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REVIEW ARTICLE

Concise Reviews and Hypotheses in Food Science

A review of food safety in low-moisture foods with current and potential dry-cleaning methods

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Abstract: Food is one of the basic needs of human life. With the increasing population, the production and supply of safe and quality foods are critical. Foods can be classified into different categories including low moisture, intermediate moisture, and high moisture content. Historically, low-moisture foods have been considered safe for human consumption due to the limited amount of moisture for microbial activity. Recalls of these foods due to pathogens such as *Salmonella* and undeclared allergens have brought attention to the need for improved cleaning and sanitization in dry food manufacturing facilities. In the food industry, cleaning and sanitation activities are the most efficient methods to prevent microbial contamination; however, water is most often required to deliver cleaning and sanitation agents. A well-written and properly implemented sanitation standard operating procedure can take care of microbial and allergen cross-contamination. Nevertheless, there are unique challenges to cleaning and sanitation processes for low-moisture food manufacturing facilities. The introduction of moisture into a low-moisture food environment increases the likelihood of cross-contamination by microbial pathogens. Hence, the use of water during cleaning and sanitation of dry food manufacturing facilities should be limited. However, much less research has been done on these dry methods compared to wet sanitation methods. This review discusses recent foodborne outbreaks and recalls associated with low-moisture foods the accepted methods for cleaning and sanitation in dry food manufacturing facilities and the limitations of these methods. The potential for air impingement as a dry-cleaning method is also detailed.

KEYWORDS
air impingement, dry cleaning, food safety, foodborne outbreaks, water activity

1 | INTRODUCTION

Food safety continues to be a major concern as the supply chain of food products is so diverse and complicated (Flynn et al., 2019). The U.S. Food and Drug Administration (FDA) and the U.S. Department of Agriculture (USDA) are the two primary federal agencies responsible for ensuring food safety in the United States. Similarly, the European Food Safety Authority (EFSA) ensures the safety of food products. More often, these federal agencies work with their regional counterparts to achieve the goal in the European Union (DeWaal et al., 2013). Food safety can be compromised by several factors including but not limited to adulteration, bacterial contamination, mycotoxins, and allergen cross-contact.

Historically, microbial cross-contamination in food products was associated primarily with high-moisture products. The high moisture combined with nutrients in food products serves as an excellent medium for the growth of pathogens, which is the case with most dairy and meat products (Farber et al., 1991). However, in recent times, detection of multistate foodborne outbreaks of low-moisture foods contaminated with *Salmonella* and *Escherichia coli* is becoming more common. In 1998, oats cereal contaminated with *Salmonella* serotype Agona was responsible for 209 illnesses and 47 hospitalizations (CDC, 1998). A total of 29 illnesses and seven hospitalizations occurred due to consumption of raw almonds contaminated with *Salmonella* serotype Enteritidis in the United States and Canada (CDC, 2004). A 2007 outbreak due to *Salmonella* serotype Tennessee-contaminated peanut butter in the United States resulted in reporting of 628 illnesses (Gerner-Smidt & Whichard, 2007). A similar but much larger outbreak due to peanut butter and peanut butter-containing products tainted with *Salmonella* serotype Typhimurium resulted in 529 illnesses, 116 hospitalizations, and eight deaths in the United States and one illness in Canada (CDC, 2009). Thirty-five cases of infection including six hospitalizations were reported due to the consumption of organic shake powder containing *Salmonella* Virchow (Gambino-Shirley et al., 2018). In another U.S. outbreak due to *E. coli* O157:H7 in soy nut butter, 32 people were infected (including 26 children) and more than 1.20 million pounds of soy nut butter were recalled (Hassan et al., 2019). Hoffmann et al. (2015) estimated that foodborne illnesses due to *Salmonella* alone accounted for $3.70 billion (for 1.02 million illnesses) annually in the United States.

Different technologies have been investigated for the inactivation of pathogens like *Salmonella* and *E. coli* in low-moisture foods. Some of these technologies employ heat, while others cannot use heat due to quality concerns for the food products under consideration. More than 5-log reductions in *Salmonella* were observed for black peppercorns with 2.50-min radio-frequency heating (Wei et al., 2018) and vacuum steam pasteurization at 75°C for 1 min (Shah et al., 2017). In a similar study using black peppercorns, 7-log reductions in *Salmonella* Typhimurium and *Salmonella* Enteritidis were noted when superheated steam treatment at 180°C was applied for 3 s (Ban et al., 2018). Using pulsed light treatment conditions of 3800 V, 14.10 cm distance, and 60 s, Oner (2017) showed a 4-log reduction in *Salmonella* Enteritidis for almonds. Recently, wheat flour treated with 395-nm pulsed light emitting diode (LED) for 60 min had 2.9-log reduction in *Salmonella*, along with undesirable quality changes like bleaching and oxidation (Du et al., 2020).

An additional concern in these environments is that pathogen cross-contamination may still occur from contaminated equipment or environmental surfaces (Beuchat et al., 2013). This contamination can be eliminated by employing effective sanitation protocols in the food industry. The sanitation methods vary according to the food products under consideration. In the dairy and beverage industry, the clean-in-place (CIP) method, which employs water and cleaning chemicals in a closed system, is commonly used (Li et al., 2019). However, in the case of low-moisture foods, an introduction of moisture in the cleaning process will increase the likelihood of pathogen harborage and growth (Beuchat et al., 2013). Hence, there is a need for cleaning without or with very minimal use of water in the low-moisture food processing industry.

This review discusses the concept of low-moisture foods, various foodborne outbreaks associated with low-moisture foods, and different dry-cleaning methods used in the food industry along with their advantages and limitations. For this review, low-moisture foods and low-water-activity foods are used interchangeably. The primary emphasis has been given on the outbreaks and recalls that occurred in the United States. Since cleaning and sanitization are two different steps in a typical sanitation process, the latter part is not relevant in the context of this review paper.

