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Review

A Review of Food Contaminants and Their Pathways Within Food Processing Facilities Using Open Food Processing Equipment

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ABSTRACT

This study focuses on the chemical, physical, and biological hazards that pose food contamination risks during the processing of food in facilities using open food processing equipment through a review of published literature from 2015 to 2023. Ten main pathways for food contamination were developed and a list of chemical, physical, and biological food hazards, along with descriptions of process parameters and inputs that can contribute to food contamination, and prevention strategies associated with each pathway were compiled. The paper briefly discusses the relation between food contamination and the sustainable development goals (SDGs). The presented overview of contamination pathways and their associated food hazards can provide insights for food safety management plans, food processing equipment design, food processing facility layout, HACCP programs, and further studies on hygienic monitoring methods.

Contents

Food safety refers to the practice of controlling all types of food-related hazards during the handling and processing of food to ensure that it is safe for human consumption and does not pose risks to human health. Food safety is becoming increasingly important due to heightened consumer awareness, increased consumption of minimally processed foods, and reduced use of preservatives (Khan & Shafiur Rahman, 2021; Sharma et al., 2021). The consumption of unsafe food is responsible for approximately 600 million cases of food-borne disease and 420,000 deaths annually (WHO, 2022). Despite the existence of numerous accepted standards, regulations, and guidelines, such as the 3-A Sanitary Standards (3-A, 2023), Codex Alimentarius (Codex, 2023), Hazard Analysis Critical Control Point (HACCP), and European Hygienic Engineering Design Group (EHEDG) (EHEDG, 2023), food-borne diseases continue to persist worldwide.

The primary objective of food processing is to convert fresh raw materials or foods into food products available for the market. It is important that food products possess desirable organoleptic characteristics and meet high standards of quality and safety. This aim is crucial

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to mitigate the health risk for consumers, the economic and reputational risk of product recalls which can have detrimental effects on a company's business as well as leading to food loss (Sharma et al., 2015). Additionally, guaranteeing the availability and accessibility of safe and nutritious food is vital in addressing the global challenge of food security and meeting the Sustainable Development Goals (SDGs), in particular goal numbers 2, 9, 12, and 13 (UN, 2015).

Food processing companies face various difficulties in ensuring the safety of their products, starting from the raw materials to delivering the product to the consumer. Indeed, food hazards are widespread in the food industry and can find their way into the food chain through various pathways. In closed food processing equipment (CFPE), food is processed in a controlled and sealed environment, compared to open food processing equipment (OFPE), where the food and its contact surfaces are exposed to the surrounding environment (EHEDG, 2020), increasing the risk of food contamination. Therefore chemical, physical, and biological hazards can contaminate the food products through various pathways, including human activities, ventilation systems, pests, building design, and waste management. Thus, there is a need for a holistic overview of food contamination pathways corresponding mitigation strategies to ensure a hygienic and safe processing environment (Møretrø et al., 2016).

Nerín et al. (2016) presented an overview of chemical food contamination sources within the food value chain, from extraction of raw material to consumption of the food product. Several sources involved in chemical food contamination were identified among which, the following were directly linked to the food processing facility; food conditioning, which involves the storage of raw materials, preheating, disinfection, cleaning, and sterilization steps, heating of foods during food processing or combining with other ingredients at high temperature in an oven or in a reactor, and food packaging. Garvey (2019) conducted a comprehensive review of chemical and biological sources of food contamination and their impacts on human health. The study showed that some of the chemical and biological contaminants present in foodstuff can be introduced or managed during food processing. A comprehensive review of the sources of chemical food contaminants within the food processing value chain was collected by Li et al. (2021). These studies show that the food processing facility is a curtail step in risk management within the food value chain. Physical food hazards are not the focus of these reviews, although it is an important source for food contamination that needs to be managed.

To reduce the risk of food contamination, food processing facilities must implement preventive measures and systems against potential food contamination hazards. In that regard, different management systems which addresses food safety issues such as HACCP, Good Manufacturing Practices (GMP), and hygienic design practices have been developed and are widely used today. HACCP is a preventive approach to the identification and control of food hazards, while GMP is a management system associated with the production of safe food and is the base of HACCP implementation (Arévalo Arévalo et al., 2022). Hygienic design practices intend to provide a preemptive approach to food contamination by designing out possible food contamination risks when designing new food processing equipment and food processing facilities. This increases the likelihood for a practical hazard-free environment for food processing, by ensuring easily cleanable and resistant equipment as well as a factory design to minimize the risk of contamination (Berg et al., 2020).

This review focuses on physical, chemical, and biological food hazards and their potential pathways to enter the food processing facility with emphasis on food processing facilities using OFPE within their processing line. From the reviewed literature, pathways for food contamination during food processing were established, and the physical, chemical, and biological food hazards were allocated to each pathway. For each contamination pathway, a list of risk factors and their link to the food hazards identified in the reviewed literature is presented. These factors are named operational risks (ORs) and describe the process parameters and inputs that can contribute to food contamination.

Given the ever-evolving nature of technology and climate change, new contaminants or ORs may emerge over time. Therefore, an updated table of physical, chemical, and biological food hazards, along with ORs associated with each pathway, is presented in this paper that can provide valuable information for food safety management plans, HACCP programs, and further studies on fast and precise hygiene monitoring methods. Additionally, the paper touches upon the current state of progress toward the sustainable development goals (SDGs), to shed light on how food contamination issues can affect the advancing and supporting of the SDGs.

Methodology

A systematic literature review on the principle of hygienic design and food hygiene in the food industry using OFPE was conducted through Oria (Oria, 2023), a search engine that can be used to find printed and electronic resources, including books, articles, doctoral theses, master's theses, music, and films from all university libraries in Norway. Search terms were collected through the "snow-ball" method, from an initial literature review of published hygienic standards, books, and papers on the topic of hygienic food processing (LibGuides, 2022). Table 1 shows the final keyword combinations used in the literature search and the number of publications found from 2015 to 2023.

Eighty-four scientific documents were selected out of 6000 by title analysis and subsequently by reviewing the abstract and conclusion. The following criteria were established for inclusion: 1. articles focusing on hygienic design, hygienic practices, and hygienic problems in the food industry using OFPE; 2. studies reporting food contaminants during food processing, cleaning, and transportation; and 3. studies on food hazards. The selected publications were grouped into three main categories; chemical, physical, and biological food hazards, and allotted to the relevant food contamination pathways. The share of the reviewed publications identified in each category is presented in Figure 1.

When it comes to microorganisms, assigning specific pathways proved to be challenging; however, the findings are discussed separately and summarized in Table 4, which gives an overview of foodborne agents described in the reviewed literature in food processing facilities. All human activities are affecting our planet and our prospects, food processing is no exception. The most relevant UN sustainable development goals, namely numbers 2, 9, 12, and 13, were evaluated and discussed in the light of hygienic design and food hygiene in the food processing industry as all industrial and economic activities need to operate within the planetary boundaries.

Food contamination pathways

The following subsections describe the main operational risks (ORs) and prevention strategies identified in the reviewed publications for each food contamination pathway in food processing facilities using OFPE. Based on the reviewed literature, ten pathways for food contamination during food processing were established and are presented in Figure 2. A summary of food hazards is provided in Table 2, outlining the pathways for contamination and the associated ORs.

