compliance scores significantly differ between Polish and Indian food retail shops, and that compliance is influenced by shop-specific factors assessed in this study.

2. Materials and Methods

2.1. Food Retail Shops

The study was conducted from March 2024 to February 2025, covering a total of 1000 food retail shops- 500 each in Mazovia (Poland) and Kerala (India). These regions were selected due to their differing regulatory environments and levels of food safety modernization, making them ideal for comparative evaluation of food safety management practices [18,24]. Both regions are known for their dense retail shop networks and significance in national food supply chains.

A stratified purposive sampling approach was used to ensure representation of different retail environments. The retail shops were selected across three location categories: large cities, small towns, and rural areas in both Mazovia and Kerala. Within these locations, shops were further categorized according to retail format, including hypermarket, supermarkets, convenience shops, and local shops. During field visits, retail shops were selected within these categories to ensure coverage of different shop sizes, operational structures, and retail practices across the study regions.

Data were collected from retail shops located in large cities (e.g., Warsaw, Trivandrum), small towns, and rural areas across Mazovia and Kerala. The retail shops evaluated in this study include hypermarkets, supermarkets, convenience stores, and local shops [25,26]. Hypermarkets are large-format stores with sales areas exceeding 2500 m², offering both food and non-food products. Supermarkets are medium-sized shops with sales areas between 400 m² and 2500 m², focusing primarily on food products. Convenience shops are smaller shops with sales areas between 300 m² and 900 m², offering a limited range of goods at higher prices and being located near transport hubs or gas stations. Local shops include small independent grocers or specialty food shops with limited sales spaces and mainly focus on packaged groceries and specific food categories [27,28].

2.2. FSMS Compliance Assessment and Scoring System in Retail Shops

Food Safety Management System compliance evaluation in retail shops was evaluated using a structured visual inspection tool. The tool is formatted as a 51-indicator checklist, based on the unified mandatory food safety requirements in both countries [12,29]. Indicators were grouped into seven key sections: design and layout, general food safety, food handling and storing practices, display, personnel hygiene practices, sanitation and cleanliness, and pest control (Table 1).

Table 1. List of indicators in the checklist.

	Please Mark Ratings 1–4 *
1. Design & layout	
1.1. Shop layout and design support safe food handling.	
1.2. Shop located away from an environmentally polluted area.	
1.3. Shop adequately lit and ventilated.	
1.4. Shop provides sufficient workspace and storage to allow hygienic operations.	
1.5. Shop surfaces (walls, floors, and other areas) designed for easy cleaning.	
2. Food Safety	
2.1. Employees' actions do not create food safety risks.	
2.2. Shop addresses any identified food safety violations promptly.	
2.3. Food safety information is displayed (manuals, posters, signs, and/or icons)	
2.4. Employees remain within assigned work areas to avoid cross-contamination.	
3. Food Handling and Storing Practices	
3.1. Food preparation conducted in a clean and sanitary manner.	
3.2. Food and equipment stored off the floor or on clean and movable platforms.	
3.3. Products segregated as needed to prevent cross-contamination (physical, microbiological, allergenic).	
3.4. No unaddressed food safety hazards observed during inspection.	
3.5. Hygienic utensils (tongs or scoops) used for food handling.	
3.6. No bulging or leaking canned products observed.	
3.7. No bulging or leaking plastic packaged foods observed.	
3.8. No damaged or leaking fruits and vegetables observed.	
3.9. Refrigerated foods are properly wrapped, labeled, and dated.	
3.10. Products stored under proper conditions. (e.g., Canned, jarred, shelf-stable products, bakery items, and dry products- clean & dry storage, refrigerated $\leq 5^{\circ}\text{C}$, frozen $\leq -18^{\circ}\text{C}$, hot foods $\geq 60^{\circ}\text{C}$, open markets protected from sunlight/contamination).	
3.11. Sensitive products (e.g., seafood, raw meats) physically separated from direct consumer contact.	
4. Display	
4.1. Displayed products labeled and signposted correctly.	
4.2. No mold observed on displayed products.	
4.3. No off-colors observed on displayed products.	
4.4. No off-odours smelled in displayed products.	
4.5. No damage, breakdown, or spillage observed in displayed products.	
4.6. No pest evidence observed on displayed products.	
4.7. No expired products found among displayed products.	
4.8. Foods displayed are protected from consumer contamination (e.g., covers, food guards).	
5. Personnel Hygiene Practices	
5.1. Employees wear protective clothing (gloves, aprons, closed footwear).	
5.2. Employees wear appropriate head coverings (hats, hairnets) when preparing food.	

Table 1. Cont.