2 | CRITERIA FOR LOW-MOISTURE FOODS AND RELATED FOODBORNE OUTBREAKS

Foods can be classified in many ways. One of the important classifications of foods uses water activity as an indicator. It is important to note that there is a difference between moisture content and water activity. While the moisture content refers to the amount of total water present in a food material, the water activity refers to the amount of water available for the activity of microorganisms (Chen, 2019).

Thus, water activity plays an important role in keeping food products safe by limiting the activity of microorganisms such as pathogenic bacteria and spoilage mold. The water activity (a_w) is defined as the ratio of p/p_0, where p is the vapor pressure of water in food material and p_0 is the vapor pressure of pure water at the same temperature (Reid & Fennema, 2008). The water activity of a food product varies from 0 to 1. While there is no direct relationship between them, an increase in moisture content usually results in an increase in water activity for a food product. This relationship between moisture content and water activity at a constant temperature and pressure is known as moisture sorption isotherm (MSI), and the MSI is in the form of a sigmoid curve (Andrade et al., 2011). Sometimes, even the products with high moisture content have low water activity due to the addition of water-binding ingredients such as salt and sugar (Gurtler et al., 2014). Similarly, there are products with low moisture content and high water activity. For example, salted butter with 17% moisture content has a_w of 0.95–0.98, whereas strawberry jelly with 34.4% moisture content has a water activity of 0.84–0.88 (da Silva et al., 2021; El-Hajjaji et al., 2020; Schmidt & Fontana Jr., 2007; Uribe-Wandurraga et al., 2021).

There are some discrepancies regarding the upper limit of water activity for defining low-moisture foods. The Food and Agriculture Organization (FAO) and the International Life Sciences Institute (ILSI) Europe define low-moisture food products as those obtained from high-moisture foods through drying and dehydration with a final water activity at or below 0.85 (FAO, 2022; ILSI Europe, 2011). Some researchers have mentioned a water activity of 0.85 or less for this purpose, because the growth of foodborne pathogens is inhibited below this cutoff (Mermelstein, 2018; Sánchez-Maldonado et al., 2018). Other researchers have assigned a maximum a_w limit of 0.70 for classifying foods as low-moisture foods, which approaches the cutoff for inhibition of all food-relevant microbial growth, including fungi (Blessington et al., 2012; Komitopoulou & Peñaloza, 2009; Snyder et al., 2019; Uesugi et al., 2006). To that end, Syamaladevi et al. (2016) set a maximum value of a_w as 0.60 for classifying as low-moisture foods. Increasing the upper limit of water activity from 0.60 to 0.85 for this purpose will add many food products into the low-moisture category. Notably, although microbial growth is variably inhibited between 0.60 and 0.85, the efficacy of thermal inactivation treatments will certainly be impacted at these levels. Thus, depending on the water activity of a food, it may be classified as low-moisture by some, while not so by others.

Food products may be subjected to various thermal and nonthermal treatments to reduce the risk from pathogenic microorganisms during manufacturing. The thermal processing methods like drying, pasteurization, canning, and aseptic processing are commonly used in the industry. In thermal processing, the food products are heated to a predetermined temperature and held at this temperature for a predetermined time (van Boekel et al., 2010). In the process of achieving food safety in thermal treatment, the quality of food is reduced depending on the composition of the products and the severity of heat treatments. Alternatively, nonthermal processing technologies such as high-pressure processing, pulsed electric field, and membrane separation were studied (Picart-Palmade et al., 2019). Table 1 gives a summary of some of the studies conducted on microbial inactivation of low-moisture food products.

Historically, low-moisture food products have been considered microbiologically safe due to the limited availability of water. However, there have been notable foodborne outbreaks among low-moisture foods and some of them are given in Table 2. As can be seen from Table 2, *Salmonella* is a leading cause of foodborne illnesses in low-moisture foods due to its heat resistance and its ability to survive in a dry environment for a longer period of time (Finn et al., 2013). In addition, the presence of water in the manufacturing environment can support the growth and spread of *Salmonella* (Beuchat et al., 2011). The Grocery Manufacturers Association (GMA) formed a *Salmonella* control task force to develop guidance that suggested control of microbial growth in the manufacturing environment through the exclusion of water and prevention of environmental cross-contamination was essential (GMA, 2009). Some of the possible sources for microbial contamination in low-moisture food manufacturing facilities include raw materials, food plant employees, equipment, utensils, and so forth (Finn et al., 2013). Thus, it is important to implement an effective sanitation program to eliminate the occurrence of microbial contamination in the food manufacturing environment.

3 | IMPORTANCE OF CLEANING IN THE FOOD INDUSTRY

The Codex Alimentarius commission defines the cleaning as “the removal of soil, food residue, dirt, grease or other objectionable matter” (FAO, n.d.). Similarly, according to the Canadian Food Inspection Agency (CFIA), cleaning is “the removal of dirt or debris by physical and/or chemical means”, whereas the sanitization is “the reduction of microorganisms to levels considered safe from a public health viewpoint” (CFIA, 2019). In the food industry, the term “sanitation” denotes all operations and methods intended for maintaining a production environment that reduces the likelihood of hazards in the food. As an important step in the sanitation cycle, the primary purpose of cleaning is the complete removal of visible

TABLE 1 Inactivation studies for pathogens of concern in low-moisture foods.

