Chapter 19
The Role of Air and Aerosols in Contaminating Food Products During Food Processing

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Introduction

The presence of airborne organisms is a significant challenge confronting the food industry. Airborne organisms are typically generated through droplets deposited in aerosols with diameters ranging from 0.5 to 50 μm (Brandl et al., 2014; Lee, 2011; Stetzenbach et al., 2004). Aerosols are microscopic particles in the air in the form of liquid or solid particles (Sutton, 2004). These aerosols can carry bacteria, mold spores, yeasts (Brandl et al., 2014; Lee, 2011; Sutton, 2004), and pathogenic microbes, that then become bioaerosols. Pathogens that could be found in food-processing bioaerosols include *Escherichia coli*, *Salmonella*, *Listeria monocytogenes*, *Bacillus cereus*, and *Clostridium* spp. (Masotti et al., 2019a, b). Hence, airborne organisms are considered one of the contributing factors to the cross-contamination of food and food contact surfaces (Masotti et al., 2019a, b). The food industry, especially food processing areas, is subject to many processing activities, including spraying, splashing, and employee movements. Those activities always create aerosolization and droplets that can persist in the plant's environment (Sutton, 2004; Xie et al., 2021). The droplets from aerosolization may hold airborne organisms and become a source of contamination (Masotti et al., 2019a, b). Airborne microorganisms in the form of bioaerosols can readily spread through the air and consequently contaminate food, and food contact surfaces, such as processing

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equipment, containers, conveyors, and other equipment (Brandl et al., 2014; Otto et al., 2011). Bioaerosols can also transmit from food processing to other areas such as chilling, packaging, and dry storage areas, in food establishments through the employees' movement or tools and equipment, leading to negative effects on the quality of food products and potential foodborne infections (Madsen et al., 2020; Mohammad et al., 2021). Usually, the processing environment is moist due to the processing activities mentioned above. Therefore, various factors affect the movement and direction of the air in this critical area, which also affects airborne microorganisms (Masotti et al., 2019a, b). Typically, food products remain longer in the processing area before being transferred to other sites and being exposed to air or aerosols for an extended period of time (Sutton, 2004). Thus, air monitoring and preventive programs are required to avoid potential cross-contamination because appropriate airborne control measures ensure the safety and quality of food products (Masotti, Cattaneo, et al., 2019a). However, it has been found that the concentration of airborne microbes varies within food establishments, with the average level being low (Mohammad et al., 2021; Okraszewska-Lasica et al., 2014; Pearce et al., 2006; Sutton, 2004).

Airborne microorganisms are expected to always be present in food processing establishments, such as poultry, beef, dairy, and pork, because animals are reservoirs of bacterial pathogens, such as *Salmonella*, *E. coli*, and others. As a result, food industries must evaluate the bioaerosol levels in their facility's environment and assess the quality and shelf life of food products. Evaluating and identifying the potential airborne sources and types of microorganisms in food processing establishments is critical for developing effective preventive and hygiene practices and reducing microbial risks. This can be achieved by air sampling the entire food plant and evaluating the microbial load (Moracanin et al., 2019; Napoli et al., 2012). Many studies assessed the level of bioaerosols in the air of food processing plants and obtained beneficial results (Altunatmaz et al., 2012; Duggan et al., 2010; Pathak & Verma, 2013; Mohammad et al., 2021; Okraszewska-Lasica et al., 2014; Pearce et al., 2006; Sutton, 2004; Wu et al., 2018). The results from studies on beef, pork, and livestock establishments confirmed the presence of airborne pathogens at processing sites. For example, Okraszewska-Lasica et al. (2014) evaluated three commercial beef, sheep, and pig plants for the presence of *Salmonella* spp. and *L. monocytogenes*. The authors reported that both pathogens were detected in all three facilities. However, they confirmed that *Salmonella* levels were higher in the pig plant, while *L. monocytogenes* were mainly found in the beef plant. Mohammad et al. (2021) collected air samples from two small and two large commercial beef abattoirs to evaluate the presence of *Salmonella* and *E. coli*, comparing two different detection methods. The authors found both *Salmonella* and *E. coli* in all plants by both methods. However, they reported that the prevalence of both pathogens was affected by the facility size and the processing stage. Another study by Pearce et al. (2006) examined the prevalence and distribution of airborne *E. coli* and *Salmonella* in a pork slaughtering establishment, and the study revealed that both pathogens were detected at different stages and levels. Therefore, the food industry should pay additional attention to their hygiene practices and keep the food processing

environment clean. Food processing management needs to monitor the flow of air direction and ensure their ventilation system is effective and working (Beck et al., 2019; Wray, 2011). To this end, novel and innovative emerging technologies would be a great addition to overcoming the challenges and risks of airborne contamination in the food processing environment. Hence, this chapter covers the transmission and sources of airborne organisms in the food processing environment, identification and detection methods, and control of airborne in food processing establishment, novel, and emerging technology to prevent, control, and inactivate airborne organisms, and factors affecting their presence and concentrations.