Material flows in and out of the processing facilities. In the food industry, raw materials are inherently considered a potential source of contamination. Such contaminations can be in the form of physical, chemical, and biological agents (Fung et al., 2018). Tables 2 and 4 illustrate the wide variety of potential hazards present in raw materials. Consequently, it is imperative for food processing companies to implement appropriate control measures and conduct proac-

Table 1
List of keywords and the number of publications over the search period 2015–2023

Keywords combination	*"Hygienic Design"*	*"Hygienic Engineering"*	*"Hygienic Process"*	*"Hygienic Working Practice"*	*"Design for Cleaning"*	*"Equipment Hygiene"*	*"Safe Design"*
	Number of Publications						
"Food"	1,298	325	237	21	207	255	891
"Food Engineering"	199	53	17	1	11	8	21
"Food Process"	104	39	14	1	12	4	8
"Food Processing"	193	36	37	12	20	43	53
"Food Safety"	641	140	75	7	55	110	103
"Pathogen"	285	53	65	15	51	125	162
"Cleaning"	931	181	111	17	671	176	392

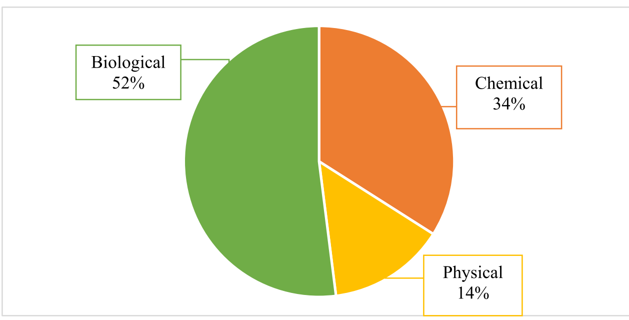

Figure 1. Share of the publications related to the different categories.

tive risk assessments for related ORs including ingredients and additives, water and ice, packaging materials, as well as final product. Ensuring the quality and safety of these elements has a great contribution to overall food safety (Li et al., 2021).

The safety and quality of food ingredients are influenced by various environmental conditions such as temperature and humidity, primary treatment, condition at capture or harvest, and storage condition (Çakli et al., 2015; Nerín et al., 2016). Extensive literature on food contamination sources has demonstrated that a range of chemical, physical, and microbial contaminants established in the company come from raw ingredients (Møretrø et al., 2016; Nerín et al., 2016). Instances have been observed where nonfood grade chemical additives, including colorants and preservatives, as well as contaminants such as pesticide residues, were detected in food products. Notably, certain food samples exhibited an elevated concentration of heavy metals such as lead, cadmium, arsenic, mercury, and copper (Fung et al., 2018). Therefore, the safety of food ingredients is a critical aspect to consider in the food industry.

Water and ice are widely used in the food industry for a variety of purposes like cleaning and sanitation, maintaining freshness, cold storage, and maintaining food temperature during transportation. The potential of water and ice to facilitate bacterial transmission and chemical contamination raises considerable concerns, due to the large quantities used in food processing companies (Kamala & Kumar, 2018). Accordingly, WHO has set rules for water and ice used in the food industry to meet the same requirements as potable water (Hampikyan et al., 2017).

Packaging materials including metallic cans, glasses, plastics, and papers could be another source of chemical, physical, or biological contamination. Any direct or indirect contact with the food may motivate the transference of the packaging substances into the food, known as migration. Migrants like iron, printing inks, colorants, and plasticizers can cross the packaging layers, resulting in food contamination (Lebelo et al., 2021; Nerín et al., 2016). An examination of legislative and inventory documents revealed that the manufacturing process of printed paper and board food-contact materials (FCMs) involves the use of over 6000 distinct substances. However, a significant portion of these substances lack proper evaluation, highlighting an important knowledge gap in terms of their safety assessment. Even though the amount of migration depends on the packaging materials, package size, environmental conditions, food properties, and migration process, a preliminary investigation suggested that approximately 64% of these unevaluated substances have the potential to migrate into food and become bioavailable upon oral consumption (Van Bossuyt et al., 2016). Therefore, it is necessary to comply with Regulation (EC) No 1935/2004 of the European Parliament on "materials and articles intended to come into contact with food" as well as prompt investigation on the actual usage of substances in printed paper and board FCM (European-Commission, 2021).

As important as raw materials, the ability of final product to support microbial growth is another concern. It is important to note some microorganisms require very specific environmental conditions to survive and thrive, so it is critical to understand the exact needs of the microorganisms when assessing a product's ability to support them (Spanu & Jordan, 2020).

The microbial ecosystem in each processing plant, during the process and after sanitation, is unique and a reflection of the raw material and preservatives used in the products like NaCl and acid (Bourdichon et al., 2021; Muhterem-Uyar et al., 2015). Therefore, knowledge of the dominant microbiota in the raw material and final product would be valuable in controlling the processing hygiene.

Food Processing. Food processing and value addition are the key steps in the food industry. The main objectives of food processing are to preserve nutritional values, improve organoleptic properties, secure the food safety, and extend the shelf life (Göncüoğlu Taş et al., 2022). Even though processing food is an essential practice, risks like formation of food contaminants, cross-contamination of microorganisms and allergens as well as physical contamination may occur during the processing (Li et al., 2021; Qian et al., 2022). These risks are contingent upon several ORs such as processing methods, processing conditions, and inherent properties of food ingredients.

Food processing methods are categorized into different types based on the energy employed; thermal (like blanching, baking, and frying), electrical (e.g., ohmic heating and microwave), chemical, biochemical (fermentation), radiation, and mechanical methods (Göncüoğlu Taş et al., 2022). While most of the processing techniques involve a series of thermal methods, it holds significant importance due to the formation of toxic compounds and microbial contamination, necessitating a thorough understanding and management of the potential risks. To date, FDA has reported some of the carcinogenic compounds like acrylamides, furan, 3-monochloropropane-1,2-diesters (3-MCPDE), glycidyl esters (GE), nitrosamines, heterocyclic amines, 4-methylimidazole (4-MEI), and polycyclic aromatic hydrocarbons (PAHs) that are formed in heat-treated products (FDA, 2023). Tables 2 and 4 provide a list of all food hazards that may arise during the processing stages. Accordingly, comprehensive knowledge about process contaminants and process optimization for reducing the risk of contamination and formation of toxic compound is essential. This involves employing various methods such as, reducing the concentration of