Low-moisture food	Pathogen/surrogate	Serotype/genotype	Technique	Treatment conditions	Log reduction	References
Flaxseed	*Salmonella enterica*	Enteritidis PT30	Vacuum steam pasteurization	75°C for 1 min	5.48	Shah et al., 2017
	Escherichia coli	O157:H7			5.71	
	Enterococcus faecium				5.23	
Quinoa	*Salmonella enterica*	Enteritidis PT30			4.29	
	Escherichia coli	O157:H7			5.89	
	Enterococcus faecium				2.39	
Sunflower kernels	*Salmonella enterica*	Enteritidis PT30			4.01	
	Escherichia coli	O157:H7			5.40	
	Enterococcus faecium				2.99	
Pecans	*Salmonella enterica*		Cold atmospheric plasma	10 min	4.04	Diaz et al., 2019
Black peppercorns					3.63	
Oat flour	*Salmonella*		Twin screw extrusion	65°C or more	6.50	Verma & Subbiah, 2019
Nonfat dry milk	*Cronobacter sakazakii*		Intense pulsed light	3–4 passes	5.27	Chen et al., 2019
	Enterococcus faecium				3.67	
Wheat flour	*Cronobacter sakazakii*				4.92	
	Enterococcus faecium				2.79	
Egg white powder	*Cronobacter sakazakii*				5.30	
	Enterococcus faecium				2.74	
Almonds	*Escherichia coli*		Gaseous chlorine dioxide followed by heating	0.270 mg ClO_2 for 4 h and heat at 65°C	4.58	Rane et al., 2018

(Continues)

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TABLE 1 (Continued)

Low-moisture food	Pathogen/surrogate	Serotype/genotype	Technique	Treatment conditions	Log reduction	References
	Listeria monocytogenes				4.10	
	Salmonella			0.40 mg ClO_2 for 6 h and heat at 65°C	4.29	
Peppercorn	*Escherichia coli*		Gaseous chlorine dioxide followed by heating	0.40 mg ClO_2 for 6 h and heat at 65°C	3.68	
	Listeria monocytogenes				2.97	
	Salmonella				3.72	
Red pepper powder	*Bacillus cereus* spores		Radio frequency	90°C for 12 min	4	Jiao et al., 2019
Oat flour	*Salmonella*		Single screw extrusion	85°C at 150 rpm screw speed	5.50	Verma et al., 2018
Almonds	*Salmonella enterica*	Enteritidis PT30	Pulsed light	3800 V at 14.1 cm distance for 1 min	4.10	Oner, 2017
Black peppercorns	*Salmonella enterica*	Typhimurium; Enteritidis	Superheated steam	180°C for 3 s	6.34	Ban et al., 2018
Pecans				180°C for 13 s	6.24	
Almonds				180°C for 8 s	6.34	
Wheat flour	*Salmonella*		Pulsed light emitting diode	395 nm for 60 min	2.91	Du et al., 2020
Red pepper powder	*Salmonella enterica*	Typhimurium	Radio frequency	70°C for 60 s	>5	Hu et al., 2018
Wheat flour	*Salmonella enterica*	Enteritidis PT30	Radio frequency	9 min at 0.45 a_w	~7	Villa-Rojas et al., 2017
				9 min at 0.65 a_w	~7	
				9 min at 0.25 a_w	~5	
	Enterococcus faecium			9 min at 0.25 a_w	~3.2	

(Continues)

TABLE 1 (Continued)

Low-moisture food	Pathogen/surrogate	Serotype/genotype	Technique	Treatment conditions	Log reduction	References
Black pepper	*Salmonella*		Atmospheric pressure plasma	60–80 s	4.50 to 5.50	Sun et al., 2014
Black peppercorns	*Salmonella*		Mild steaming	75°C for 5 min	>5	Zhou et al., 2019
	Listeria monocytogenes				>5	
Peppercorns	*Salmonella enterica*	Enteritidis PT30	Vacuum steam pasteurization	75°C for 30 s	>5	Shah et al., 2016
Sunflower kernels	*Salmonella enterica*	Enteritidis PT30		75°C for 4 min	5.09	
	Escherichia coli	O157:H7		75°C for 1 min	5.40	
	Enterococcus faecium			85°C for 2 min	5.69	
In-shell walnuts	*Staphylococcus aureus*	ATCC 25,923	Radio frequency	70°C for 10 min	>4	Zhang et al., 2019
Pecans	*Salmonella enterica*		Hot water	90°C for 2 min	6 to 7.70	Kharel et al., 2017
	Escherichia coli	O157:H7		90°C for 4 min	>5.60	
Oats	*Salmonella*		Hot oil bath	210°F for less than 30 s	>5	Yeow & Showalter, 2016
	Listeria monocytogenes				>5	
	Escherichia coli	O157:H7			>5	
Pecan nutmeat	*Salmonella*		Oil roast	132°C for 1 min	5	Beuchat & Mann, 2011
Wheat kernels	*Salmonella enterica*	Enteritidis PT30	Vacuum steam	65°C for 8 min	3.21	Snelling et al., 2020
	Escherichia coli	O121			3.57	
Whole-grain flour dough	*Salmonella*		Baking	190.6°C for 16 min	>6	Wilder et al., 2016
Raisins	*Enterococcus faecium*	NRRL B-2354	Pasteurization	180°F for 28 min	3.30	Ceylan et al., 2017
	Salmonella				6.10	
Dry-cured beef	*Listeria monocytogenes*		Cold atmospheric plasma	100% O_2 for 300 s	0.85	Gök et al., 2019
	Staphylococcus aureus				0.83	

TABLE 2 Notable foodborne outbreaks associated with low-moisture foods in the United States.