Source and Transmission of Airborne Microorganisms in the Food Industry Environment

The source of airborne microorganisms in food processing environments varies and can be from different sources, depending on the size, activities, and sanitation practices of food plants. Airborne microorganisms are typically in the form of droplets known as bioaerosols (Sutton, 2004). Bioaerosols can be produced by wastewater, rinse water, aerosolized spilled products, air-conditioning systems, food production systems, raw ingredients, and worker activity (talking, sneezing, and coughing) (Mohammad et al., 2021; Nerin et al., 2016; Sutton, 2004). Heldman (1974) found a strong correlation between worker activity and airborne bacteria. Bioaerosols can also be generated through operation equipment, sink, floor drain, and high-pressure spraying (Mohammad et al., 2021; Sutton, 2004). Food processing environments typically have high moisture, ventilation and air conditioning systems, and heating, which provide an ideal environment for the growth of microorganisms and the consequences of airborne microbe growth (Altunatmaz et al., 2012; Nerin et al., 2016). Therefore, air sampling of food in the processing environment helps identify the sources of airborne microorganisms and potential contamination with airborne pathogens (Gollakota et al., 2021). The food industry can also use air sampling to determine the risk of airborne contamination and prevent the further spread of airborne microorganisms (Gollakota et al., 2021; Napoli et al., 2012).

Airborne or bioaerosols usually spread to food and food contact surfaces through the air. Therefore, many factors contribute to the transmission of airborne organisms from the air to food, food contact surfaces, and processing equipment (Brandl et al., 2014). The most common factors contributing to the spread of bioaerosols in food processing environments include the construction of food plants (doors, drains, etc.), activities during cleaning processes and disinfectant, washing, packing, incorrectly or inadequately designed and mainlined ventilation and air conditioning systems, and of course, employees and people activities, and poorly constructed interior and roof structures that lead to drainage or leakage (Moracanin et al., 2019). Hence, in the food processing environment, some of the above-mentioned factors usually allow microorganisms suspended on particles in bioaerosols to transmit to the food

products or food contact surfaces, resulting in contamination. Additionally, many other factors such as temperature, humidity, airflow, and nutrient sources, provide conditions for the growth and transmission of airborne organisms (Moracanin et al., 2019). Thus, air is not ideal for airborne growth if moisture, nutrients, and the correct temperature are unavailable in the plant's environment (Moracanin et al., 2019; Sutton, 2004). However, any point where food products or food contact surfaces are exposed to air is considered a route for airborne transmission. Air serves as a transient place but not as a source of airborne microbes. In this case, if airborne microorganisms are present in food processing environments, there is a suitable condition for their growth and survival and potential contamination risks are present (Moracanin et al., 2019). Therefore, the food industry should pay additional attention to their plant environment, identify potential sources of airborne transmission, and avoid any sources that lead to the generation of bioaerosols. Airborne microorganisms may persist in aerosols derived from activities, such as water spraying and sanitation in food processing establishments, and multiply, which may lead to food contamination. Identifying the sources of bioaerosols and the transmission of airborne microorganisms is of utmost importance for understanding the role of air in the food processing atmosphere and controlling the spread of potential contaminants.

Identification and Detection Methods of Airborne Contamination in Food Processing Environments

The transmission of airborne microorganisms is a food industry concern because they can contaminate foods and food contact surfaces and cause foodborne diseases. Therefore, effective monitoring procedures and robust and timely detection methods are essential to control and prevent airborne contaminations and potential foodborne illnesses from pathogenic microbial particles in aerosols (West & Kimber, 2015). In the food industry, monitoring air quality and microbial concentration is implemented by collecting air samples and identifying the microbial load through proper quantitative or qualitative analyses of collected bioaerosols. However, the results are significantly affected by the air samples collection, the type of air sampler, the sample size selected for analysis, the collection medium (which may affect the level of microbial recovery and viability), and the detection methods, quantitative versus qualitative (Dybwad et al., 2014; Hoisington et al., 2014). Therefore, an adequate air sampler for aerosol collection, isolation of airborne microorganisms, the concentration of the samples, and differentiation and detection methods of pathogens should be the focus to ensure effective detection and identification. Typically, air samples are collected using two methods (passive and active) (Okraszewska-Lasica et al., 2014). Different air samplers and their advantages and disadvantages are shown in Table 19.1.