	Please Mark Ratings 1–4 *
5.3. Employees do not smoke or use tobacco in food areas.	
5.4. Employees do not eat or drink in food preparation/handling areas.	
5.5. Employees do not spit in the workplace.	
5.6. Employees follow jewelry policy (no rings, watches, loose accessories).	
5.7. Employees with visible wounds, infections or sores do not handle food.	
5.8. Employees avoid touching their face, nose, or hair while handling food.	
5.9. Employees demonstrate hygienic behaviour when handling food and interacting with customers.	
6. Sanitation and Cleanliness	
6.1. Equipment in direct food contact is suitable for safe handling and maintained in good condition.	
6.2. Surfaces, equipment, and utensils are clean and free from debris.	
6.3. Floors, walls, and ceilings are properly maintained and cleaned.	
6.4. Shop overall appearance is clean and well kept.	
6.5. Cleaning equipment (mops, brooms, etc.) stored neatly and hygienically.	
6.6. Exterior areas clean and well drained; back areas free from debris.	
6.7. Regular cleaning and sanitizing practices observed during inspection.	
6.8. Shop staff monitor and act on any observed product mishandling by customers.	
6.9. Shelves, refrigeration, and freezer units are clean and free of corrosion.	
7. Pest Control	
7.1. External openings (doors, windows, vents) screened or otherwise protected against pest entry.	
7.2. No evidence of active pest infestation (rodents, insects, mold) observed.	
7.3. No live animals or birds observed in food preparation or storage areas.	
7.4. External doors and screens are self-closing and in good working condition.	
7.5. Pest control devices present and properly maintained.	

* Rating scale: 1—non-compliant, 2—partially compliant, 3—mostly compliant, and 4—fully compliant.

Each food safety practice was scored on a 4-point ordinal rating scale [10]. Numerical scores were assigned to each indicator, where higher scores indicated better compliance. The scale was defined as follows:

- 1—Non-compliance, where the requirement was not implemented;
- 2—Low compliance, where the requirement was partially implemented but major deficiencies were observed;
- 3—Moderate compliance, where most requirements were implemented with minor deficiencies; and
- 4—Full compliance, where the requirement was fully implemented according to food safety guidelines.

For example, when assessing refrigerated food storage, a score of 1 was assigned when foods were stored without temperature control or outside safe refrigeration conditions; a score of 2 was assigned when refrigeration equipment was present but major deficiencies were observed, such as missing temperature monitoring records or overloaded storage; a score of 3 was assigned when refrigeration was generally maintained but minor issues, such as incomplete labeling or irregular monitoring records, were noted; and a score of 4 was assigned when proper temperature control and appropriate storage conditions were fully maintained.

All indicators were assigned equal weight, and the overall compliance scores for each retail shop were calculated as the average of all indicator scores. The final score reflected both the general level of compliance and variation across individual FSMS categories. In

addition, the checklist considers the contextual information about retail shops, such as country, location, retail format, and number of employees.

To verify the clarity, applicability, and consistency of the inspection checklist, a pilot assessment was conducted in 10 retail shops in each study region prior to the main investigation. The pilot inspections were carried out using the same structured checklist and scoring procedure intended for the full-scale assessment. The purpose of the pilot study was to evaluate the operability of the indicators during on-site inspections and to ensure consistent interpretation of the scoring criteria. Based on the pilot observations, minor adjustments were made to improve the wording and ordering of several checklist items and to clarify certain scoring descriptions. These modifications enhanced the clarity and usability of the inspection tool before conducting the main field investigation. This methodology aligns with validated visual inspection procedures used for food safety evaluations [15,30].

Data was collected through unannounced on-site observations during normal operational hours to ensure an authentic evaluation of FSMS performance. The assessment was carried out by the first author of this study, who has extensive experience in the food industry, having served as Quality Assurance in Charge/Food Safety Team Leader, and Preventive Control Qualified Individual (PCQI), and has strengthened her expertise in food safety management through continuous professional development and assessments based on ISO 19011 (2011) [31].

2.3. Statistical Analysis

The reliability and internal consistency of the indicators were tested by Cronbach's alpha [32]. Descriptive statistics, such as mean and standard deviation (SD), were calculated to interpret the results. The Mann-Whitney U test was applied to determine whether there were statistically significant differences in FSMS compliance scores between the two independent groups- Polish and Indian retail shops- as the distribution of scores in all sections deviated from normality, according to the Shapiro-Wilk test ($p < 0.05$) [33,34]. The Kruskal-Wallis test was used to evaluate differences in FSMS compliance scores (dependent variable) across categorical grouping variables (independent variables): country, shop location, food sector, and number of employees. When significant differences were detected, post hoc pairwise comparisons were conducted using Dunn's multiple comparisons test with Bonferroni correction. Principal Component Analysis (PCA) was used to evaluate the relationship between retail formats and FSMS compliance levels in Mazovia and Kerala. Multivariate cluster analysis was performed to group food retail shops in each country based on compliance level, using Ward's method and Euclidean distance [10]. The results could be considered significant when $p < 0.05$. All the statistical analyses were performed using Statistica software version 13.3 (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

The internal consistency of the inspection checklist was assessed using Cronbach's alpha, which indicated excellent reliability of the tool, yielding a coefficient of $\alpha = 0.97$.

3.1. Compliance Scoring in Retail Shops

The Kruskal-Wallis test indicated that the average total compliance scores of retail shops were significantly influenced by four key factors: country ($p < 0.001$), location ($p < 0.001$), food sector ($p < 0.001$), and number of employees ($p < 0.001$). Post hoc multiple comparisons revealed that retail shops in Mazovia ($R = 559.67$, i.e., Mean rank) had significantly higher compliance than those in Kerala ($R = 441.33$) ($p < 0.001$). The post hoc Dunn's multiple comparisons within each country confirmed significant differences across the four key factors ($p < 0.001$). The analysis data can be found in the Supplementary Materials.