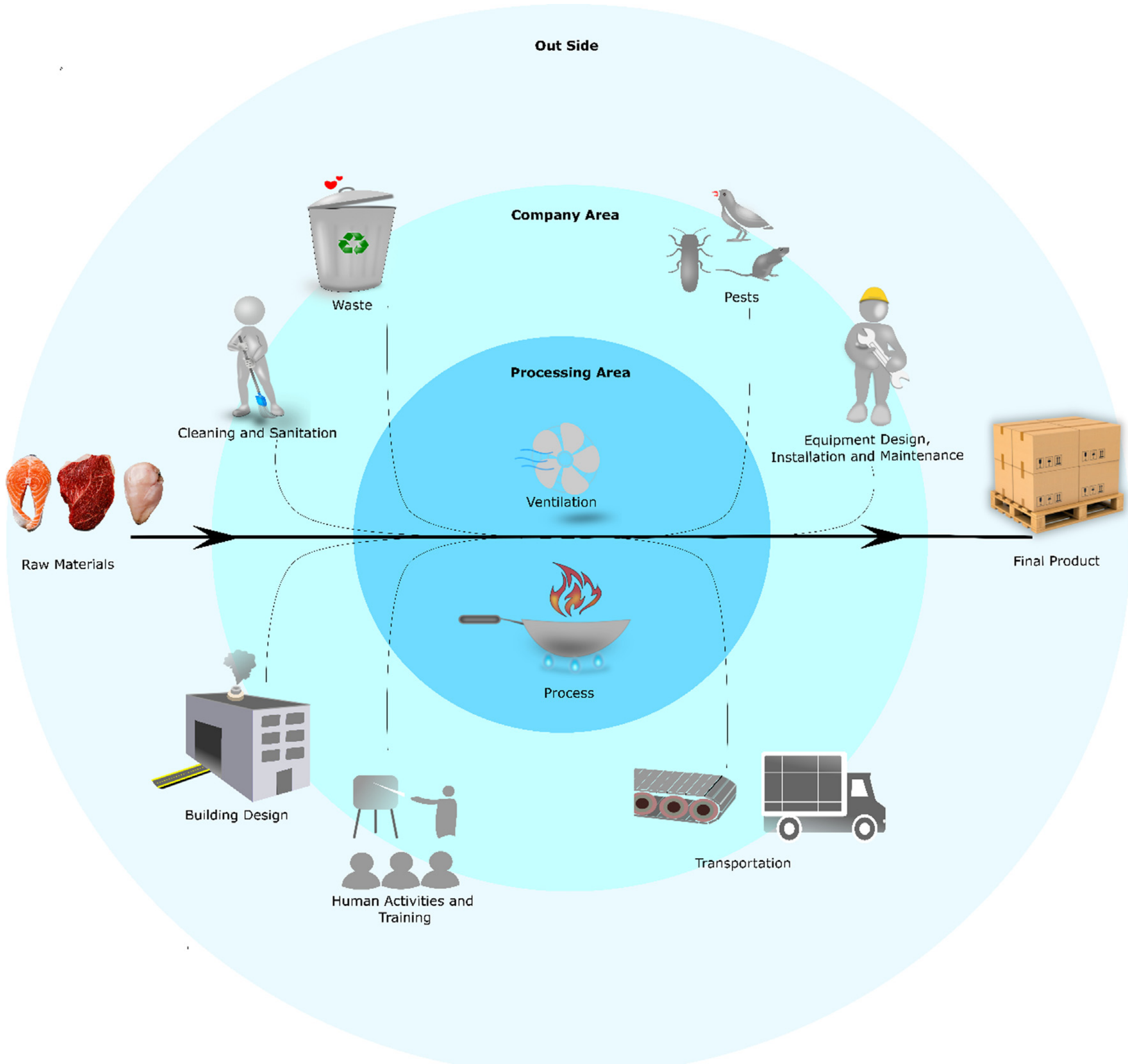

Figure 2. Food contamination pathways.

reactants, using biological methods to reduce precursors, and optimizing storage methods (Fan et al., 2023; Garvey, 2019). In this regard, Muttucumaru et al. (2017) conducted a study about the impact of reducing sugar concentrations on acrylamide levels in thermally processed potatoes. It was found a significant positive correlation between sugar content and acrylamide formation, which means that the selection of raw materials with a minimal concentration of reactants is a highly effective and fundamental mitigation strategy. Furthermore, a valuable strategy to prevent the spread of allergens from one product to another involves optimizing the processing order based on the allergen contents in the final product. By carefully sequencing production to first manufacture items without allergens and then thoroughly cleaning and sanitizing the processing line before proceeding to products containing allergens, this systematic approach effectively minimizes the risk of allergen cross-contamination during production (Eyvazi et al., 2021; Goel et al., 2019). Foreign bodies can also be introduced during the process in addition to chemical and biological contaminants (Djekic et al., 2017). However, they can be limited through adequate inspection and procedures on raw materials, as well as through hygienically designed or maintained equipment (Sharma et al., 2021).

On the other hand, optimizing the processing condition is another issue to reduce the risk of contamination. Factors such as time, temperature, water activity, pH, and air condition need to be precisely controlled during the process to avoid food safety issues (Nerín et al., 2016). Processing temperature, both heating and cooling, is a concern in food processing facilities which requires measurements and control during the procedure. Certain foods need special process temperature for eliminating the initial microorganisms associated with the raw materials (Ehuwa et al., 2021). Therefore, precise time and temperature optimization during the procedure to inhibit both microbial growth and the formation of toxic compounds is highly recommended for the food industry.

Currently, thousands of food ingredients have been considered safe by Joint Expert Committee on Food Additives (JECFA), Food and Agriculture Organization (FAO), and World Health Organization (WHO), and maximum intake has been determined by Codex Alimentarius Commission (Bayram & Ozturkcan, 2022). However, demand for information on the toxicity of food additives, including synthetic preservatives like sulfites, benzoates, sorbates, and nitrates, is high due to potential adverse health effects when they exceed Acceptable Daily Intake (ADI) (Bayram & Ozturkcan, 2022; Bhavadharini et al., 2022). Indeed, the risks associated with process contaminants extend beyond the inherent toxicity but also their presence in commonly consumed foods such as bakery products, potatoes, and more (Fan et al., 2023).

Equipment. Machinery, equipment, and components intended for the preparation and processing of foodstuffs in food processing facili-

Table 2
Overview of food contamination pathways, operational risks, and associated food contaminants

Pathway	Operational Risks (OR)	Contaminants	
		Chemical	Physical
Raw materials and Final Product	• Food Ingredients • Water and Ice • Packaging Materials • Final Product	• Ingredients ○ Fertilizers ○ Pesticides and veterinary residues ○ Heavy metals ○ Antibiotic residue ○ Agricultural contaminants (Polychlorinated Biphenyls (PCBs)) ○ Chlorates in drinking water ○ Halogenated compounds ○ Alkaloid toxins (Garvey, 2019; Li et al., 2021; Nerín et al., 2016; Rahaman et al., 2022; Thakali & MacRae, 2021) • Packaging materials: ○ Metallic ion (iron, tin) ○ By-products from the manufacture of epoxy resins e.g., bisphenol, bisphenol A diglycidyl ether (BADGE), cyclo-di-BADGE ○ Melamine ○ Benzene ○ Printing ink ○ Adhesives ○ POPs ○ Stabilizers ○ Antioxidants, plasticizers e.g. di-(2-ethylhexyl) phthalate (DEHP) ○ Decolorizer ○ Nanoparticles (NPs) ○ Poly and per fluorinated alkyl substances (PFASs) (Garvey, 2019; Goel et al., 2019; Li et al., 2021; Thakali & MacRae, 2021)	• Microplastics • Nanoplastics • Glass, metal, wood, and plastic fragments • PVC gaskets • Paper and board • Adhesives in packaging materials (acrylic, hot-malt, rubber, or polyurethane adhesives) • Leaves, stalks, and other extraneous pieces of plant material • Soil and stone • Bone or organ tissue leaves, stalks, and pieces of insect and animal parts (Allen et al., 2022; Djekic et al., 2017; Nerín et al., 2016; Waring et al., 2018)
Process	• Processing Method • Processing Conditions • Food Ingredients	• Hazardous chemicals formed during the processing like ○ N-nitroso compounds (NOCs) ○ Chloropropanol ester (MCPDE) ○ Ethyl carbamate ○ Acrylamides ○ Polycyclic aromatic hydrocarbons (PAHs) ○ Polychlorinated biphenyls (PCB) ○ Heterocyclic aromatic amines (HAA) ○ Furans • Oxidation reactions ○ Acetaldehyde ○ Propionic aldehyde ○ Malondialdehyde • Metal contamination • Additives (Ahmad et al., 2019; Bansal & Kim, 2015; Goel et al., 2019; Li et al., 2021; Nerín et al., 2016; Thakali & MacRae, 2021)	• Glass • Metal • Plastic fragments • Insect and animal parts or residue (Sharma et al., 2020)
Equipment	• Design • Construction • Installation • Maintenance	• Heavy Metals ○ Mercury ○ Lead ○ Arsenic • Lubricating fluids • Cleaning fluids	• Metal or plastic fragments • Rust or loose nuts or screws • Fragments of packaging material (Sharma et al., 2020)