Table 19.1 Methods of collecting airborne microorganisms

Method	Advantages	Disadvantages
Settle plates (sedimentation)	Reliable Easy Cheap No stress to microorganisms Standard	Low correlation with counts Inability to measure the number of viable particles per volume of air Long sampling times Bias to large particles Low correlation with counts
Impingers	Easy to implement Cheap Good for highly contaminated environments	Liquid impingers used for areas high concentration bioaerosols Cannot collect bioaerosols particles smaller than 1 μm
Impactors Slit	High recovery rates Low sampling stress, No additional steps are needed after air collection High sampling efficiencies Simple to operate	Complex and huge to handle Expensive, unmanageable Unsuitable for large outdoor air collection Long-time sampling
Impactors Sieve	Multiple flow rates Small size allowing for easy placement Virtually no particle generation Comparable recover to traditional Slit-to-Agar designs Standard 90 mm test plates	Complex and huge to handle, expensive
Cyclonic separation	Ability to collect large volumes of air continuously for a long time Collect bioaerosols into a liquid solution Airflow rates of 100–300 L/ min High effective A wet collection system protects cells from osmotic stress	Selective for large air particles Higher counts than other air samplers
Electrostatic precipitators	High particle collection efficiency High sampling rate Less resistance to airflow.	Produce ozone and nitrogen oxide, Subject microorganisms to toxicity Complex and requires professional management and handling.
Thermal precipitation	Adequate for collecting particles smaller than 5 μm Helpful for microscopic investigations	Not typically used in the food industry Requires accurate adjustments collects low-rate air sampling ranging from 300 to 400 ml/ min.

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Table 19.1 (continued)

Method	Advantages	Disadvantages
Centrifugation samplers	Subject microorganisms to less stress Does not create high-velocity provide more representative samples High air volume Simple Cheaper than impactor methods.	Only suitable for big particles
Filtration	Easy Fast Flexible Cheap Used to quantify mold and bacteria Collect large volumes of air short sampling time	Exposed cells to stress

Settle Plates In passive methods, aerosols are collected using settle plates (Petri dishes) by exposing the open plates containing non-selective medium to the air for a specific time and incubating overnight, then counting colonies (Dybwad et al., 2014; Sutton, 2004). This sample collection method is limited as the plates only collect viable airborne microbes that are sediment from the air and settle onto the agar surface within the exposure time. It is only suitable for bigger aerosol particles and cannot detect small ones. Additionally, with settle plates, it is not possible to collect a specific amount of air; therefore, the results could be more qualitative (Sutton, 2004). The settle plates become overgrown in a facility with high airborne concentrations, resulting in uncountable colonies (Hoisington et al., 2014). The settle plates can also become contaminated with non-air particles and deteriorate and dry quickly, making it difficult to interpret results. Some advantages are that it is easy to use and can collect bioaerosols in their actual state. The main drawback of this method is its incapability to measure the number of viable particles per volume of air. Other drawbacks of using this method are sampling times as it takes too long, significant dependence on air currents, bias towards big particles, and low correlation with counts obtained using different methods. This approach is proper when falling out onto a specific area to determine the presence of airborne organisms.

In the active sampling method, usually, air samplers are used to collect bioaerosols, and different devices with different structures and functions are utilized, such as impingement, impaction, cyclonic separation, filtration, thermal or electrostatic precipitation (Masotti et al., 2019a, b). However, each of these devices gives different results for the same sampling site and at the same time due to their structure and properties differences (Masotti et al., 2019a, b; Verreault et al., 2011). In active air sampling, a determinate volume of air/aerosols can be collected from the food establishment testing sites using one of the above-mentioned devices (West &

Kimber, 2015). The active air samplers based on popularity for use in air sample collection are hereby described.

Impingers Impingers are air samplers that collect aerosols using a liquid medium. Typically, the airflow through the inlet facilitates air transfer to the liquid medium. When the air hits the surface of the medium, the suspended particles impinge on the collection liquid medium. An appropriate liquid medium such as peptone water, phosphate buffer saline, or nutrient buffer, must be used to ensure the recovery of various types of microorganisms, maintain the microorganism's viability, and at the same time inhibit their growth (Sutton, 2004). After sample collection, the total air and medium liquid volumes are determined. The collected air samples in a liquid medium are analyzed using culture or rapid detection methods (Sutton, 2004). The advantages of using impingers are that they are easy to implement and inexpensive. However, some limitations of liquid impingers include the fact that they are usually used in areas with high bioaerosol contaminations and that they cannot collect bioaerosol particles smaller than 1 μm (Sutton, 2004).

Impactors These types of air samplers are used by most of the food industry for bioaerosol collection. Impactor air samplers collect samples using a solid medium. The impactor employs a solid agar plate and has two stages of work based on the size differentiation of aerosol particles. After the air is sieved through a plate for particle collection, the air is directed by a vacuum toward the agar or adhesive-coated surfaces. Following sample collection, the plates are incubated for 24–48 hours, and the colonies are counted to determine the level of airborne microbes in the air. Two types of impactors are available: slit and sieve air samplers, which are different in their shape and functions (Sutton, 2004).

A slit air sampler usually comes in a cylindrical shape with a tapered slit tube and functions by pulling the air by vacuum; it has a tapered slit tube that forms a jet stream during air sample collection. The vacuum in a slit sampler requires a constant flow rate of 28.3 liters per minute (L/min) (Masotti et al., 2019a, b). This type of air sampler collects air onto an agar plate while the plate rotates, which allows for even particle distribution over the agar plates. An example of a slit air sample is STA, New Brunswick Sci. Co. Inc., Casella, BGI Inc.