As shown in Table 2, higher compliance scores were observed in hypermarkets and shops located in big towns in both countries. The lowest scores were consistently found among local shops, rural areas, and shops with only one staff member. These findings suggest that better compliance is associated with larger, urban-based retail shops with more employees, whereas smaller, less resourced shops in rural areas demonstrated consistently lower food safety management scores. The pattern was similar in both countries, though Polish shops showed less variation and generally higher compliance across all factors.

Table 2. Current compliance scores in retail shops by location, retail format, and number of employees.

		Compliance Rating (Mazovia)		Compliance Rating (Kerala)	
		N	Mean ± SD	N	Mean ± SD
Location	Big town	257	3.49 ± 0.48 ^a	175	3.59 ± 0.38 ^a
	Small town	181	3.41 ± 0.48 ^a	165	3.00 ± 0.58 ^b
	Rural area	62	3.00 ± 0.60 ^b	160	2.88 ± 0.48 ^b
Retail format	Hypermarket	33	3.70 ± 0.40 ^a	106	3.67 ± 0.48 ^a
	Supermarket	206	3.51 ± 0.41 ^b	221	3.18 ± 0.48 ^b
	Convenience shop	138	3.66 ± 0.29 ^a	84	3.16 ± 0.48 ^b
	Local shop	123	2.84 ± 0.50 ^c	89	2.54 ± 0.35 ^c
Number of employees observed	>10	41	3.44 ± 0.53 ^{ab}	81	3.75 ± 0.32 ^a
	5–10	90	3.56 ± 0.43 ^a	52	3.42 ± 0.49 ^b
	4–5	72	3.58 ± 0.32 ^a	121	3.21 ± 0.54 ^b
	2–3	113	3.36 ± 0.55 ^b	179	3.02 ± 0.48 ^c
	1	184	3.26 ± 0.56 ^{ab}	67	2.59 ± 0.41 ^d

Different superscript letters within each column indicate statistically significant differences between groups ($p < 0.05$) based on post hoc Dunn’s multiple comparisons test. Values sharing the same letter are not statistically significant.

Table 3 shows the mean scores of FSMS compliance per section for food retail shops in Mazovia and Kerala. The Mann–Whitney U test revealed significant differences ($p < 0.05$) across six of the seven evaluated FSMS sections: 2, 3, 4, 5, 6, and 7. In these areas, Polish retail shops exhibited higher mean compliance scores than Indian shops. No significant difference was observed in the Design & Layout section ($p = 0.103$). The highest differences were observed in Sections 4, 5, and 7, which are related to the requirements for display, personal hygiene practices, and pest control.

Table 3. Mean scores of food retail shops across Mazovia and Kerala.

Section Number	Sections	Mazovia	Kerala	p^*
		Mean Score of FSMS Compliance	Mean Score of FSMS Compliance	
Section 1	Design & Layout	3.146	3.108	0.103
Section 2	Food Safety	3.157	3.010	0.000
Section 3	Food Handling and Storing Practices	3.537	3.318	0.000
Section 4	Display	3.615	3.374	0.000
Section 5	Personnel Hygiene Practices	3.484	3.174	0.000
Section 6	Sanitation and Cleanliness	3.227	3.096	0.019
Section 7	Pest Control	3.346	2.815	0.000

* Mann–Whitney U test.

3.2. Principal Component Analysis Using Full Compliance Benchmark

The biplot (Figure 1), obtained from Principal Component Analysis (PCA), displays the projection of average compliance scores of eight retail formats (four from Mazovia and four from Kerala), along with a benchmark for full compliance. The first two principal components explain 80.23% of total variance (PC1 = 53.97% and PC2 = 26.26%), making the plot to assess the variability in FSMS compliance.