Year	Implicated food	Pathogen	Number of cases	Reference
1998	Toasted oats cereals	*Salmonella* Agona	209	CDC, 1998
2003–2004	Raw almonds	*Salmonella* Enteritidis	29	CDC, 2004
2006–2007	Peanut butter	*Salmonella* Tennessee	628	CDC, 2007
2008	Cereals	*Salmonella* Agona	33	Russo et al., 2013
2008	Peanut butter	*Salmonella* Typhimurium	714	CDC, 2009
2009	Red and black pepper	*Salmonella* Montevideo	272	Gieraltowski et al., 2013
2011	Turkish pine nuts	*Salmonella* Enteritidis	43	CDC, 2011a
2011	In-shell hazelnuts	*Escherichia coli* O157:H7	8	CDC, 2011b
2012	Dry dog food	*Salmonella* Infantis	53	Imanishi et al., 2014
2012	Peanut butter	*Salmonella* Bredeney	42	Viazis et al., 2015
2013	Tahini sesame paste	*Salmonella* Montevideo; *Salmonella* Mbandaka	16	CDC, 2013
2014	Almond and peanut butter	*Salmonella* Braenderup	6	CDC, 2014a
2014	Organic sprouted chia powder	*Salmonella* Newport; *Salmonella* Hartford; *Salmonella* Oranienburg	31	CDC, 2014b
2015	Sprouted nut butter spread	*Salmonella* Paratyphi B variant L(+) tartrate(+)	13	CDC, 2015
2016	Flour	*Escherichia coli* O121; *Escherichia coli* O26	63	CDC, 2016a
2016	Pistachios	*Salmonella* Montevideo; *Salmonella* Senftenberg	11	CDC, 2016b
2017	Soy nut butter	*Escherichia coli* O157:H7	32	CDC, 2017
2018	Tahini	*Salmonella* Concord	8	CDC, 2018a
2018	Cereal	*Salmonella* Mbandaka	135	CDC, 2018b
2018	Dried coconut	*Salmonella* Typhimurium	14	CDC, 2018c
2019	Flour	*Escherichia coli* O26	21	CDC, 2019a
2019	Tahini	*Salmonella* Concord	6	CDC, 2019b
2021	Cake mix	*Escherichia coli* O121	16	CDC, 2021
2022	Peanut butter	*Salmonella* Senftenberg	21	CDC, 2022
2023	Flour	*Salmonella* Infantis	14	CDC, 2023a
2023	Dry dog food	*Salmonella*	7	CDC, 2023b

organic and inorganic residues from the equipment and food-contact surfaces. A surface not cleaned adequately will render the sanitization or disinfection step ineffective, since the soil residues will decrease the efficiency of chemical sanitizers by reacting with them (USDA APHIS, 2020). The cleaning and sanitization steps are very important in food manufacturing facilities to ensure the safety and quality of the finished products (Hasting, 1999). The food plants develop sanitation standard operating procedures (SSOP) for each component in the facility, where the steps for cleaning and sanitizing are clearly explained, implemented, and documented upon completion. The Code of Federal Regulations (CFR) title 21 part 117 by the FDA requires that all food-contact surfaces should be cleaned as frequently as needed to avoid microbial contamination (FDA, 2020a). Regulatory agencies in the United States do not set the cleaning frequency, and it is at the discretion of food manufacturers to ensure this is a frequency that will guarantee the safety of the food products while balancing productivity.

Undeclared allergens continue to be a major reason for recalls associated with the food products. Wang et al. (2010) studied the influence of different cleaning steps on the removal efficiency of wheat allergens in a chicken processing facility and suggested that adenosine triphosphate (ATP) bioluminescence could be used as an indicator of residual allergen (gliadin) on food-contact surfaces. In a survey of various manufacturers making food products with at least one allergen, cleaning procedures were identified as one of the most effective strategies for the control of allergen cross-contamination in their allergen control plan (Gupta et al., 2017). A study conducted by Bedford et al. (2020) found that the effectiveness of wiping and cleaning processes on the allergen removal was dependent on type and quantity of allergens present on a surface, the food-contact surface texture, and the composition of surface. Thus, an effective cleaning process should reduce the possibility of microbial cross-contamination in addition to the allergen cross-contamination.

4 | TRADITIONAL DRY-CLEANING METHODS IN THE FOOD INDUSTRY

The dry-cleaning methods are used when the addition of water might result in a microbial contamination or growth. If the process is done effectively, the dry-cleaning methods offer advantages over wet cleaning methods in terms of savings in time (drying), energy, water, and other cleaning chemicals (Moerman & Mager, 2016).

4.1 | Vacuum cleaning

Vacuuming is a well-known method for dry cleaning in food manufacturing facilities that make products like powders and flours. An image of a vacuum cleaner used for cleaning in the food industry is shown in Figure 1. This method can be used on either food-contact surfaces or non-food-contact surfaces like floors, walls, or ceilings. The advantage with vacuuming is that a larger surface area can be cleaned in a well-contained manner within a short time. Care must be taken to ensure that vacuum cleaners are maintained in a hygienic condition to minimize any microbial contamination (Moerman & Mager, 2016). The vacuum method will work when the surface is easily accessible and without any crevices or cracks. Any irregularity in the surface will adversely affect the cleaning efficiency of the vacuum cleaning method.