Sieve impaction air samplers are a second type of impaction device. These devices function by using the acceleration of air with a rated flow of 28.3 L/min that moves particles through a sieve mesh (a metal plate with numerous small holes) (Sutton, 2004). The particles in the air then impact onto the surface of the agar medium. This is an aggressive and effective method of gathering air samples. Sieve air samplers comprise of single or multiple stages. For example, it may include one, two, six, or eight stages. The air samplers with multiple stages have smaller holes that increase based on each stage resulting in increased particle velocity while the air moves through the sampler. For example, large air particles are impacted in the first stages, and smaller particles stay to be impacted in the subsequent stages.

Typically, single-stage air samplers do not distinguish between particle sizes. Therefore, these types of impactors are used when the purpose is to collect the total

number of viable particles per unit of air volume (Sutton, 2004). The two-stage air impactors are used when the purpose is to discriminate between respirable and non-respirable particles and usually separate almost all the viable particles that are 0.8–5 μm in size (West & Kimber, 2015). Multiple-stage impactors are used when the purpose is to collect and enumerate viable particles per unit of air volume based on the size of particles in the bioaerosol (Xu et al., 2011). They are usually utilized in healthcare operations and are uncommon for food processing establishments. Impaction air sampling methods are widely used due to their higher recovery rates than other air sampling methods, especially in environments with low bioaerosol levels. Additionally, this method has low sampling stress, and no additional steps are needed after air collection as particles are on agar plates, possess high sampling efficiencies, and are simple to operate (West & Kimber, 2015). However, like any other device, sieve impactors have some drawbacks, including being complex and huge to handle, expensive, and unmanageable. Also, they require special care to maintain sterility inside the samplers and the agar plates outside to prevent contamination (Sutton, 2004). In addition, they are unsuitable for expanded outdoor air collection because these air samplers are designed to collect low flow rates of 1.5 to 300 L/min and require long-time sampling (Sutton, 2004).

Cyclone This type of air sampler collects aerosol particles into a liquid medium, unlike impactor air samplers that collect aerosol particles onto solid/semi-solid mediums, exposing cells to stress by filters trapping bioaerosol particles surfaces of fine fibers or porous membrane. On the other hand, impingers function by channeling air flow through nozzles into a chamber of liquid (Sutton, 2004). Bioaerosols are collected by cyclone-air samplers via the collection chamber into a spiral, swirling flow where they are exposed to a centrifugal force based on their diameter, density, and speed. The centrifugal force then separates bioaerosol particles from the air by transporting particles into a liquid with sufficient inertia toward the cyclone wall (Sung et al., 2017).

Compared to other air samplers, the cyclone has many advantages, including the ability to collect large volumes of air continuously and for a long time, collecting bioaerosols into a liquid solution with airflow rates of 100–300 L/min, which prevent cell stress due to sample drying. Cyclones are found to be highly effective at collecting bioaerosols (Sung et al., 2017). They can be used in real-time monitoring of microorganisms in the air (Sung et al., 2017), including pilot studies at poultry facilities. Particles in a large volume of air are concentrated in a relatively small amount of liquid and tested by qualitative or quantitative methods to determine bacterial pathogens' presence and/or concentration. A wet collection system protects cells from osmotic stress. An example of this type of air sampling is a dry, wet-walled, and two-stage cyclone.

Filtration This method of air sampling is based on the separation of aerosol particles from the air by passing the air through a filter for a certain time at the same speed (Sutton, 2004). Usually, the filter is attached to a holder and connected to a vacuum origin with a control flow rate (Sutton, 2004). The filter can consist of any

material, such as sodium alginate, cellulose fiber, glass fiber, gelatin membrane with a pore size of 3 μm, and a synthetic membrane with a pore size of 0.45 μm or 0.22 μm (Sutton, 2004). For direct culture-based analysis, gelatin membrane filters are used because they are water-soluble and are placed directly onto an agar surface for analysis and enumeration of microorganisms (Zand et al., 2022). In comparison, synthetic membrane filters are restless into a liquid before analysis. These air sampling methods are widely used because they are easy, fast, flexible, cheap, can be used to quantify mold and bacteria, and can collect large volumes of air within a short sampling time (Zand et al., 2022). However, they exposed cells to stress due to drying, making them less effective for most vegetative cells than other air samplers (Sutton, 2004). Example of this type of air sampling is Button, IOM, and virtual impaction (MVI).

Centrifugation Samplers Similar to cyclone air samplers, centrifugation air sampling approaches create a force that pushes airborne particles onto the surface of agar. Aerosol is moved in a circular motion at a high velocity, and the centrifugal force causes the particles to impact against an agar surface. The advantages of using these air sampling methods include less stress on microorganisms than other methods, such as impaction or impingement sampling methods, because centrifugation does not generate high-velocity jet forces during sample collection (Masotti et al., 2019a, b). Additionally, they can provide more representative samples because they are fast and collect a high air volume. They are also simpler and less expensive than impactor methods. However, centrifugation methods are only suitable for big particles. An example of these air samplers is the Reuter centrifugal air sampler (RCS Sampler, Biotests Diagnostics Co.), which is portable, battery-operated, easy to use, and can collect 100% of 15 μm particles and 55% to 75% of 4 μm to 6 μm particles (Oliveira et al., 2020).