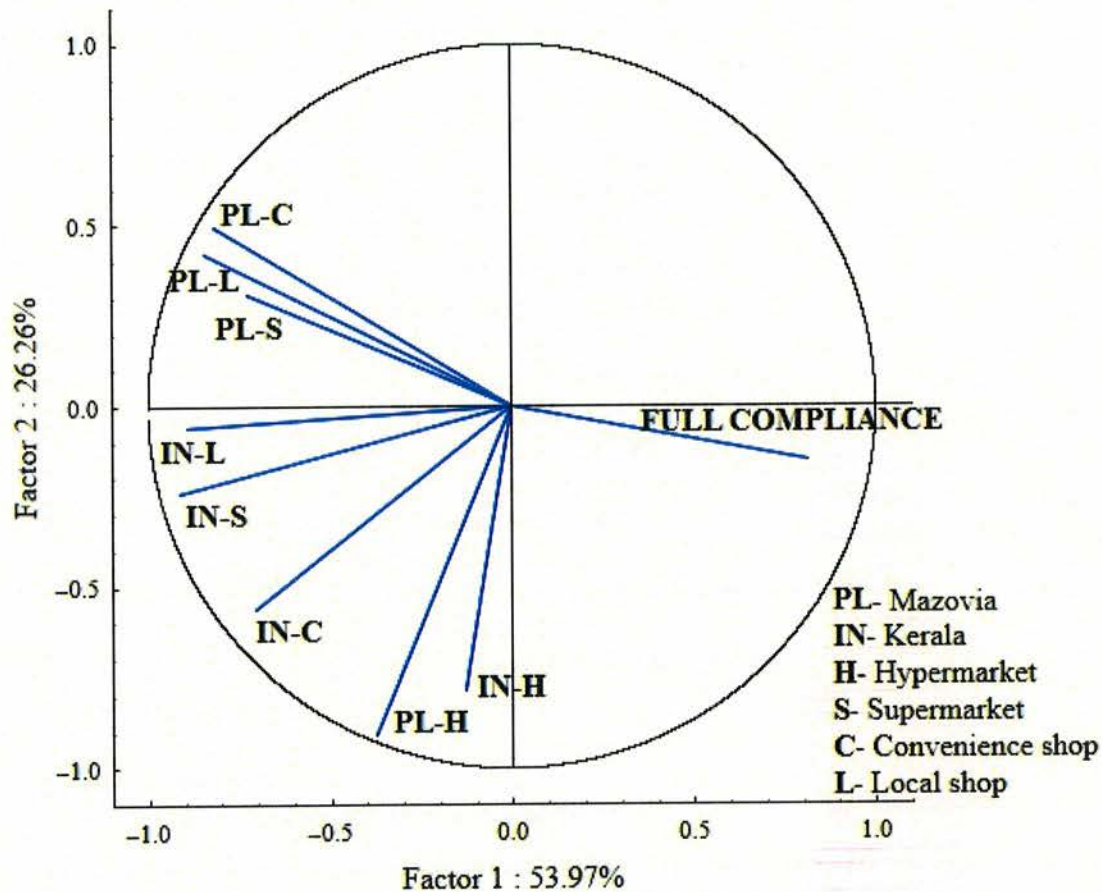


Figure 1. Principal component analysis (PCA) biplot showing the relationship between retail shop types and FSMS compliance levels in Mazovia (Poland) and Kerala (India). Retail shop categories are represented as vectors indicating their relationship with FSMS compliance. The direction of the “Full Compliance” vector represents higher compliance levels, and shop categories positioned closer to this direction show better compliance.

The PCA biplot indicates associations among retail shop categories based on their FSMS compliance patterns. The full compliance vector was located furthest along PC1, serving as the ideal benchmark. Among all retail shops, Polish (PL-H) and Indian (IN-H) hypermarkets aligned most closely with this benchmark, indicating strong adherence to food safety practices. In contrast, supermarkets, convenience shops, and local shops from both countries were located farther away. Moreover, Indian shops, especially IN-S (supermarkets), IN-C (convenience shops), and IN-L (local shops), were positioned further from the full compliance vector than their Polish counterparts, reflecting a lower overall adherence to food safety practices.

This distribution highlights that hypermarkets in both countries demonstrate the strongest food safety compliance, while supermarkets, convenience shops, and local shops, particularly those in Kerala, show notably lower levels of compliance compared to similar types in Mazovia.

3.3. Comparative Cluster Analysis of FSMS Implementation in Mazovia and Kerala

Cluster analysis resulted in two clusters (Figure 2). Cluster 1 consisted of all the FSMS sections: design and layout, general food safety, sanitation and cleanliness, food handling and storing practices, display, personnel hygiene practices, and pest control. The close grouping of these sections indicates a high level of internal consistency and uniformly strong FSMS implementation across Polish retail shops. Cluster 2 included all corresponding FSMS sections from India: design and layout, sanitation and cleanliness, general food safety, pest control, food handling and storing practices, display, and personnel hygiene practices.

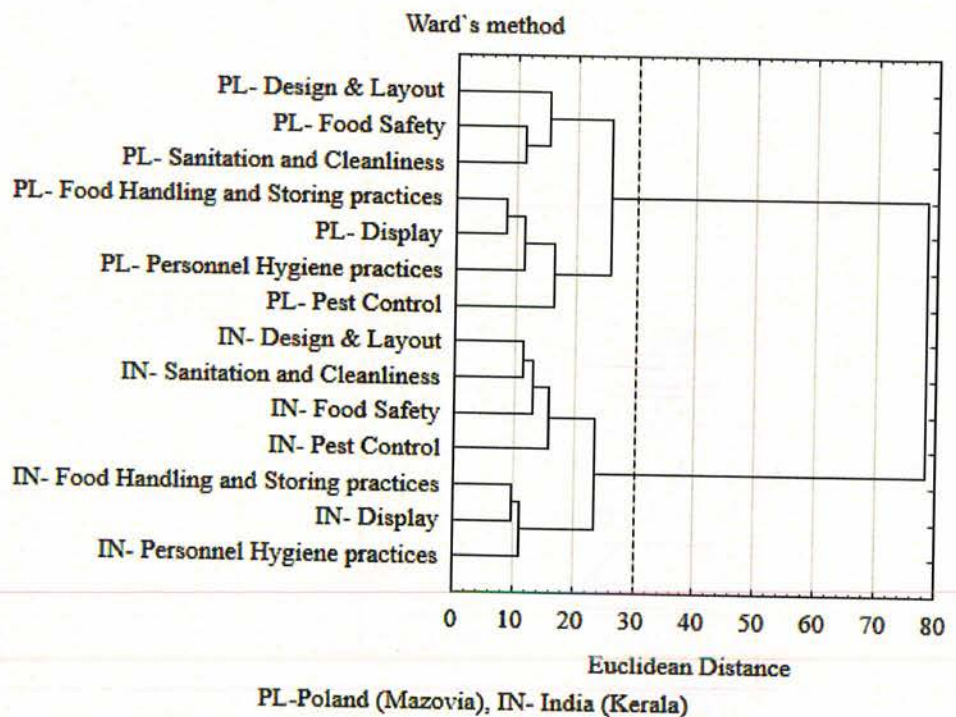


Figure 2. Dendrogram showing clusters extracted from Mazovia (Poland) and Kerala (India) retail shops based on section-wise FSMS compliance performance.