Vacuum cleaning systems may be central or portable in design, with each system having its own advantages and limitations (Moerman & Mager, 2016). The food industry uses both large central vacuum systems and small portable vacuum systems for dry cleaning. However, there is a preference in food facilities to employ portable vacuum cleaners even for larger cleaning areas to avoid any potential cross-contamination, especially when multiple allergens are involved in production (Jackson et al., 2008). This point was earlier emphasized by Cordier (1994), who recommended using designated vacuum cleaners for clean zones and unclean zones to avoid any cross-contamination from one area to another in chocolate manufacturing facilities, although the concept can be applied across the food industry in general. Jackson and Al-Taher (2010) compared

FIGURE 1 An image of vacuum cleaner used for cleaning in the food industry (courtesy Delfin Industrial Corporation).

the cleaning efficiencies of alcohol-moistened swabs and high-efficiency vacuum for selected food matrices (containing milk, soy, egg, and peanut) applied on different types of surfaces. When the foods were cooked to a temperature of 80°C for 1 h, the alcohol-moistened wipes removed the residues, whereas the vacuum cleaning could not remove the residues. The vacuum cleaning removed the uncooked deposits on the surface in visual observation, though more sensitive methods like ELISA detected the residues on the surface. The authors concluded that vacuum cleaning might not be appropriate for removal of allergenic residues from surfaces.

In another study to understand the dissemination of *Cronobacter* in a food plant, Mullane et al. (2008) extracted *Cronobacter* isolates from the environmental sampling of a production vacuum in a powdered milk protein facility, and the authors emphasized the necessity of containing any dust particles generated in the production process, including cleaning operations. The percentage of *Enterobacter sakazakii*-positive samples varied between 9% and 35%, when nine food factories were sampled for this strain, and one of the sampling points was vacuum-cleaner bags (Kandhai et al., 2004). The above studies show the importance of maintaining vacuum cleaners in a hygienic manner to avoid or minimize microbial cross-contamination in low-moisture food manufacturing facilities.

4.2 | Brushing and scraping

Brushing and scraping are simple methods that can be used primarily for low-moisture food manufacturing facilities. Both of them can be used in food-contact surfaces in addition to non-food-contact surfaces. The equipment used for manual cleaning must be inexpensive, durable, and ergonomically efficient. Cleaning tools and equipment like brushes and scrapers need to be cleaned and sanitized properly, so they do not become a source of contamination for pathogens like *Salmonella*. After use, they must be cleaned and sanitized according to written procedures (Todd et al., 2010). Damaged hand-held cleaning tools must not be used in a food manufacturing facility due to the possibility of missing parts ending up in packaged products (EHEDG, 2001).

If cleaning with brushes is not done properly, it will create a dust cloud in the facility (Smith & Holah, 2016). The accompanying dust might create both microbial and allergen cross-contamination. The sanitation program should have policies in place to prevent a microbial cross-contamination due to brushes used (Smith & Holah, 2016). One way to achieve this goal is to employ a color-coded system. In this system, a brush of a specific color is used only on specific areas or surfaces with certain allergens. For example, a white brush may be assigned for food-contact surfaces, while a blue brush can be designated for cleaning non-food-contact surfaces, such as floors and walls. The condition of the brushes must be periodically monitored and evaluated for their usefulness. The brushes must be discarded and replaced when they can no longer effectively clean a surface. Figures 2a and 2b show the color-coded long-handle and short-handle brushes, respectively.

Scraping is commonly employed in cases where the debris is strongly attached or adhered to a surface. Color-coded plastic and stainless-steel scrapers used for cleaning are shown in Figure 3. A scraper with a blade is pressed against the surface to detach the debris from the surface followed by collection of debris using a method like vacuum cleaning or brushing (Moerman & Mager, 2016). It is also important to make sure that the scrapers are not a source of contamination. The scrapers need to be cleaned and sanitized if they are reusable. In addition, implementing a color-coding system will help to segregate the scraper blades for specific areas and applications. The scraper blade may be made of plastic or stainless steel. The plastic scrapers are light in weight and safe for the employees to use in addition to being inexpensive. However, there is a potential for foreign material contamination if there is any breakage of plastic scraper blades. While not prone to breakage, stainless-steel blades might cause other issues such as scratching on the surfaces they contact (Moerman & Mager, 2016). The abrasive nature of stainless steel should be considered carefully, since a crevice in a food-contact surface might eventually serve as a substrate for pathogen harborage and growth. The employees using the stainless-steel scrapers must be trained properly to avoid any potential problems due to abrasion on the surface, since the cleanability is directly influenced by surface roughness (Moerman & Mager, 2016). One way to reduce the problems is to select scrapers based on the type of surface and soil that need to be cleaned. Middleton et al. (2003) recommended that the stainless-steel scrapers should be used for rough and raised surfaces, while the plastic scrapers can be used only on plastic surfaces. Employees must be trained to notice any abnormalities in scrapers like cracks or missing pieces and replace them on a needed basis. The facilities can also employ X-ray systems so that any pieces of plastic or metal from scrapers that end up in food products are detected in the process. Scrapers are more suitable for cleaning belts with a smooth surface, and the design of the scraper unit along with rake angle needs to be carefully considered in their design. The use of scrapers is not recommended when the belts have elevated structures like guides, side walling, and flights (Kold & Silverman, 2016).

The efficiency of cleaning by brushing and scraping can be influenced by many factors. Cleaning by brushing or scraping methods can be time consuming and costly and require disassembly of equipment (Vansant & Rogiers, 2019). The cleaning performance by brushing depends mainly on the approachable area for the bristles; if the bristles cannot reach the surface, the area will not be cleaned (Fuchs, 2015). Röder et al. (2010) evaluated the manual scraping method from an allergen cleanability perspective. The researchers found that using plastic scrapers alone did not remove the hazelnut allergen residue sufficiently, unless the scraping was followed by a cleaning with 52°C hot water. Very recently, researchers at Cornell University studied the efficacy of brushing and scraping as dry-cleaning methods in the removal of organic residues. Cleaning by scrapers was found to be more effective for