(*continued on next page*)

Table 2 (*continued*)

Pathway	Operational Risks (OR)	Contaminants: Chemical	Contaminants: Physical
		(Garvey, 2019)	
Cleaning and Sanitation	• Chemicals • Mechanical Energy • Time • Temperature • Monitoring • Drying	• Sanitizers and Disinfectants ○ Quaternary ammonium compounds (QAC) ○ Chlorine ○ Nonionic surfactant e.g., stearyl alcohol ethoxylate ○ Sodium hypochlorite (NaCLO) ○ Hydrogen peroxide (H2O2) ○ Iodophors ○ Peroxyacetic acid (PAA) (Garvey, 2019; Neethirajan et al., 2018; Nerín et al., 2016)	• Glass cleaner • Metal cleaner (Djekic et al., 2017)
Human Activities and Training	• Personnel Hygiene/Hygiene Practices • Training	-	• Hair, fingernails, plaster for cuts, jewellery (Djekic et al., 2017; Hussain, 2016)
Transportation	• Hygienic Design • Temperature • Barrier Properties	• Petrol • Diesel • Organic compounds ○ Naphthalene ○ Methylbromide ○ Toluene ○ Ethylbenzene ○ Ortho- and paraxylenes ○ Protein oxidation products (Li et al., 2021; Nerín et al., 2016; Rather et al., 2017)	-
Pest	• Foreign Materials • Chemicals • Carcasses	• Pesticides ○ Permethrin, endosulfan, hexacyclohexanes ○ POPs (dioxin, DDT, PCDDs, OCPs) (Garvey, 2019; Thakali & MacRae, 2021)	• Insect, animals, or birds' parts • Droppings (Djekic et al., 2018; Hussain, 2016)
Building Design	• External Risks • Internal Risks	• Migration ○ migration from packaging materials at high temperatures and humidity • Condensation in cold storage rooms • Coating and resins Leakage (Dioguardi & Franzetti, 2010)	• Peeling paint • Glass or wood splinter • Dust • Pests (Djekic et al., 2017; Hussain, 2016)
Ventilation	• aw • Temperature • pH • Nutrients • Oxygen • Inhibitory Compound • Airflow	• Chlorine gas • Chemical taints • Organochlorine pesticides (OCPs) • Polychlorinated biphenyl (PCB) • Polycyclic aromatic hydrocarbons (PAHs) (Garvey, 2019; Li et al., 2021; Thakali & MacRae, 2021)	• Dust • Straw-type debris • Insects (Hussain, 2016)
Waste	• Food Waste • Water Waste • Solid Waste	• Nutrient loading ○ Nitrogen and Phosphorus compounds • Pesticide • Residual Chlorine ○ Chlorites ○ Chlorates (Khedkar & Singh, 2018; O'Connor et al., 2022)	• Plastic ○ Chlorine-based plastics like PVC • Metal • Glass • Raw material residues ○ Bone, skin, internal bodies, seeds (Garvey, 2019; Khedkar & Singh, 2018; O'Connor et al., 2022)

ties using OFPE have a significant impact on the hygiene level of the final product. Hygienic equipment design considers functionality, initial cost, cleaning cost, and food safety, as well as reduced need for disassembly and maintenance (Giske et al., 2020). Indeed, good hygienic design prevents the entrapment of food materials, and build-up of microorganisms, and chemical residue which could endanger safety of the food leading to additional cleaning expenses with more intensity, ultimately shortening the lifetime of the equipment (Lars Andre Langoeyli Giske & Emil Bjoerlykhaug, 2017). In terms of hygienic design, all levels of design, construction, installation, and maintenance are considered as ORs (Table 2).

Designing the new equipment requires a certain knowledge of the intended use of the equipment and associated food hazards to define hygienic design level suitable for each individual component within the equipment (Pirondi et al., 2021). There is a substantial difference in the level of hygienic design between the equipment used for processing wet products in OFPE and those employed for dry products. Furthermore, the principles of design for cleaning should be considered in the design procedure to avoid pits, folds, cracks, crevices, and dead areas in the equipment (Djekic et al., 2018). Thus, equipment design must follow hygienic design guidelines to avoid any hygiene-related risks (Faille et al., 2018; Feno et al., 2017).

The construction of equipment must consider normal mechanical design factors, as well as the toxicological and bacteriological compatibility of the materials to comply with relevant regulations. Each component should be constructed from appropriate materials to be suitable for the intended use and reduce the risk of chemical, physical, and biological contamination (Faille et al., 2018; Skåra & Rosnes, 2016).

Equipment installation by considering the entire processing line and ensuring sufficient accessibility for inspection, cleaning, and maintenance, greatly supports the hygienic design aims (Greg, 2020). Well-installed equipment needs a series of maintenance controls in place to secure hygiene level of equipment throughout its lifetime. Evaluating the hygienic design needs some validation and testing methods to ensure hygiene requirements for both individual components and assembled equipment (Greg, 2020; Losito et al., 2017; Løvdal et al., 2017).

Cleaning and Sanitation. For many food processes, developing knowledge about the cleaning system to be safe, efficient, and environmentally friendly process is vital for an effective procedure without any chemical residue (Nerín et al., 2016). Both cleaning and disinfection are equally essential to prevent food contamination since they help to reduce the risk of hazards such as microorganisms, allergens, and physical hazards that can occur at several points of the food processing. Therefore, employing the right cleaning techniques including dry or wet cleaning or a combination thereof, to eliminate the adherent and vegetative bacteria, spores, yeasts, and molds are required to meet the demand for food safety and avoid cross-contamination (Agüeria et al., 2021; Møretrø et al., 2016).

The most powerful mechanism for cross-contamination is the collection of adherent cells on the surfaces within a matrix of polysaccharides, proteins, and DNAs, known as biofilm (Ripolles-Avila et al., 2019). Indeed, the hotspot for hygiene problems is where microorganisms attach to the surfaces and then detach. Even though cleaning and disinfection cannot completely sterilize the equipment, the goal is to decrease the bacterial count to an appropriate level and eliminate pathogens (Møretrø & Langsrud, 2017). An appropriate cleaning practice should remove 1. large and small debris, 2. dirt and microorganisms, and 3. the possible food and shelter for pests (Çakli et al., 2015).