Electrostatic Precipitators This air sample collection method consists of a glass chamber.

The air is drawn inside the chamber, and bioaerosols are subject to an electrostatic charge, and the charged air particles are then attracted to oppositely charged plates. Briefly, the air is drawn into a chamber, which is comprised of top and bottom parts (Masotti et al., 2019a, b). Inside the chamber, the air is subjected to an electrostatic charge of 13 kV. This high charge creates ions and ionizes the air and bioaerosols inside the chamber. After aerosols and droplets become charged, they are attracted by the oppositely charged plates at the bottom of the chamber, which is covered with collected medium. The advantages of using this method are high particle collection efficiency, high sampling rate, and less resistance to airflow. However, this method may produce ozone and nitrogen oxide, subjecting microorganisms to toxicity and death before enumeration. Additionally, this method is complex and requires professional management and handling (Masotti et al., 2019a, b; Oliveira et al., 2020).

Thermal Precipitation This air sampling method captures airborne microorganisms through the precipitation of bioaerosols using thermal precipitators through a temperature gradient. Like electrostatic precipitation, thermal precipitation also collects aerosols by drawing air onto a cylindrical chamber by suspending a wire that goes through the chamber with an airflow rate of 7–20 ml/min. The suspending bioaerosol particles then move from the high-temperature zone to the low-temperature zone. The thermal force here is only effective for a 750 °C cm^{-1} temperature gradient and less. This method is adequate for collecting particles smaller than 5 μm and helpful in microscopic investigations. However, thermal precipitation is not typically utilized in the food industry as it requires accurate adjustments and collects low-rate air sampling ranging from 300 to 400 ml/min (Masotti et al., 2019a, b; Oliveira et al., 2020).

To this end, the food industry commonly used settle plates or liquid impactor air samplers. However, wet-walled cyclones and liquid impingers with swirling liquid and the CIP 10-M provide additional advantages of keeping the viability of the cells and more accurate counts of airborne microorganisms compared to solid-based surfaces air sampling (Oliveira et al., 2020).

Analysis of Airborne Microorganisms After air sample collection, the air sample is analyzed to determine the concentration of airborne microorganisms using culture, rapid methods, or microscopic analysis (Mbareche et al., 2018; Reponen et al., 2011). Culture-based analysis is the most commonly used method in the food industry for counting airborne microbes as a direct method of analysis (Oppliger, 2014). However, selecting the appropriate air sample analysis technique is critical because not all air sampling systems used to collect air samples are compatible with specific analyses. For example, settled plates rely on culture-based analysis, while impaction air sampling methods use both culture-based and microscopy analysis. Impingement, cyclone, and filtration sampling methods are more suitable for analysis with rapid air samples, such as molecular or immunological approaches, as these methods collect air samples in the liquid or on a filter (West & Kimber, 2015).

Airborne microorganisms exposed to stress during sampling may not be able to grow under the nutrient medium used for culturing (Masotti et al., 2019a, b). In this case, using different types of nutrient media during sampling could help to recover the most microorganisms during the analysis. Nonselective agar, such as tryptic soy and nutrient agar, is usually used for culture-based analysis. After incubation, the culturable microorganisms are grown on the agar, and the airborne microorganism's concentration is determined by counting the number of colonies which are recorded as colony-forming units (CFU) (Napoli et al., 2012). Further analyses are performed for bacterial identification using biochemical tests, microscopic morphology, and Gram stain reactions to determine the types of airborne microorganisms. Direct culture-based methods are easy to use, reliable, and considered a gold standard. However, they are labor and material-intensive, inaccurate, time-consuming, unsuitable for nonculturable organisms, and subject to contamination (Vasavada et al., 2020).

Rapid analysis approaches like molecular and immunological approaches overcome these limitations of traditional direct methods. Immunological methods like enzyme-linked immunosorbent assays (ELISA), precipitin assays (immunodiffusion), and particle agglutination assays (latex agglutination) function based on the interactions between microbial antigenic and antibody (antigen-antibody) (Vasavada et al., 2020), whereas molecular approaches, like polymerase chain reaction (PCR), are based on the amplification of DNA or RNA analysis or amplification of the 16 S rDNA, then sequencing and DNA hybridization (Vasavada et al., 2020). The latter increases the sensitivity and specificity of the test and decreases the analysis time (Stetzenbach et al., 2004). To conclude, the food industry should consider both direct culture methods and modern rapid approaches for identifying the airborne concentration in their plants' environment.