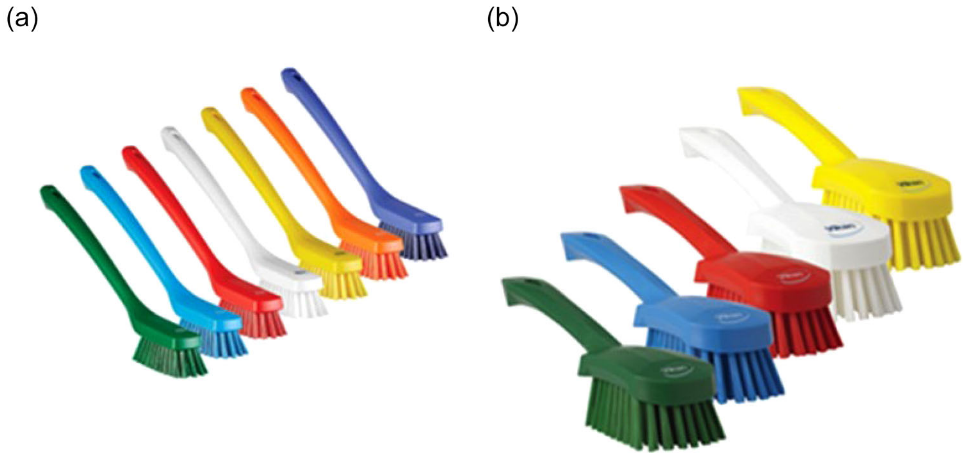

FIGURE 2 Color-coded brushes used in the food industry: (a) long handle and (b) short handle (courtesy Nelson Jameson).

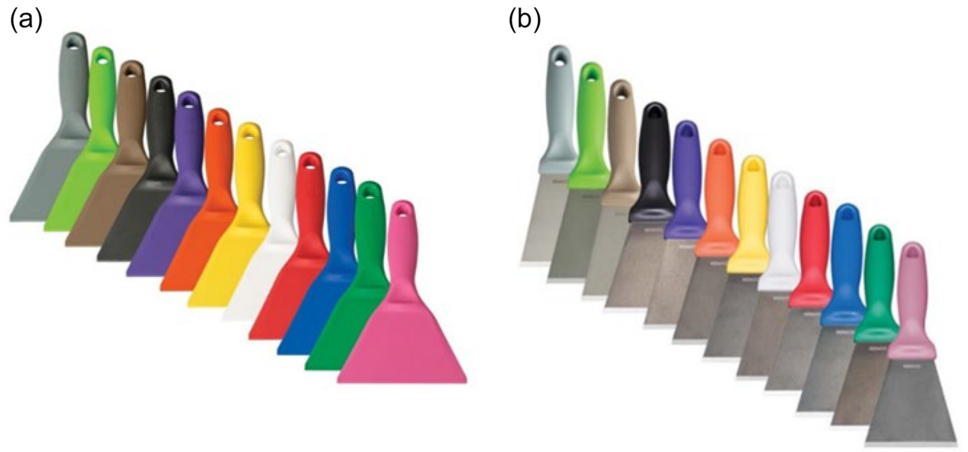

FIGURE 3 Color-coded scrapers used in the food industry: (a) plastic and (b) stainless steel (courtesy Nelson Jameson).

paste products like peanut butter compared to powder products like nonfat dry milk (Rana et al., 2022). A study conducted by Chen et al. (2022) concluded that although efficacy depended on the food matrix and environmental conditions, neither method consistently provided allergen removal. The study found that brushing was more effective than scraping for the removal of proteins in nonfat dry milk and wheat flour samples from a stainless surface. They also noticed a significant effect of particle size in addition to its interaction with surface roughness, although the effect of roughness itself was not statistically significant in cleaning. They suggested a combination of scraping to clean a string adhesive layer followed by brushing to improve the efficiency. In a similar study using brushing as a dry-cleaning method, He et al. (2022) found that the role of water activity was significant in the removal of fruit powder deposits from a stainless-steel surface. The cohesion and adhesion of fruit powders directly influenced the cleaning outcome, which also depended on the physicochemical properties of fruit powders (He et al., 2022). The findings from the above studies emphasize that the application of brushing and scraping as dry-cleaning methods must be considered carefully.

4.3 | Dry ice blasting

The dry ice is the solid carbon dioxide with a sublimation temperature of −78°C in atmospheric pressure (Máša et al., 2021). In the dry ice blasting, compressed ice pellets are sprayed at a high velocity (around 100 m/s) on the surfaces contaminated with food residue. Due to microthermal shock, the contaminated layer is detached from the surface as seen in Figure 4. Sodium bicarbonate or calcium carbonate is used as an additive with dry ice to increase the porosity of the soil and facilitate the removal of the

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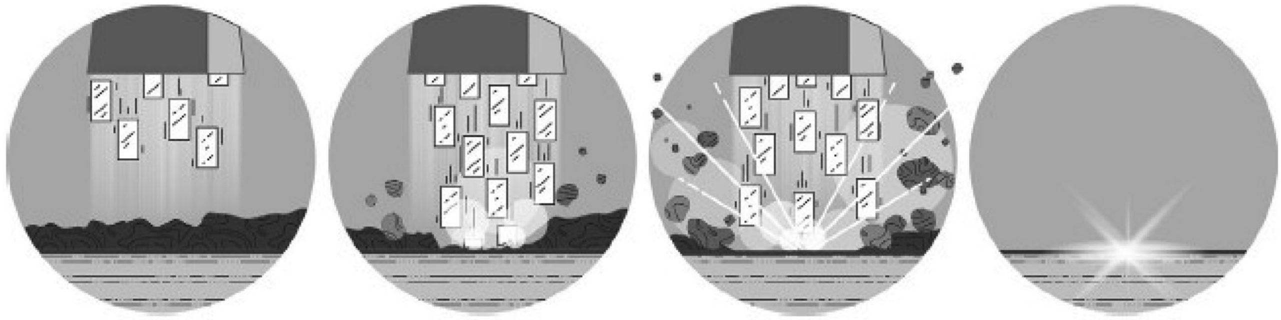

FIGURE 4 Schematic of dry ice blasting (from Vansant & Rogiers, 2019).

soil from the surface (Moerman & Mager, 2016). Dry ice, a food-grade medium, has been approved by various federal agencies in the United States, like the FDA, the USDA, and the Environmental Protection Agency (EPA). As an environmentally friendly technology, dry ice blasting is commonly used in industries such as food, automotive, and machinery (Máša & Kuba, 2016).