The fundamental procedure of cleaning and sanitation is now widely applied in most areas of the food industry. However, there are some ORs including chemicals, mechanical energy, time, temperature, monitoring as well as drying that should be considered, Table 2 (Faille et al., 2018).

Despite the great contribution of chemical agents in promoting food safety, concerns arise regarding residual concentrations and their potential transfer to the food. The food industry continually seeks to develop detergent formulas that are not only safe, efficient, and environmentally friendly but also compliant with the regulations (Muhterem-Uyar et al., 2015; Nerín et al., 2016). Moreover, relying solely on a single type of disinfectant may result in microbial resistant. Therefore, it is crucial to incorporate a variety of acidic and alkaline disinfectants, while ensuring proper applications and exposure time (Fung et al., 2018). Compounds like hydrogen peroxide, peracetic acid, ammonium products, and sodium hypochlorite are commonly used within the food industry at permitted levels to effectively enhance rinsability (Lebelo et al., 2021).

Mechanical energy serves as a valuable method for removing dirt, debris, and biofilms from equipment surfaces. This can be achieved through various techniques such as scraping, manual brushing, automated scrubbing, or utilizing pressure jet washing or dry cleaning. However, it is important to note that certain materials, such as glass or metal cleaners, are not allowed to be used in the food industry due to the residues they may leave behind (Schmidt & Piotter, 2020).

Time plays a crucial role in the efficiency of cleaning processes, along with other contributing factors. In general, the longer cleaning periods lead to the more effective dirt removal. Extending the duration of the sanitation program can be beneficial in reducing water and energy consumption, as well as the amount of chemicals required for the cleaning process (Løvdal et al., 2017).

At high temperatures, the effectiveness of chemicals increases, while certain debris may become more adhesive. Therefore, it is essential to adopt an efficient and effective cleaning and sanitation temperature that is tailored to the specific process line and final product. This approach ensures optimal cleaning performance while minimizing the risk of residue build-up and contamination (Løvdal et al., 2017).

Continuous monitoring of protein residues and biofilms after sanitation is crucial to prevent the loss of disinfectant efficacy and the saponification process. It is essential to verify the sampling plan and provide specific guidelines for selecting sampling sites, determining sample size, and establishing sampling frequencies to effectively identify and address the presence of dominant microbiota in food processing facilities. These measures are key to maintaining a safe food processing environment (Agüeria et al., 2021; Muhterem-Uyar et al., 2015).

Furthermore, it is highly recommended to ensure thorough drying of surfaces after cleaning. Proper drying helps eliminate moisture that can support the survival and proliferation of microorganisms. Special attention should be given to areas prone to water accumulation, such as floor corners, equipment crevices, and drainage systems. Adequate drying not only reduces the chances of microbial contamination but also contributes to overall cleanliness and hygiene within the facility (Muhterem-Uyar et al., 2015).

In order to effectively reduce contamination pressure, food companies are advised to develop a sanitation plan tailored to the specific type of product and need. This plan should be implemented in a gradual, step-by-step manner (Agüeria et al., 2021; Giske et al., 2020). Muhterem-Uyar et al. (2015) introduced the concept of critical control areas (CCAs) within food processing establishments, which are designated areas requiring thorough decontamination to prevent widespread contamination. However, none of the food business operators experiencing significant contamination issues had established a CCA concept. The CCAs within a food processing establishment should be clearly identified, and access should be restricted to trained personnel. Therefore, comprehensive disinfection plans specifically for CCAs, incorporating up-to-date knowledge and placing particular emphasis on preventing dilution failures on wet surfaces, must be developed for each facility (Muhterem-Uyar et al., 2015).

Human activities and Training. The most critical components of GMP are hygiene practice and personal hygiene, which play important role in preventing microbial transmission and food-borne diseases. The occurrence of food-borne disease is often linked to food handling practices, especially in food processing facilities using OFPE, which emphasizes the necessity for food handlers to strictly adhere to high hygiene standards for minimizing the risk of contamination (Ehuwa et al., 2021; Lema et al., 2020).

Tables 2 and 4 present the potential food hazards associated with food handlers, highlighting two ORs: 1. personnel hygiene and hygiene practices, and 2. training.

Personnel hygiene in food processing facilities using OFPE is of utmost importance for ensuring the safety and quality of food products. Food handlers in food processing facilities with OFPE can act as reservoir and vector for physical contamination or spread of microorganisms (Çakli et al., 2015). The transfer of microorganisms or physical contaminants from people who naturally carried them can occur via the gastrointestinal tract, skin, hair, mouth, nose, ears, eyes, and nails, while indirect contamination or cross-contamination involves people acting as a vector. Transferring between different hygienic zones, handling raw materials, touching food-contact surfaces, and using unclean clothes and footwear can cause cross-contamination (Belias et al., 2022; Evans & Redmond, 2019). It has been shown that despite diverse guidelines and standards in the food industry, hands or gloves of the operators are still a main source of microbial contamination due to a lack of personal hygiene (Reynolds & Dolasinski, 2019). The implementation of fundamental hygiene practices, such as thorough disinfection of hands and shoes, along with the installation of sanitizing barriers has been identified as potential means to reduce the risk of cross-contamination in the food processing environment (Evans & Redmond, 2019; Fung et al., 2018).

The hygiene practices among food handlers are highly dependent on the basic knowledge and training about specific activities such as the need for hand hygiene, using gloves and work clothes, covering wounds, cuts, or abrasions with a waterproof dressing, and communicable diseases such as hepatitis, diarrhea, vomiting (Çakli et al., 2015; Ehuwa et al., 2021). Training the maintenance staff, installers, and other employees about the requirements of the hygienic design, the need for good manufacturing practices, and the need for cleaning equipment is an effective method to minimize the human-caused hazards on products and procedures (Evans & Redmond, 2019; Greg, 2020). Although numerous countries mandate food safety training, there remains a lack of standardization concerning the specific types of training required. Food companies encounter challenges in determining the appropriate training methods, assessing the associated costs and an effective evaluation process to ensure compliance with training requirements (Kamana et al., 2017; Reynolds & Dolasinski, 2019). Furthermore, the training challenges become more complicated by the diverse demographics within the workforce, encompassing individuals from various ethnic backgrounds, educational levels, and cultural differences (Fung et al., 2018). Therefore, it is imperative to periodically assess the type of training being implemented and update the publications concerning food safety training.

Transportation. Transportation of the raw materials and final products, as another pathway for food contamination, should be done in a hygienic way to avoid contamination. Transportation does not only address transferring the raw material or the final product by truck or ship outside the company but also any kind of short-distance movement in the processing hall by using pallet trucks or conveyor belts.

Three main ORs including the hygienic design of vehicle, temperature, and barrier properties of packaging materials have been identified that can endanger food safety during transportation, Table 2.

According to the type of materials that are transported, policies and regulations on hygienic design of vehicles could be different. Nonetheless, it is essential that all vehicles are intentionally designed for easy cleaning and effective protection against contaminants. The maintenance of hygiene and cleanliness in vehicles plays a vital role in their day-to-day operations. Neglecting this aspect can lead to the contamination of food products, posing potential risks to consumer safety. The significance of maintaining hygiene is highlighted in components such as conveyor belts, which play a significant role in transporting products throughout the factory and connecting different sections together (Çakli et al., 2015; Waldhans et al., 2023). Previous studies have revealed the potential for biofilm formation at the junction point between the conveyor belts and other components, especially steel, particularly in areas that are not directly accessible. Thus, to ensure hygiene and safety within the processing system, the construction of conveyor belts should encompass various shapes, designs, and materials, tailored to the specific processing line and final product requirements (Løvdal et al., 2017; Pirondi et al., 2021).