Current and Emerging Technology to Prevent, Control, and Inactivate Airborne Contamination in Food Processing

The presence of airborne microorganisms in the air of food industry environments is random, and their load is variable, usually ranging from 10 to 10,000 CFU/m3 (Ehavald et al., 2007). However, understanding the level of microbial load and having information about bioaerosols is vital for evaluating the risk to food product safety and quality and protecting public health. Usually, air entering a food processing establishment from the outside is filtered and chilled to eliminate unwanted microorganisms that are expected to enter the plant's environment from the outside. However, factors such as processing activities, personnel, and facility structures cannot be fully controlled. They may contribute to the generation of droplets and bioaerosols that hold pathogenic microorganisms inside the food processing plant, which is variable among food processing plants and in the same facility based on the type of daily activities (Masotti et al., 2019a, b). Monitoring and evaluating airborne microorganisms using adequate air sampling and reliable and sensitive analysis techniques is the first step to preventing and reducing the occurrence of airborne contamination. The food industry is aware that monitoring airborne microorganisms has become a must, and now it is part of their quality control practices (Masotti et al., 2019a, b). Airborne microbial monitoring can be included as a section in the food industry HACCP plan (Beletsiotis et al., 2011; Oliveira et al., 2020).

Air disinfection methods are performed to reduce airborne microbial loads in the air of food plants in addition to their standard chemical sanitation practice. Air disinfection is implemented using chemical fogging, ozone treatment, UV irradiation, hydrogen peroxide, and cold plasma methods (Brown & Wray, 2014). Personal hygiene, preventing cross-contamination, zone separation, and water purification also assists in reducing airborne microorganisms (Gurnari & Gurnari, 2015). Proper food storage conditions, facility maintenance, and air filtration are effective ways to

improve food safety. Effective air quality management can significantly reduce airborne microorganisms in food processing environments. Proper ventilation removes moisture discharged during processing activities and prevents surface condensation and mold growth. Airflow is one of the significant factors contributing to the transmission of bioaerosols from dirty areas to clean areas in food processing facilities (Beck et al., 2019). In this regard, computational fluid dynamics programs are suitable programs that assist the food facilities in anticipating the movements of airflow within the facility (Oliveira et al., 2020), which also helps improve ventilation systems and enhance sanitation programs (Skåra & Rosnes, 2016).

Airborne pathogens have been found in the air of produce packing houses (Cevallos-Cevallos et al., 2012), poultry plants (Kwon et al., 2000), pork production environments (Pearce et al., 2006), and turkey production environments (Harbaugh et al., 2006). Additionally, airborne pathogens and endotoxins were found in two herb processing plants (Dutkiewicz et al., 2001). Current disinfection methods include chemical fogging, ozone, and hydrogen peroxide. Numerous oxidizing agents with solid antimicrobial activity have been evaluated to disinfect the air of food plant environments, and most of them are suitable sanitizers. The most common sanitizing agents used are chlorine dioxide (ClO2), organic acids, hydrogen peroxide (H2O2), and ethanol (Hoehn et al., 2010; Tuladhar et al., 2012). Typically, gaseous disinfectants provide advantages over liquid disinfectants because they are more easily spreadable and can reach difficult areas (Tuladhar et al., 2012; Morino et al., 2011; Yeap et al., 2016). Therefore, fogging, in this case, can enhance the application of sanitizers to reduce airborne microorganisms more efficiently than general liquid sanitizers. Hedrick (1975) tested the application of fogging and found that fogging with chlorine fog reduces airborne counts in the environment. However, the application of fogging was found to be less effective than other disinfection methods such as UV irradiation or ozone (Oliveira et al., 2020). The application of hydrogen peroxide leaves no chemical residue in treatment areas since it decomposes to water and oxygen. It can be used as a liquid or a gas, alone or in combination with heat, as high temperatures enhance its antimicrobial activity (Oliveira et al., 2020). Hydrogen peroxide fogging has been used to minimize pathogens in contaminated environments and surfaces (Oliveira et al., 2020).

Typical disinfection systems may not be sufficient to control potential airborne microorganisms in the food processing environment. Therefore, assessing emerging and innovative disinfection technologies for controlling airborne food processing facilities is necessary. Novel and new approaches for reducing and inactivating airborne microorganisms have been evaluated for food processing plants, including UV irradiation, carbon nano-tube filtration, and electrostatic field (Liang et al., 2012). UV irradiation is a potent treatment that inactivates microorganisms by damaging the molecular bonds in DNA (Brandl et al., 2014). A study found that shortwave UV radiation (254 nm) reduces microbial levels in the air and on surfaces (Bintsis et al., 2000). However, the efficacy of UV irradiation depends on different parameters, including UV intensity, exposure time, location of the lamp, and air

movement and airflow. UV irradiation disinfection has been widely used in medical and veterinary operations to decontaminate the air, surfaces, and equipment (Memarzadeh et al., 2010; Rutala & Weber, 2011). This disinfection treatment has several advantages over chemical sanitizers, including the absence of chemical residuals in the environment or surfaces, instantaneous and specific biocidal action, ease of use and installation, no maintenance required, low costs, and no chemical hazards (Brandl et al., 2014). Thus, UV technology is one of the most promising technologies as a control measure for airborne organisms.