The inclusion of these variables for Indian retail shops in a separate cluster highlights a distinct FSMS performance profile, characterized by greater variability and generally lower compliance scores compared to the Polish retail shops. The formation of two clear clusters for each country suggests a marked divergence in FSMS implementation across national contexts.

3.4. Observations from the Retail Environment

Various conditions of compliance and non-compliance were observed using the inspection tool. The audit tool, although limited to a few retail shops, has demonstrated the ability to identify various unsafe food handling conditions in the retail environment. Figure 3 illustrates selected examples of FSMS non-compliance observed during the inspection in both regions. It was noted that retail shops operating under the same franchise exhibited similar FSMS compliance patterns; however, variations were observed across different franchise chains.

Infrastructural setups in hypermarkets were generally consistent across both countries. In contrast, some local shops and supermarkets in Mazovia and Kerala lacked adequate working space and storage capacity. Certain small Indian shops, such as supermarkets, also

operate under the label of ‘hypermarkets’ despite lacking the infrastructure or layout typically expected with this format. Regarding the food safety behavior patterns, Polish retail shops, excluding some local shops, frequently displayed visual food safety materials such as hygiene signs and posters, supporting daily compliance. However, such materials were rarely observed in Indian shops. Personal hygiene compliance also reflected this disparity. In Mazovia, hygiene compliance among staff in high-risk sections was generally adequate, though less consistent in local shops. Managerial supervision was generally observed, though not consistently across all shops. In Kerala, while uniforms were commonly worn, hygiene practices such as handwashing, use of head coverings, and jewelry policies varied.

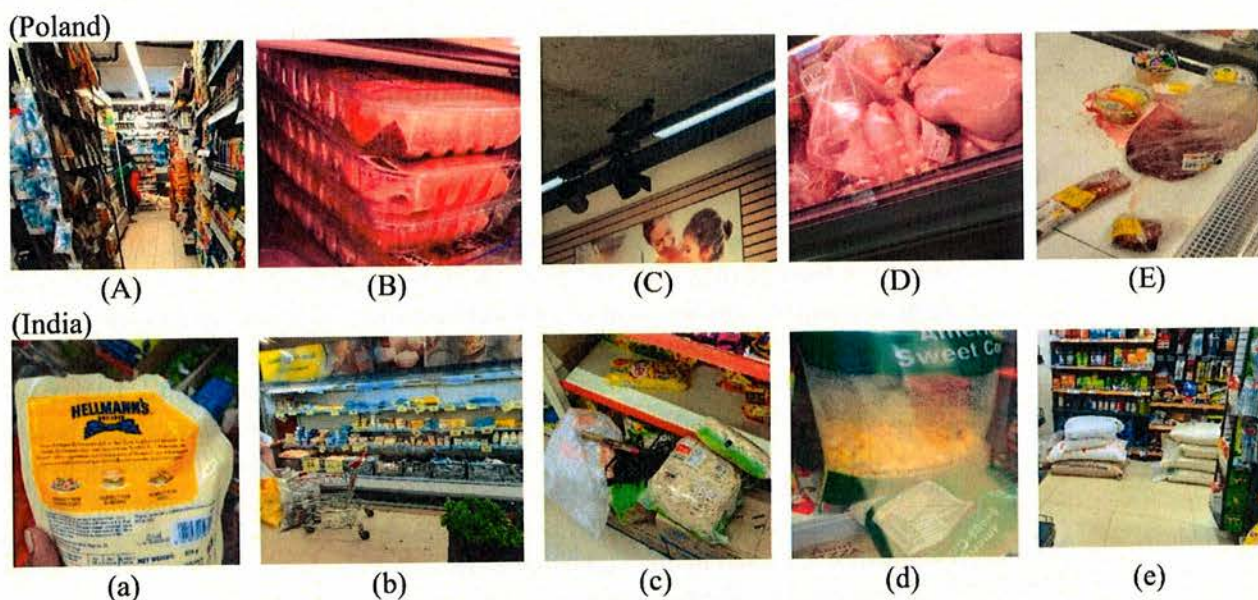


Figure 3. Examples of non-compliance observed during unannounced inspections of retail shops in Mazovia (Poland) and Kerala (India). (Mazovia): (A) presence of animals inside a retail shop, (B) open chicken packaging, (C) presence of a bird inside the shop, (D) visibly bulged chicken packaging, (E) product spillage. (Kerala): (a) rodent-damaged packaging (mayonnaise), (b) improper use of refrigeration units, (c) improper storage of a cleaning mop, (d) visibly bulged sweetcorn packet, and (e) improper stacking of packaging bags.

The food handling and storage practices section also revealed mixed outcomes. Equipment suitable for food contact was present in all formats, except in some local shops in both countries. Although refrigeration temperatures were generally within acceptable limits, temperature log sheets were visible only in a few Polish hypermarkets and some supermarkets and were largely absent in Indian retail shops. Refrigeration-related issues such as non-defrosted units, rust, residue, and overcrowding were noted in both countries, though more frequently in Polish supermarkets and Indian local shops. Rare incidents of bulging food packets, leaking fruits and vegetables, and open packets in display were observed in both countries.