Effective temperature control along with transportation is considered to be a prerequisite, especially for frozen or perishable products, since any fluctuations have detrimental effects on product quality and increase the risk of microbial contamination (Li et al., 2021). Therefore, manufacturers should recognize their product characteristics and allocate sufficient resources to equip their facilities for food handling and transportation. This includes investing in appropriate storage facilities, refrigeration systems, and transportation vehicles that can effectively maintain the required temperature conditions to ensure the quality and safety of the products throughout the entire production and delivery system (Ahmadi-Javid et al., 2023; Davies et al., 2021).

Packaging materials and vehicles used for long-distance transportation should be carefully chosen to provide suitable barrier properties, effectively shielding the products from various environmental hazards (Alamri et al., 2021). These hazards include CO_2, CO, O_2, dust, and water vapor, as well as organic compounds, diesel, and petrol that may potentially leak from vehicles during transportation. By selecting appropriate packaging materials with robust barrier capabilities, the integrity and quality of the transported goods can be preserved, minimizing the risk of contamination and storage (Alamri et al., 2021; Nerín et al., 2016).

Pests. Pest control in the factories is considered another concern because of the potential risks they pose to raw materials, final products, and factory building. Pests could be potential sources of microbial contamination and dirt since the raw material and processed foods are highly attractive to them. Achieving a hygienic production requires a holistic program and rigorous physical (which is mostly fixed by plant design), chemical, and biological obstacles to limit their entry, harbourage, and infestation into the processing area. However, pest control is potentially hazardous, as it involves the use of foreign materials and chemicals to reduce the risks from live pests and deal with carcasses (Table 2) (Giske et al., 2020).

Foreign materials used in pest control may help to hinder pests, but they could also be a source of contamination, dirt, and dust if they are not cleaned and used properly. Certain control methods including installing interlocutors, glue boards, and mousetraps are being used in the plants by trained personnel. However, these methods may not be completely effective as they are not tailored to the specific needs of each facility (Çakli et al., 2015).

Moreover, there are several poisons and pesticides that are regulated to be used in processing areas due to the nonforeseeable risks they may cause. In most countries, government approval is required for the use of pesticides. Organizations such as the British Retail Consortium (BRC) (BRC, 2020), the International Featured Standard (IFS) (IFS, 2020), and the American Institute of Baking (AIB) (AIB, 2023) have established guidelines to determine the best acceptable pest control programs.

Dead insects or captured rodents also carry risks, since it is hard to determine where the carcasses end up; therefore, a strong and explicit monitoring system is needed to detect and control their activities (Çakli et al., 2015).

Building Design. The design of the processing plant has a substantial effect on safe production. Attention to the plant layout and in particular plant components e.g., floor, drains, ceilings, and walls limits the challenges of food hazards and enhances the chance of proper cleaning and disinfection (Moerman & Wouters, 2016b). Potential

Table 3
General standards of plant design

	Component	Properties	References
1	Walls, Floors, and Ceilings	- Materials should be smooth, nonporous, easily cleanable, and resistant to chemical and mechanical stress - Minimize transitions - Avoid sharp corners (radius >2 cm) - Floors should be sloped and have sufficient drainage (>2°) - They should be structured in a way that prevents dirt accumulation - There should not be any place for birds, insects, or rodents at the entrance and harboring	(Çakli et al., 2015; Moerman & Lorenzen, 2017)
2	Toilets	- Be far from the processing area	(Çakli et al., 2015; Holah, 2023a)
3	Processing lines	- Should be continuous, from raw material to the final product - There must be sufficient sanitary facilities, agents, and disinfectant	(Çakli et al., 2015)
4	Drainage	- Should be sufficient, flow from the clean area to less clean and outside the building	(Çakli et al., 2015)
5	Ventilation	- Flow from the clean area to the polluted area - Must remove excessive heat, condensation, dust, steam, and odors - More in section Ventilation	(Masotti et al., 2019)
6	Lightening	- Should be equivalent - Protected - Cleanable	(Çakli et al., 2015)
7	Processing rooms	- Must be distributed according to the flow - Separate among the places with different hygienic standards - Pest control	(Beetz et al., 2017)
8	Exhaust ducts	- Be able to remove water vapor or other steam - For discharge, it should be located properly, far from fresh air, to prevent product or even equipment contamination	(Moerman et al., 2023)
9	Storage rooms and facilities	- Professionally installed thermometer and humidity meter - Enough space and pallets - Raw material and finished product separation - Pest control	(Çakli et al., 2015)

food hazards in terms of chemical, physical, and biological hazards related to building design are summarized in Tables 2 and 4. Building design by providing a series of hurdles against various food hazards aimed to protect the processing area, raw materials, and products against external and internal risks.

External risks such as dust, pests, rain, airborne particles, and unauthorized human access can be effectively managed by considering key aspects (Holah, 2023b). These aspects include the careful selection of a suitable site, implementation of procedures to maintain exterior cleanliness, and hygienic design of the factory building which encompasses proper foundations, walls, and roof to ensure the overall structural integrity (Moerman & Wouters, 2016a).

While internal risks in a factory building encompass nonfood processing activities and cross-contamination. In order to maintain maximum hygiene level inside the factory, it is essential to implement proper prevention methods like proper planning for locating and controlling doors, windows as well as all air inlets, ensuring the hygienic design of structural elements like floors, columns, and beams inside the building, and stablishing correct material, air, waste, and personnel flows (Masotti et al., 2019; Moerman & Wouters, 2016b).

Table 3 presents a summary of key elements and necessary properties related to building design. In most cases, designing the building based on the hygienic level need for environment and activities, as well as implementing risk-zoning concept can effectively contribute to controlling the food contaminants in the final products (Çakli et al., 2015; Kamana et al., 2017). Furthermore, in order to produce safe and high-quality food products at competitive costs, it is essential to regularly assess the design of a food factory. Over time, previously reliable and advanced design factories may become inadequate due to various factors, such as new product developments, introduction of different food safety risks, stricter regulations, evolving processing technologies, equipment design, construction materials, environmental demands, hygiene and safety prerequisites, and changing building structure. Modern food manufacturers are obliged to anticipate future needs, develop a strategic vision, and adapt to meet forthcoming legislative requirements, consumer expectations, sustainability objectives, and competitive demands (Moerman & Wouters, 2016a).

Ventilation. Air quality within the food processing plant directly affects the food safety. The food processing environment is usually wet, leading to the generation aerosols that contribute to microbial contamination. This is particularly notable in food processing facilities with OFPE where the products are subjected to prolonged exposure to air (Masotti et al., 2019). Although the presence of microorganisms in the air of food facilities is highly variable, ranging from 10 to 10,000 CFU/m^3, specific characteristics in terms of humidity, temperature, pH, nutrients, oxygen, inhibitory compounds, and airflow are considered as ORs for air control, Table 2 (Masotti et al., 2019; Moerman et al., 2023).