Ozone is another emerging disinfection approach that can be used to control airborne microorganisms in food processing environments. Ozone possesses powerful antimicrobial effects and inactivates microorganisms by oxidation of nucleic acids and critical cell elements, such as glycolipids, glycoproteins, sulphhydryl groups, and enzyme amino acids (Burfoot et al., 2007). It has been widely used for water disinfection and is tested for air disinfection. The application of ozone is not new. Ozone has been used in many food processing plants, including meat, poultry, eggs, fish, fruits, produce, and dry ingredients, to inactivate different microbial contamination (Pirani, 2011). In the food industry, ozone is mainly used to disinfect environments and water. It has high penetration ability and high reactivity and leaves no toxin byproducts (Pirani, 2011). These properties make ozone effective against most microorganisms and an attractive disinfectant agent to control microorganisms in the food industry. Additionally, ozone can be used as a gas or liquid in water as it has gaseous or aqueous phases. Besides its potent antimicrobial effect, the application of ozone is not expensive compared to other treatments. Thus, ozone may become an alternative disinfection of chlorine, chlorine dioxide, hydrogen peroxide, and others (Weavers & Wickramanayake, 2001). However, ozone treatment has specific limitations, including its efficacy depending on concentration, temperature, contact time, and the targeted organisms. At high concentrations, it may cause the oxidation of food ingredients and can affect the human respiratory tract as it produces toxins (Oliveira et al., 2020). Therefore, it is suitable to use as a combined treatment with other treatments to minimize the risk of its toxicity.

Due to its unique antimicrobial properties, nanoparticle application is another promising technology for controlling airborne contamination in food processing plants. For this purpose, carbon nanotubes are coated with an antimicrobial using an electrospray system. These coated nanoparticles are used in air filters to enhance their efficiency as antimicrobials. Nanotubes and nanoparticles can be combined to form hybrid nanoparticles that settle onto the air filter medium. The hybrid nanoparticles form dendrites on the surface of the filter, making filter efficiency higher than those of original nanoparticles or nanotubes alone. The application of nanotechnology for controlling airborne contamination has been tested by Hwang et al. (2015), and the results showed a promising use for controlling airborne in indoor air environments. The above-mentioned controlling measures are typically used as a single treatment. However, hurdle approaches using a combination of two or more treatments enhance the efficacy of treatment compared to a single one.

Factors Affecting Levels of Airborne Microorganisms in Food Processing Environments

Hygiene, safety, and safe production are top priorities in food processing plants. During production, food may be subjected to bio-contamination. Among microbial vectors, air is considered an important potential source of microorganisms, including pathogens (Masotti et al., 2019a, b). Microorganisms may be responsible for the upsurge of food-related illnesses or food spoilage. In food processing plants, contamination via air, surface contact, and personnel are microorganisms' major routes of food recontamination (Fig. 19.1) (den Aantrekker et al., 2003). In food processing areas, air must be controlled and attain minimum standards. However, environmental air with specific quality factors such as temperature, humidity, dust, and microbial content are generally required to produce particular products. For example, in food industries, the zone where food products' chilling is carried out is mainly run at 10–12 °C to maintain the chilling temperature before packaging food products. Once the product is packaged, it is more difficult to chill it if it is above the required temperature (Brown & Wray, 2014).

Moreover, for high-care and high-risk areas, the main objective of an air handling system is to provide adequately filtered air at the right temperature and humidity and at a slight overpressure to prevent the ingress of air from external and uncontrolled sources. In addition, in cereal milling operations, control of airborne dust also plays an essential role in workers' health and in reducing the risk of explosions (Brown & Wray, 2014). Moreover, environmental or air quality in dairy farms also plays a vital role in the food safety of the dairy industry because it may influence the microbial communities in milk. The bacteria or microorganisms in different dairy farm areas influence this environmental quality, using air as a dissemination vehicle (Quintana et al., 2020). For example, in the cheese-making process, the hygienic quality of milk that will be used for the elaboration of unpasteurized cheese is essential because air is an important source of contamination with microorganisms being transported through it, affecting the properties of the final product (Albenzio et al., 2005). Therefore, special attention should be given to the possible contamination routes through the dairy farm environment.

Factors that affect the dairy farm environment include temperature, relative humidity, ventilation, dust, and livestock housing. Temperature plays an essential

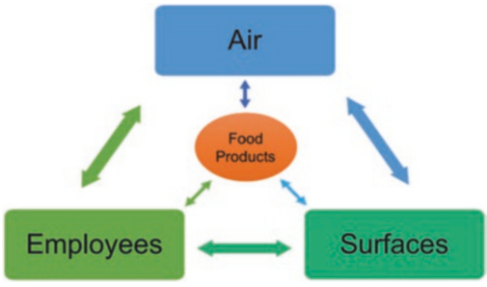

Fig. 19.1 Major routes of microbial contamination and their interactions in the food processing plant

role in a dairy farm environment, especially when temperatures are high, because a proper selection of temperature range improves the quality of the air and, thus, animal welfare (Quintana et al., 2020). Moreover, the appropriate relative humidity level in the environment should be considered to avoid the propagation of microorganisms on the farm. In addition, proper ventilation should be provided on the farm to prevent environmental pollution (Lange et al., 1997).