In terms of product display, Polish hypermarkets maintained strong compliance. However, some Polish discount supermarkets and rural area shops exhibited cleanliness issues and a rare occurrence of expired and moldy products. In Kerala, dusty shelves, outdated displays, poor organization, and minor storage issues, such as food sacks temporarily placed on the floor, especially in certain convenience shops and local shops, are more frequently observed. In addition, a unique operational practice was observed in several Indian retail shops with more than 10 employees. Despite well-organized, self-service layouts, staff were routinely instructed to assist customers by handing packed products directly

from shelves. While this management-driven approach aimed to enhance customer service, it diverges from standard self-service expectations and may affect customer autonomy.

Pest control non-compliance also varied by country. Although pest control devices such as traps were present in most Polish shops, insect activity was still observed during the summer. In Kerala, signs of insect activity and rodent-damaged products were observed in certain local shops and supermarkets. Even where self-closing doors were installed, they were left open throughout operating hours, reducing effectiveness, which is observed in most Indian supermarkets in small towns and certain Polish convenience shops. In other local shops in India, rolling shutters were used as main entrances and remained fully open during the day, offering no physical barrier to pest entry. Despite this, in Mazovia, most convenience shops allowed the presence of domestic animals such as dogs and cats to enter the premises despite displaying “No animal entry” signage, with no staff intervention, contradicting international food safety guidelines that necessitate the exclusion of pests and pets in food-handling areas [35].

4. Discussion

Retailers engage in food safety regulations primarily to mitigate liability claims, ensure high food quality, standardize products, prevent incidents, and enhance customer trust. Inadequate implementation of Food Safety Management Systems (FSMSs) is a key predictor of non-compliance in retail food environments, with establishments that maintain well-developed FSMS showing significantly fewer non-compliances with food safety practices [36]. This study assessed compliance with FSMS practices across retail shops in Mazovia (Poland) and Kerala (India), revealing several areas, including operational and structural factors, that influence compliance levels. The analysis showed that country, location, food sector, and the number of employees significantly influenced the level of compliance observed in retail establishments.

The superior FSMS performance observed in hypermarkets may be attributed to structural advantages such as improved infrastructure, systematic operational procedures, and greater staff-to-task allocation. Similar observations have been reported in other studies conducted in other developed regions. For example, in Belgium, small establishments were found to have lower uptake of certified FSMS and a higher rate of non-compliance during inspections, suggesting that poor FSMS performance is not solely resource-driven but also reflects systemic gaps in oversight [37]. Similarly, small and medium-sized enterprises (SMEs) often face challenges in implementing effective FSMS due to a lack of motivation, such as inspection and auditing, limited resources, and financial constraints [6,10]. These challenges were also evident among small-sized retail shops in both Mazovia and Kerala. Dzwolak (2014) reported that certain small food enterprises in Poland adopted HACCP elements mainly for audit purposes, with limited integration into routine operations due to misconceptions regarding system complexity and resource limitations [38].

Observational studies have demonstrated that improper retail food handling practices, including inadequate hand hygiene and direct contact with ready-to-eat foods, increase the risk of cross-contamination [4]. A nationwide investigation conducted by the U.S. Food and Drug Administration (FDA) also identified persistent violations in retail food establishments, particularly improper cold holding, poor hand hygiene, and inadequate sanitation of food-contact surfaces, despite existing regulations and training initiatives [3]. Similarly, a hygiene survey conducted in Slovakian food stores during the COVID-19 pandemic found that although general hygiene practices were adequate, implementation varied considerably due to operational limitations and inconsistent staff practices [39].

Inadequate documentation practices hinder the verification of whether food safety practices are consistently implemented, underscoring the need to assign responsible person-

nel to oversee FSMS activities [40]. Differences in hygiene culture and managerial practices may also influence compliance levels across regions. In the present study, Polish retail stores more frequently displayed hygiene-related signage and food safety information, whereas such visual reminders were less common in Indian retail establishments. This distinction supports the findings of Wu et al. (2020), who highlighted that visual hygiene communication, regular staff training, and managerial supervision play a critical role in strengthening food safety culture [41].

The results also revealed notable differences between the two regions in the FSMS dimensions related to product display, personnel hygiene, and pest control. These differences may reflect variations in retail sector organization and operational management structures. Retail operations in Poland often function within organized retail chains and franchise networks that apply standardized operational procedures and internal monitoring systems. Such structures can facilitate consistent implementation of hygiene and product display practices. In contrast, the food retail sector in India includes a substantial number of small and independently operated shops where operational procedures and staff training may vary considerably. Previous studies have reported that workforce training, managerial commitment, and supervision play a critical role in maintaining hygienic behaviour among food handlers in retail environments [42,43]. In addition, infrastructure-related factors such as shop layout, building maintenance, and pest exclusion measures may influence pest control effectiveness in small retail establishments, particularly where preventive maintenance practices are inconsistently applied [6].