Controlling temperature dramatically mitigates the risk of microbial growth and biofilm formation, ensuring the safe handling, processing, and storage of food products. Extensive efforts have been invested over several years to evaluate the impact of temperature on the persistence of microorganisms and the formation of biofilms, especially in the niches that are hard to reach in daily cleaning procedure (Bourdichon et al., 2021; DeFlorio et al., 2021; Møretrø & Langsrud, 2017; Nowak et al., 2017; Thakali & MacRae, 2021). The influence of temperature on microorganisms varies depending on the species as well as strain type, whether it is persistent or transient sporadic (Nowak et al., 2017). Among different microorganisms, *Listeria monocytogenes* has a great ability to thrive at refrigeration temperatures (Spanu & Jordan, 2020). In previous study by Magalhães et al. (2016), the growth behavior of 31 persistent strains and 10 sporadic strains of *L. monocytogenes* at different temperatures (4°C, 22°C, 37°C) was investigated. The study revealed that persistent strains exhibited higher average growth rates at 22°C compared to sporadic strains, indicating that both high and low temperatures can contribute to the tendency of *Listeria* strains to colonize equipment. In the study conducted by Losito et al. (2017), microbiological analyses were carried out in March, July, and October, unveiling variations in the total aerobic count. Specifically, it was observed that the count was higher in

Table 4
Common food-borne agents in food processing facility

Agent	References
• *Bacillus cereus* • *Listeria monocytogenes* • *Staphylococcus aureus* • *Salmonella* species ○ *S. enteritidis* ○ *S. typhimurium* •*Campylobacter jejuni* • *Escherichia coli* • *Vibrio* • *Yersinia enterocolitica* • *Clostridium* ○ *C. perfringens* ○ *C. difficile* ○ *C. botulinum* • *Cronobacter sakazakii*	(Eyvazi et al., 2021; Fung et al., 2018; Garvey, 2019; Li et al., 2021; Thakali & MacRae, 2021)
• Fungal species and mycotoxins ○ *Aspergillus* (aflatoxin and ochratoxin A) ○ *Candida* ○ *Penicillium* (ochratoxin A) ○ *Fusarium* (deoxynivalenol and zearalenone) ○ *Mucormycetes*	(Davies et al., 2021; Fung et al., 2018)
• Viral species ○ *Norovirus* ○ *Rotavirus* ○ *Hepatitis virus A and E*	(Fung et al., 2018; Warmate & Onarinde, 2023; Yin et al., 2019)
• Parasitic species ○ *Cryptosporidium parvum* ○ *Giardia lamblia* ○ *Toxoplasma gondii*	(Poissant et al., 2023; Robertson, 2018)

July, potentially due to the elevated temperature and humidity levels that create a more favorable environment for microorganism proliferation. Moreover, the microbial diversity demonstrated notable variations throughout the 6-year monitoring period.

Evidence on air control throughout the food industry showed that some pathogens and spoilage bacteria, including *Escherichia coli, Salmonella*, and *Listeria,* can survive and move by airflow (Çakli et al., 2015). Due to the strong electrostatic attraction at the microscopic scale, microbes can attach to the airborne particles and move with the airflow around the processing area, regardless of the existence of physical obstacles between the contaminated and clean zones. In consideration of recontamination and cross-contamination by the airflow, it is necessary to renew the air with fresh air regularly, and the airflow needs to be from the clean areas to the dirty areas to reduce the possibility of contamination and then be suitable for human breath (Belias et al., 2022; Spanu & Jordan, 2020). Effective utilization of air-handling equipment is highly suggested to minimize the risk of airborne particles coming into contact with exposed food items. One method to reduce the microbial load in the air involves employing air filtration systems that purify the incoming air in designated areas. Additionally, heating, ventilation, and air conditioning (HVAC) systems are commonly utilized to further enhance air quality control. These systems enable the management of temperature, humidity, airflow direction, and pressurization within specific areas, thereby facilitating control over airborne microorganisms and other contaminants (Moerman et al., 2023).

Waste Management. Abundant liquid and solid waste are frequently produced in the food processing plants in all stages of food preparation, processing, packaging, and especially during the cleaning and sanitation process. These wastes consist mainly of organic materials and cause serious environmental pollution both within and outside the company as well as nutrient loss in the case of food wastage. The high-water content and rapid accumulation rates of such wastes give rise to bacterial contamination, accompanied by other challenges in waste disposal management and financial issues (Reynolds et al., 2019). Therefore, there is an urgent need for increased efforts to make significant progress in developing effective strategies and measures for proper management and waste disposal (Ravindran & Jaiswal, 2016). Food industrial waste management is concerned with three ORs, namely food waste, water waste, and solid waste, Table 2.

Food waste is damaged or low-value products that are generated due to pest attacks, improper handling, transportation, microorganisms, insufficient processing, and losses during processing which result in food deterioration and consequently food wastage (Thakali & MacRae, 2021). Food waste contains a variety of valuable substances such as complex carbohydrates, proteins, lipids, and nutraceuticals, which can serve as raw materials for important commercial products. Current regulations concerning food waste management primarily prioritize waste prevention, with less emphasis on disposal practices (Lemaire & Limbourg, 2019). However, studies exploring the valorization of food waste within the supply chain have identified promising opportunities for the production of biofuels, enzymes, bioactive compounds, biodegradable plastics, nanoparticles, and other valuable molecules from food wastes (Ravindran & Jaiswal, 2016).

Water waste generated during various stages of food processing, especially during cleaning, contains a range of contaminants, including pathogenic organisms, nitrogen and phosphorus compounds, residual pesticides, chlorine-based detergents, as well as liquid remnants of raw materials like blood and suspended particles (Khedkar & Singh, 2018). Unfortunately, a large portion of this wastewater is often released untreated into nearby water bodies and open spaces. Consequently, this uncontrolled discharge poses a significant threat to both company's environmental hygiene and human health, while also adversely affecting aquatic ecosystems. As a result, utmost significance lies in the industrial wastewater treatment process before discharge to the ecosystem. Techniques including physicochemical treatments, the use of effective coagulant agents, as well as biological treatments for pollutant degradation were suggested by Shamsan et al. (2023) for wastewater treatment before releasing into the environment. Moreover, implementing an efficient drainage system within the company is essential to prevent water accumulation and contamination.

Solid waste includes solid materials remained from raw ingredients like skin, seeds, bones, internal organs, and packaging materials like plastic, metal, or glass (Khedkar & Singh, 2018). In accordance with regulations, waste separation and disposal should be done regularly, in a hygienic and environmentally friendly way, since they are a rigorous source of contamination (Çakli et al., 2015). Insufficient infrastructure for recycling and waste management results in the build-up of unwanted materials and food waste, which can attract pests and insects, thereby increasing the risk of food contamination. Unsanitary conditions in the food processing and preparation areas contribute to inadequate storage, transportation, and the sale of unhygienic food (Fung et al., 2018). Therefore, it is essential to address these issues by implementing improved waste management practices, sanitary measures, and effective control of pests and insects to ensure food safety and hygiene.