The dry ice cleaning method has been studied extensively. Liu et al. (2011) studied the dry ice cleaning effectiveness of a surface contaminated with micron- and submicron-sized particles and showed a satisfactory performance. The authors also noted that the cleaning effectiveness increased with an increase in jet pressure. In a similar study, Witte et al. (2017) found that cleaning efficiency of dry ice blasting was affected by the pressure and quantity of solid CO_2. Although the authors achieved some bacterial reduction from the contaminated surfaces, they cautioned against the use of dry ice blasting as a potential disinfection method due to reaerosolization of bacterial cells removed from the surface. Akkara and Kayaardi (2013) evaluated the disinfection efficiency of dry ice cleaning on poultry carcasses and showed a 1- to 2-log reduction in the mesophilic aerobic bacterial count. With dry ice decontamination method, Uyarcan and Kayaardı (2018) showed a 3.92-log reduction in total aerobic mesophilic bacterial count of surface swabs. In addition, the authors noticed a complete elimination of *Salmonella* ssp., though they detected *Listeria* spp. on surfaces of pluckers and chiller cylinders. They observed an improved efficiency of dry ice with spraying method over the immersion method and suggested the potential of dry ice decontamination in the poultry industry.

Significant savings in time and cost have been reported due to the use of dry ice blasting in the food industry. The cleaning time for a bagging area was reduced from 96 h to 5 min in a bakery. An estimated savings of $17,979 per month in labor costs was noted for a snack food manufacturing plant. Similarly, by employing dry ice blasting, the bottling plants could save around $6000 per month due to reduced downtime for cleaning and corresponding labor costs (Vansant & Rogiers, 2019). Cost and energy savings need to be considered when implementing any new technology in the manufacturing process. A compressed air system accounts for majority of energy consumption in the dry ice blasting technology, and thus, there should be an efficient way to make this technology less energy intensive. Máša and Kuba (2016) studied the energy consumption of different components in dry ice blasting. They recommended a replacement of pneumatic motor by an electric motor in addition to a supplementation with an efficient compressor, which in turn will save 38% energy for a block shaving system. Similarly, replacing a conventional nozzle with a centrifugal separator and adding an efficient compressor would reduce the energy consumption of dry ice technology by 87% (Máša & Kuba, 2016). However, these savings are only theoretical estimates based on calculations. In a similar study, Dzido et al. (2021) analyzed the operational costs related to the dry ice technology. The authors estimated that the cost of dry ice alone accounted for 70.63%–77.22% of total cost, whereas employees accounted for 19.84%–23.81%. The remaining portion (less than 7%) was attributed to compressed air (Dzido et al., 2021).

Both merits and demerits should be considered while using the dry ice blasting technique in the food industry. The dry ice cleaning method is environmentally friendly since the dry ice evaporates at room temperature and leaves no harmful residues (nontoxic). This technology has an advantage over the use of water (when a lot of electrical components are involved) and cleaning chemicals that might create problems in the management of waste disposal. In some circumstances, dry ice blasting is faster compared to conventional cleaning with labor and thus improves the productivity (Marlowe, 2018). However, the capital investment with dry ice blasting can be high. There may be some safety concerns associated with the dry ice blasting. The cleaning employees are exposed to unfavorable conditions like high pressure and noise levels along with an increased concentration of CO_2 in the surrounding air due to the sublimation of dry ice (Otto et al., 2011). These

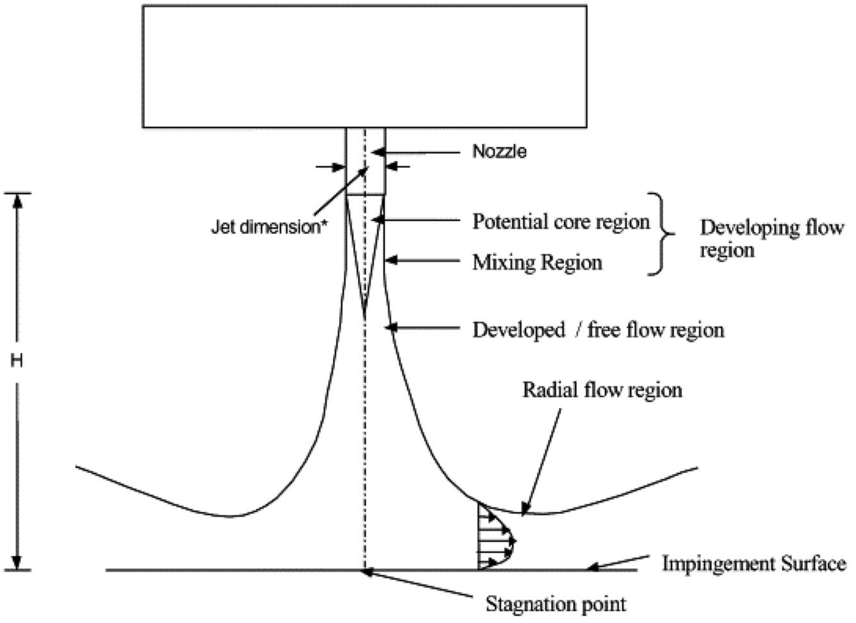

FIGURE 5 Regions under impinging air jet (from Sarkar & Singh, 2004).

safety issues need to be considered with dry ice blasting as a cleaning method in food manufacturing facilities.