No significant difference was observed between Mazovia and Kerala in the design and layout dimension. The mean scores for both regions were close to 3 on the four-point compliance scale, indicating moderate compliance with structural requirements in retail food establishments. This similarity may reflect the presence of minimum regulatory standards governing food premises in both systems, including the European Union hygiene regulations applied in Poland and infrastructure requirements implemented under the Food Safety and Standards Authority of India (FSSAI). These regulatory frameworks require retail food premises to maintain adequate lighting, ventilation, and sufficient working space to support hygienic operations [14,21]. Consequently, even smaller retail establishments are required to meet baseline facility requirements, which may explain the comparable compliance levels observed in this dimension. However, the results also suggest that optimal structural conditions have not yet been fully achieved across all retail shops. Another factor that may influence compliance patterns relates to the variability of retail formats in emerging markets. In some cases, retail outlets categorized as supermarkets may operate with more limited floor space, staffing levels, or operational infrastructure than those typically observed in large organized retail chains. Such variation in retail format characteristics may affect the consistency of operational procedures and the implementation of standardized food safety practices.

Beyond regulatory and resource-related factors, broader socio-organizational characteristics may also influence FSMS compliance. Retail food businesses in Poland operate within a structured European retail environment where franchise networks and organized retail chains play a major role in food distribution. These organizational structures often implement standardized procedures, centralized management systems, and routine internal monitoring that support consistent food safety practices. In contrast, the Indian retail sector includes a significant proportion of independently operated and informal retail establishments alongside modern retail chains. Studies examining retail modernization in developing markets have reported that the coexistence of organized and traditional retail formats can lead to considerable variation in operational management and staff training across establishments [44,45]. In addition, behavioural factors associated with food safety

culture and consumer expectations may influence how consistently hygiene practices are implemented within retail environments [46].

Temperature control remains another critical challenge in retail food safety management. Studies have reported that retail food products often deviate from recommended temperature limits due to equipment conditions, product positioning, and handling practices once products leave the manufacturer's control. A study evaluating FSMS implementation in retail chain stores in Greece reported high compliance in temperature documentation and sanitation practices [10]. In the present study, although refrigeration facilities were generally available in both regions, temperature monitoring practices were less consistent, particularly in Indian retail shops, where only a limited number of hypermarkets and supermarkets maintained visible temperature logbooks. Additional issues such as non-defrosted refrigeration units, corrosion, residue accumulation, and overcrowded storage conditions were observed in both regions. Similar shortcomings have been reported in previous studies examining retail food safety compliance [40,47,48].

Pest control compliance also presented notable challenges. Common violations included open shutters, lack of structural barriers, and animal tolerance within retail premises. International food safety guidelines recommend strict exclusion of animals (cats and dogs) and pests (rodents or insects) from premises and emphasize the importance of maintaining clean facilities to prevent contamination [15,27]. Robertson et al. (2014) further reported that although retail food handlers often possess basic food safety knowledge, this knowledge does not always translate into consistent hygienic behaviour during daily operations [49]. The authors emphasized the importance of more engaging training approaches to improve behavioural practices among food handlers.

The findings of this study confirm that FSMS implementation remains particularly challenging for small retail establishments such as local shops and supermarkets. These challenges are not limited to developing countries, as similar difficulties have been reported in developed retail environments. Addressing these issues requires a multifaceted approach that includes improved training programs, consistent regulatory inspections, and practical operational guidelines tailored to the constraints faced by small retail shops [50,51]. Simplified documentation procedures, low-cost sanitation tools, and targeted training programs may help small-format retailers improve compliance without imposing unrealistic operational burdens [6].

This study has certain limitations. First, the data were collected from only two regions, Mazovia and Kerala, which may limit the generalizability of the findings to other areas within these countries or to other international contexts. Second, the study design did not allow evaluation of changes in FSMS compliance over time. Third, the assessment relied on visual inspections conducted by a single auditor, which may introduce observer bias. Finally, the study did not evaluate FSMS compliance at the franchise network level. These limitations provide important directions for future research aimed at improving FSMS implementation in retail food environments.

5. Conclusions

This study assessed Food Safety Management System (FSMS) compliance in food retail shops across two countries representing distinct regulatory frameworks and stages of food system modernization. None of the assessed retail shop categories in Mazovia (Poland) and Kerala (India) reached full compliance with all evaluated food safety requirements. The findings provide insights into the overall level of FSMS compliance and identify key areas of non-compliance that require attention to ensure food safety at the final stage of the supply chain. The study revealed significant differences in compliance levels between the two regions, with FSMS performance associated with shop-specific factors such as location,

retail format, and number of employees. These factors provide a basis for developing more targeted strategies to improve food safety practices within the retail sector. Overall, the results support the study hypothesis that FSMS compliance differs between retail shops in Poland and India and is influenced by shop-specific characteristics; however, no significant difference was observed in the design and layout dimension. The results also highlight the need for differentiated strategies to improve FSMS compliance across retail formats. Large retail outlets may benefit from strengthened internal monitoring systems and staff training, whereas smaller retail shops may require simplified FSMS guidelines and targeted hygiene training. Such tailored approaches may help improve food safety practices across diverse retail environments. The inspection checklist developed and applied in this research may serve not only as a regulatory assessment tool but also as a practical self-assessment tool for retailers. It may support awareness-building, identification of compliance gaps, and implementation of corrective actions, thereby contributing to the continuous improvement of food safety management practices in retail environments.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16073130/s1>, Table S1: Statistical analysis of the effect of FSMS compliance scores on its country (Kruskal-Wallis test, Dunn's multiple comparisons test); Table S2: Statistical analysis of the effect of FSMS compliance scores on its kind of place in each country (Kruskal-Wallis test, Dunn's multiple comparisons test); Table S3: Statistical analysis of the effect of FSMS compliance scores on its food sector in each country (Kruskal-Wallis test, Dunn's multiple comparisons test); Table S4: Statistical analysis of the effect of FSMS compliance scores on the number of employees in each country (Kruskal-Wallis test, Dunn's multiple comparisons test).