Effect of Temperature on Air Quality Temperature always plays a vital role in the environment of dairy farms because it is closely related to the welfare of the animals. In the last few years, the average global temperatures have risen by up to 4 °C in some parts of the world due to climate change. These temperature increases have had an impact on livestock farming systems as well as human and animal health (Marino et al., 2016). The effect of temperature on dairy farms is determined by two factors: location and season. One study observed differences in the concentration of microorganisms in the environment depending on the season (Vissers et al., 2007) or meteorological factors. Sanz et al. (2015) observed a seasonal effect on the number of isolates of bacteria (*Escherichia coli*) in the air. They observed a double concentration of bacteria in the hot season (summer) compared to the cold season (winter). They also observed the influence of the time of day on the concentration of microorganisms. Similarly, Popescu, 2011 found a positive relation between the increase in temperature and the increase in bacteria population in the environment, both in the morning and in the evening. As a result, there are seasonal and daily variations exist that cause the bacterial count to increase in the hottest seasons and during the hottest hours of the day. Furthermore, more microorganisms were detected in the air during the summer study. According to Dungan et al. (2011), environmental microorganisms are positively correlated with air temperature but negatively correlated with humidity and solar radiation.

Proper farm building design protects against climatic conditions, relieving animal stress and avoiding increases in respiration rate and exchanges between the animal's body surface and the environment, contributing to air pollution (Caroprese, 2008). The appropriate temperature is determined by the farming system. For example, in dairy cattle, the temperature should be maintained between – 5 °C to 22 °C for animals; however, this condition may vary depending on the animal's physical condition, available resources, and environmental factors. Sevi et al. (2009) suggested a range of air temperature from 5 °C to 20 °C for efficient production in small ruminants.

Effect of Humidity on Air Quality Relative humidity is a vital factor affecting respiratory damage. Because of this, it always plays an essential role in human and animal health building. Infectivity of pathogens found in the environment depends on the humidity level, due to which humidity is also critical to the welfare of animals (Xiong et al., 2017). Moreover, humidity may depend on other factors such as air distribution, ventilation, and temperature. For example, poor ventilation will occur without good air distribution, the temperature will fluctuate from its optimum range, and relative humidity will be affected, influencing the count of microorganisms

and molds. Therefore, it has been concluded that specific space in the stables is necessary for each animal to secure the correct relative humidity (Sevi et al., 1999). If living space is reduced, the concentration of pathogenic microorganisms in the environment increases. For dairy cattle, the relative humidity is between 55% and 75%; for small ruminants, around 70% relative humidity is recommended (Sevi et al., 2009). However, these values match the optimum criteria for the survival of most bacteria and fungi, 55% - 75% (Xiong et al., 2017). In addition, humidity control is necessary to minimize the risk because low humidity level negatively affects the collection of microorganisms from the environment, possibly due to their lower presence (Wilson et al., 2002). Moreover, another study found a positive correlation between the increased humidity of the air and fungi (Popescu, 2011). However, Tang (2009) observed a complicated relationship between airborne bacteria and relative humidity.

Conclusion

Air is recognized as a potential and important source of contamination in food processing establishments. Airborne microorganisms are suspended in droplets as bioaerosols. These bioaerosols may be transported from contaminated areas to clean areas in food facilities, causing food safety issues, reducing the shelf life of food products, and causing economic losses (Oliveira et al., 2020). Airborne microorganisms can originate from different sources, including ventilation systems, food production systems, raw ingredients, activities, water spraying and sanitation, and worker activity. Monitoring and timely identification of airborne microorganisms in the food processing environment are essential steps to control and prevent airborne contamination. Two methods of air sampling (passive and active air samples) are used. In active air sampling, various air samplers are available for collecting air samples from food plant environments. These air samplers have advantages and disadvantages, including impingement, impaction, cyclonic separation, filtration, and thermal or electrostatic precipitation. Air samples are analyzed to determine the concentration of bioaerosols in the air of food plants using direct culture methods or rapid methods, such as molecular and immunological approaches. To this end, the first step to controlling airborne microorganisms is to understand the level of airborne organisms in the air of food processing environments through continuous monitoring and sampling of the air. Then, maintaining good plant hygiene and sanitation is essential. Different disinfection measures are already in place for controlling airborne contamination, such as chemical fogging, hydrogen peroxide, and other chemical disinfectants. The application of many emerging and promising technologies has also been evaluated for potential use to control airborne contamination in food processing environments. However, many factors affect the level of airborne microorganisms in food processing operations and should be considered when developing new control measures.

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