5 | POTENTIAL FOR AIR IMPINGEMENT AS A DRY-CLEANING METHOD

Air impingement is a technology in which high velocity air jets (10–100 m/s) impinge on a surface to increase the heat transfer rate. This method is widely used in applications such as drying, baking, and freezing in the food industry (Ovadia & Walker, 1998; Sarkar et al., 2004). Some of the factors like exit velocity at the nozzle, design of nozzle, equipment design, and boundary layer conditions affect the efficiency of an air impingement application (Sarkar & Singh, 2004). The different regions under the air impingement jet are shown in Figure 5. Many studies have been conducted regarding air impingement from a heat transfer point of view (Arganbright & Resch, 1971; Arik et al., 2013; Cronin et al., 2008; Ekkad & Singh, 2021; Erdogdu et al., 2007; Jafari & Alavi, 2008).

The air impingement technology has the potential to be used as a dry-cleaning method in the food industry. In a typical application, the air impingement is applied perpendicular to a surface, and this impinging air has a high velocity that creates a shear stress parallel to the surface. This shear stress at the surface generates the mechanical energy needed to remove residues or deposits. The removal of the deposits from the surface using air jet impingement is influenced by the velocity of the impinging air jet, diameter of the nozzle, nozzle-to-surface distance, and impinging angle (Leung et al., 2017). When the air jet velocity is high or the nozzle-to-surface distance is small, the resulting shear stress on the surface will be high. According to Keedy et al. (2012), the particle removal by the air jet impingement was dependent on factors like the particle, type of surface, and properties of the air jet. The impinging high-velocity air jet on a solid surface generates a tangential flow with a thin boundary layer, and this results in high shear stresses on the impinging surface. The force created by the high shear stress on the particles could possibly overcome the adhesive forces attaching the particles to the surface as well as the particles' own weight and suspend them in the gas stream (Keedy et al., 2012). The impinging air jet must overcome both the cohesive and adhesive forces to efficiently clean the surface.

The FDA allows the use of compressed air for cleaning in food manufacturing facilities. According to the 21CFR117.40, "compressed air or other gases mechanically introduced into food or used to clean food-contact surfaces or equipment shall be treated in such a way that food is not contaminated with unlawful indirect food additive" (FDA, 2020a). The compressed air must be treated so that it is free of microorganisms by properly filtering the incoming air. The compressed air should be periodically checked for bacteria, yeast, and mold.

There have been few studies conducted on the use of air jet impingement as a cleaning technique. In an earlier study by Otani et al. (1994), the authors examined the use of pulsed air jet impinging from a rectangular nozzle on removal of 0.25- to 3-μm polystyrene latex (PSL) particles on a silicon wafer and noted that air jet was able to remove the smallest particles instantly from the wafer surface. Bayoudh et al. (2005) studied the influence of air jet impingement on the removal of *Pseudomonas stutzeri* from surfaces of different hydrophobicity. Fletcher et al. (2008) compared the removal efficiencies of air jet impingement for muslin cloth and polycarbonate surfaces using particles of different sizes. Although the release rate for both the surfaces is similar, the removal efficiency was affected by the particle size, in which the larger particles were easier to remove than finer particles. Leung et al. (2017) studied the effect of air jet impingement on the removal of micrometer- and millimeter-sized droplets from a plastic surface. The authors suggested that air jet cleaning of liquid droplets might be different from that of solid particles.

There are some possible concerns associated with the air impingement technology for use in the low-moisture food manufacturing industry. The cleaning mechanism is primarily governed by the wall shear stress generated by the impinging air jets. The estimation of wall shear stress varies based on location and it can be complicated depending on the geometry of the surface under consideration. Since the removal efficiency can be impacted by many factors, the technology needs to be flexible based on the environment. For example, the wall shear stress needed for removal of milk powder deposits at a 50% relative humidity (RH) might be higher than those at 30% RH. Thus, an improper design of an air impingement system will result in an ineffective cleaning of a surface. Moreover, there is a possibility of creating aerosolized powders that can result in cross-contamination of different parts of the facility. A system must be in place to reduce or capture all aerosolized components resulting from air impingement cleaning.

6 | CONCLUSIONS

Continued outbreaks associated with low-moisture foods are a concern for the food industry. The challenge of maintaining a dry manufacturing environment is unique. In addition to food-contact surfaces, it is essential to keep the manufacturing environment (floors, walls, and ceilings) in a hygienic condition to eliminate any possibility of cross-contamination. A well-written and properly implemented sanitation program is one of the key components for this purpose, and the cleaning process is an essential component of the program. The cleaning process is complex and is influenced by many factors, such as time, temperature, mechanical action, and cleaning chemistry. Currently, operations like vacuuming, brushing, scraping, and dry ice blasting are used as cleaning methods in low-moisture food manufacturing facilities. Each of these methods in the industry offers some advantages along with some limitations as well. While these methods have been practiced in the food industry for a long time, there is always a room for innovation. It is important to recognize that food safety depends on an effective cleaning process. Air impingement technology has the potential to become an effective dry-cleaning method. Further research is needed to ensure the efficiency of this technique from a cleaning point of view and as a precursor to the sanitization step.

AUTHOR CONTRIBUTIONS

Veeramani Karuppuchamy: Conceptualization; methodology; writing—original draft. **Dennis R. Heldman**: Supervision; funding acquisition; resources; writing—review and editing. **Abigail B. Snyder**: Funding acquisition; resources; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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