Microbial contamination

As previously discussed, food contaminants are classified into three groups: physical, chemical, and biological. Identifying the sources of physical and chemical contaminants appears to be relatively straightforward. However, when it comes to microorganisms, assigning specific pathways for each becomes very challenging (Eyvazi et al., 2021). In a food facility, exposure to contaminated surfaces or materials and

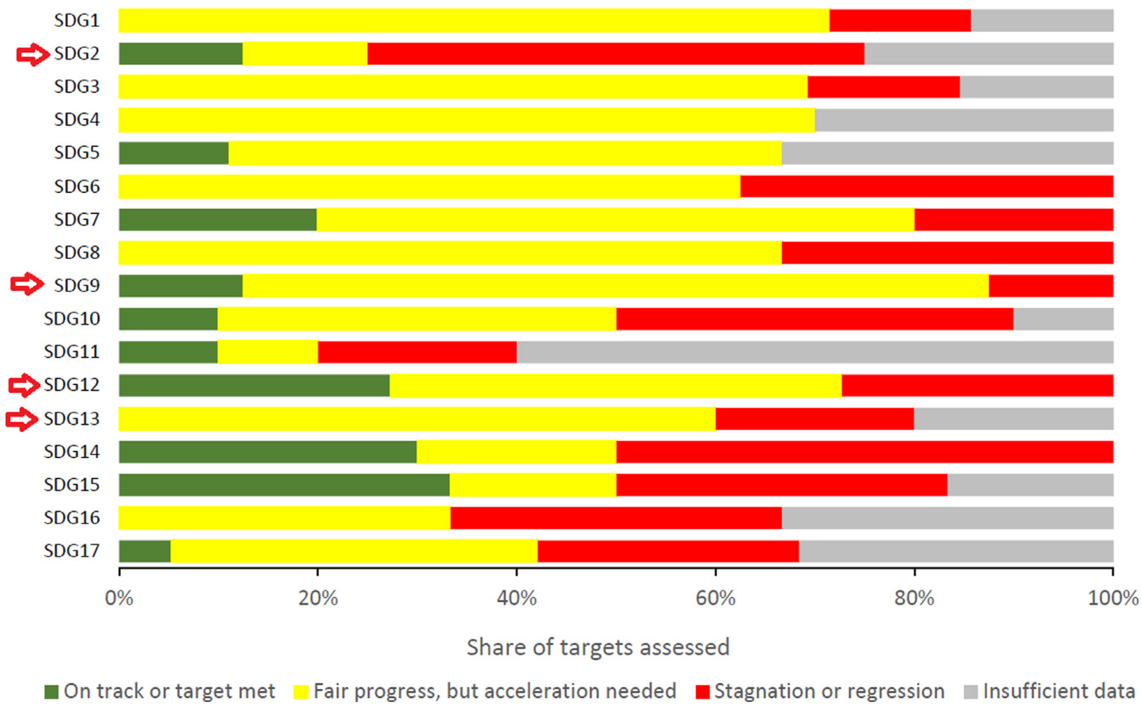

Figure 3. Progress assessment for SDGs based on assessed targets, 2023 or latest data. Source: (UN, 2023).

the risk of cross-contamination between food-contact and non–food-contact surfaces (e.g., drains, hallways, and entrances) can lead to the accumulation of microorganisms and other debris, resulting in their dissemination. Table 4 gives an overview of food-borne agents found in food processing facilities, identified in the reviewed literature. The complexity of microbial transfer highlights the necessity for an integrated approach to effectively prevent or minimize food contamination. Inadequate cleaning and disinfection may result in the persistence of microorganisms as well as organic and inorganic residues, providing an ideal environment for the development of bacteria to form biofilms. Biofilms have become a considerable challenge in various food industries (Lars Andre Langoeyli Giske & Emil Bjoerlykhaug, 2017). To combat microbial contamination and adhere to regulatory requirements (EN1672-2:2020), factors such as hygienically designed equipment and building structure design, proper sanitation practices, personal hygiene, zone separation, effective management of food processing, encompassing the selection of ingredients, food storage conditions, plant maintenance, and air filtration play a pivotal role in enhancing food safety (Fung et al., 2018; Masotti et al., 2019; Qian et al., 2022).

Food safety, security, and sustainability

Food safety is essential for our well-being and is a basic human need. It not only supports the economy, trade, and tourism but also ensures food security, contributing to a sustainable future (Fung et al., 2018). The estimation of global population will raise to approximately 8.5 billion in 2030, and reaching a total of 9.7 billion by the year 2050 (UN, 2022). As the global population grows, further actions need to be taken to increase in global food production of 70% by 2050 (FAO, 2009). Therefore, the importance of meeting sustainable development goals (SDGs) becomes very critical. However, as we approach the midpoint of implementing the 2030 agenda, it becomes apparent that the global progress toward achieving most of the goals by 2030 is inadequate. Although there have been some improvements in certain areas, most of the targets are progressing slowly or even experiencing obstacles, which is a cause for concern (UN, 2023). Several of the SDGs are directly affected by the improvements in food safety and industrial development, which will influence public health and environmental sustainability in different ways. As shown in Figure 3, the progress of goals number 2, 9, 12, and 13 which are the most relevant goals from the agenda 2030 for food processing industries is not satisfying. Food processing companies play a vital role in contributing to the achievement of these goals. The key aspects of their relationship are as follows:

Goal 2; Zero Hunger. Food companies have a direct impact on this goal as they are responsible for food processing, distribution, and accessibility. By adopting sustainable hygiene practices, hygienic design, reducing food waste, and producing safe foods, food companies can help to enhance food security.

Goal 9; Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. The relationship between food processing companies and this goal is multifaceted, with their contributions having a significant impact on its achievement. Developed infrastructure for food companies in accordance with hygienic design guidelines, efficient transportation of raw materials and final products, proper waste management, pest control, and effective ventilation and cleaning. By investing in and supporting the development of such infrastructure and technological innovation, food companies can help enhance overall economic productivity and growth by improving production processes, reducing environmental impact and better food safety and quality.

Goal 12; Responsible Consumption and Production. Food companies can promote responsible production by implementing sustainable agricultural practices, GMP, reducing resource utilization, and minimizing food waste (Opoku et al., 2022).

Goal 13; Climate Action. Food companies can contribute to climate action by following the hygienic design guidelines both for the equipment and building, adopting eco-friendly practices, reducing carbon footprints, and supporting sustainable production. Food waste and loss have significant impacts not only from economic and nutritional perspectives but also on the environment during processing, transportation, and disposal. For instance, in the UK, about 20% of greenhouse gas emissions in the food supply chains result from food packaging and transportation (Ahmadi-Javid et al., 2023). It is important to note that while some food companies are actively working toward sustainability and the SDGs, others may still face challenges in fully integrating these goals into their operations. Encouraging greater transparency in the food industry, such as publishing annual sustainability report, is important to achieve the SDGs and build a more sustainable world for the next generations.

Conclusion

Food hazards are pervasive within the food processing environment, and they can enter the food chain through diverse pathways. This challenge is amplified for food companies using open food processing equipment (OFPE), requiring greater control over food safety due to environmental hazards within the processing facilities environment. Consequently, a broad hygienic strategy addressing all food contamination pathways is imperative. For food processing companies using OFPE, ten pathways were developed based on the reviewed literature: raw materials, processing, cleaning, transportation, equipment and building design, ventilation, human activities, waste management, and pests. This review serves as an updated information applicable to food safety management plans, HACCP programs, and hygienic design processes by providing a comprehensive list of physical, chemical, and biological food hazards during the food processing stage of the food value chain. By acknowledging the connection between food safety and sustainability, the paper emphasizes the significance of food processing in achieving sustainable development goals, particularly focusing on objectives numbers 2, 9, 12, and 13.

CRediT authorship contribution statement

Anna Olsen: Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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