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Abbreviations

The following abbreviations are used in this manuscript:

FSMS	Food Safety Management System
SMEs	Small and Medium-Sized enterprises
FDA	Food and Drug Administration
PCA	Principal Component Analysis
PCQI	Preventive Control Qualified Individual

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SUPPLEMENTARY MATERIAL

Table S1. Statistical analysis of the effect of FSMS compliance scores on its country (Kruskal-Wallis test, Dunn's multiple comparisons test)

Depend.: COMPLIANCE SCORES	Multiple Comparisons p values (2-tailed); COMPLIANCE SCORES Independent (grouping) variable: Country Kruskal-Wallis test: H (1, N= 1000) =41.99234 p =.0000	
India	India R:441.33	Poland R:559.67
Poland	0.000000	0.000000

Table S2. Statistical analysis of the effect of FSMS compliance scores on its kind of place in each country (Kruskal-Wallis test, Dunn's multiple comparisons test)

Depend.: COMPLIANCE SCORES	Country=Poland Multiple Comparisons p values (2-tailed); COMPLIANCE SCORES Independent (grouping) variable: Kind of place Kruskal-Wallis test: H (2, N= 500) =36.24377 p =.0000					
Big town	Big town R:275.35	Small town R:248.82	Rural area R:152.39			
Small town	0.175300	0.175300	0.000000			
Rural area	0.000000	0.000017	0.000017			
Depend.: COMPLIANCE SCORES	Country=India Multiple Comparisons p values (2-tailed); COMPLIANCE SCORES Independent (grouping) variable: Kind of place Kruskal-Wallis test: H (2, N= 500) =150.0324 p =0.000					
Big town	Big town R:356.40	Small town R:211.63	Rural area R:174.75			
Small town	0.00	0.000000	0.000000			0.064275
Rural area	0.00	0.064275				

Table S3. Statistical analysis of the effect of FSMS compliance scores on its food sector in each country (Kruskal-Wallis test, Dunn's multiple comparisons test)

		Country=Poland Multiple Comparisons p values (2-tailed); COMPLIANCE SCORES			
		Independent (grouping) variable: Food sector Kruskal-Wallis test: H (3, N= 500) =166.0268 p =0.000			
Depend.: COMPLIANCE SCORES	Hypermarket	Hypermarket R:351.91	Supermarket R:274.33	Local shops R:110.22	Convenience shops R:315.70
	Supermarket	0.025133	0.025133	0.00	1.000000
	Local shops	0.000000	0.000000	0.00	0.055451
	Convenience shops	1.000000	0.055451	0.00	0.000000
		Country=India Multiple Comparisons p values (2-tailed); COMPLIANCE SCORES			
		Independent (grouping) variable: Food sector Kruskal-Wallis test: H (3, N= 500) =195.0323 p =0.000			
Depend.: COMPLIANCE SCORES	Hypermarket	Hypermarket R:382.49	Supermarket R:252.53	Local shops R:92.579	Convenience shops R:245.93
	Supermarket	0.000000	0.000000	0.000000	0.000000
	Local shops	0.000000	0.000000	0.000000	1.000000
	Convenience shops	0.000000	1.000000	0.000000	0.000000

Table S4. Statistical analysis of the effect of FSMS compliance scores on the number of employees in each country (Kruskal-Wallis test, Dunn's multiple comparisons test)

		Country=Poland Multiple Comparisons p values (2-tailed); COMPLIANCE SCORES				
		Independent (grouping) variable: No. of employees Kruskal-Wallis test: H (4, N= 500) =28.63002 p =.0000				
Depend.: COMPLIANCE SCORES	more than 10 people	5-10 people	4-5 people	1 person	2-3 people	
	R:272.00	R:297.92	R:288.03	R:212.30	R:243.21	

more than 10 people		1.000000	1.000000	0.167373	1.000000
5-10 people	1.000000		1.000000	0.000041	0.073534
4-5 people	1.000000	1.000000		0.001628	0.396364
1 person	0.167373	0.000041	0.001628		0.735116
2-3 people	1.000000	0.073534	0.396364	0.735116	

Country=India Multiple Comparisons p values (2-tailed); COMPLIANCE SCORES					
Independent (grouping) variable: No. of employees Kruskal-Wallis test: H (4, N= 500) =183.2994 p =0.000					
Depend.:	more than 10 people	5-10 people	4-5 people	1 person	2-3 people
COMPLIANCE SCORES	R:403.06	R:315.54	R:261.35	R:105.84	R:209.39
more than 10 people		0.006526	0.000000	0.000000	0.000000
5-10 people	0.006526		0.236989	0.000000	0.000031
4-5 people	0.000000	0.236989		0.000000	0.022457
1 person	0.000000	0.000000	0.000000		0.000006
2-3 people	0.000000	0.000031	0.022457	0.000006	

