PEER-REVIEWED ARTICLE

Food Protection Trends, Vol 43, No. 2, p. 126–143
https://doi.org/10.4315/FPT-22-023

2900 100th Street, Suite 309, Des Moines, IA 50322-3855, USA

Susan M. Leaman,[1*] Justin Kerr,[2] Sonia Salas,[3] Afreen Malik,[3] Trevor V. Suslow,[4] Martin Wiedmann,[5] and De Ann Davis[3]

[1]iDecisionSciences, LLC, Bellevue, WA 98009, USA
[2]Factor IV Solutions, LLC, Atascadero, CA 93422, USA
[3]Western Growers, Irvine, CA 92618, USA
[4]University of California–Davis, Davis, CA 95616, USA
[5]Cornell University, Ithaca, NY 14853, USA

Fresh Produce Harvesting Equipment – A Review of Cleaning and Sanitizing Practices and Related Science

ABSTRACT

During produce harvesting operations, various types of tools, equipment, and containers have direct contact with crops. Best practices for harvesting equipment include routine cleaning and sanitation of food-contact surfaces and areas adjacent to food-contact surfaces. Studies investigating transfer of human pathogens to produce during harvesting operations have revealed numerous crop-contact points with the potential to serve as conduits for pathogen transfer, including harvesting machinery, knives, conveyors, cutting boards, harvest bins and cartons, and cleaning equipment. When these surfaces are contaminated with human pathogens, the pathogens can be transferred to crops during harvesting activities. Minimizing and controlling microbial hazards to prevent contamination of produce during harvesting operations in both indoor and outdoor settings presents challenges that require a transformative level of risk awareness and vigilance from all involved in management and operations. Although new technologies are being explored to improve equipment cleanability, prevention combined with robust cleaning and sanitizing methods remain the most critical maintenance aspects of harvesting equipment that is at low risk for contamination. As part of the produce industry's continuous efforts to enhance the safety of harvested fresh produce crops, this review summarizes scientific findings that harvesting equipment operators can utilize to evaluate and further inform current cleaning and sanitation practices.

INTRODUCTION

In the 1998 *Guide to Minimize Microbial Food Safety Hazards for Fresh Fruits and Vegetables* from the U.S. Food and Drug Administration (FDA) *(166)*, the agency named harvesting machinery, knives, containers, tables, baskets, packaging materials, brushes, buckets, etc., as field equipment that "can easily spread microorganisms to fresh produce" and recommends keeping harvesting and packing equipment "as clean as practicable." Those early minimal recommendations for cleaning field equipment were expanded to more extensive requirements under the federal Food Safety Modernization Act following the 2015 finalization of the FDA's *(168)*

*Author for correspondence: Phone: +1 206.498.2825; Email: susan@idecisionsciences.com

Standards for the Growing, Harvesting, Packing, and Holding of Produce for Human Consumption (the Produce Safety Rule). Subpart L of the Produce Safety Rule addresses equipment and tools "that are intended to, or likely to, contact covered produce; and those instruments or controls used to measure, regulate, or record conditions to control or prevent the growth of microorganisms of public health significance. Examples include knives, implements, mechanical harvesters, waxing machinery, cooling equipment (including hydrocoolers), grading belts, sizing equipment, palletizing equipment, and equipment used to store or convey harvested covered produce (such as containers, bins, food-packing material, dump tanks, flumes, and vehicles or other equipment used for transport that are intended to, or likely to, contact covered produce)." Requirements address equipment and tool design, construction, workmanship, installation, maintenance, storage, and inspections as well as cleaning and sanitation. On a global level, the 2003 *Code of Hygienic Practice for Fresh Fruits and Vegetables,* the Codex Alimentarius *(36)* incorporates routine cleaning and sanitizing of food-contact surfaces into their recommendations for the primary production of fresh produce. Within the industry, commodity groups have developed commodity-specific food safety guidelines in which best practices address cleaning and sanitizing of equipment used in the field.

Since the 1990s, as evidenced by the aforementioned food safety guidelines and standards, equipment has been recognized as a potential conduit for pathogen transmission from the environment to fresh produce. However, equipment had often received less scrutiny than other means of microbial cross-contamination in the field until recent circumstances brought renewed attention to field equipment cleaning and sanitation practices. During a foodborne illness outbreak attributed to *Listeria monocytogenes* contamination of prepackaged salads, swab samples taken from equipment surfaces and internal framework used to harvest lettuce contained in the mixes tested positive for this pathogen. Genetic analysis of *L. monocytogenes* isolates from equipment samples revealed a match with the outbreak strain isolated from patients affected by this outbreak *(30)*.

As noted above, various types of tools, equipment, and containers have direct contact with crops during produce harvesting operations *(44, 110, 158)*. Many produce commodities (e.g., fruit, vegetables, and nuts) are harvested with hand-held tools and placed by hand into containers or onto mechanized harvest-aide equipment surfaces or conveyer belts *(45, 135, 161, 188)*. However, use of mechanical and/or automated harvesting equipment is becoming increasingly necessary and attractive, driven primarily by challenges in labor availability that have affected the industry's ability to harvest product in a timely fashion or to its full productivity per acre. In addition to equipment and tools used to separate product from the remaining plant and roots, harvesting operations may also involve crop contact with auxiliary accumulation and transport equipment and implements such as bins and cartons *(87, 103, 125, 146, 157)*, cloths used to wipe harvested product *(151)*, and workers' hands or gloves *(19, 52)*. For numerous produce commodities such as head lettuce, berries, and cantaloupe, it is a common practice to pack harvested product into retail-ready packaging (e.g., plastic clamshells, bags, or cartons) in the field. Berries are placed directly into consumer units (clamshells) of various sizes by individual workers. Field-packed cantaloupes are generally placed on a conveyor, distributed on a large mobile packing platform for size grading, and placed in single-use corrugated fiber cartons or reusable packaging containers. For diverse leafy greens, harvested product is typically placed on individual packing station platforms or a common conveyor and may be further trimmed by machine or hand-held tools and sprayed with water containing a minimal amount of an antimicrobial and antibrowning agent before being packaged or packed for transport. Equipment used in these activities includes various types of food-contact surfaces (e.g., blades, bands, conveyors, tabletops, and cutting boards) constructed with a variety of materials such as plastics, silicone, rubber, textiles, or metal. Many of these food-contact surfaces have components that are difficult to clean, due to either their design and construction (e.g., niches or places that are hidden or unreachable) or the wearing or corrosion of materials (e.g., formation of grooves or cavities) *(57)*.

For some commodities and/or growing regions, preharvest, harvest, and postharvest operations are fully integrated within a company, whereas for other commodities or growing regions these activities are segregated among several contractors. During harvest season, harvesting equipment use is highly dynamic; equipment is frequently moved between fields within a ranch, among crop owners (as defined by business contracts), and even among growing regions as production shifts with seasonal changes. Because of these supply chain and business structure complexities, cleaning and sanitizing activities can often be a daily or even split-use day logistical challenge. Beyond decisions regarding when to clean, decisions about cleaning methods, cleaning location and frequency, and even next-day preoperational recleaning also present significant challenges to equipment operators. This review includes a discussion of current industry practices, the food safety hazards related to equipment and tools used during produce harvesting and field packaging or packing activities, and the subsequent food safety risk to harvested produce within and between lots and farms when harvesting equipment and tools become contaminated. The objective of this review was to compile and summarize relevant research and synthesize relevant findings to broaden awareness of and enhance the use of best practices for produce harvesting equipment cleaning and sanitation.

HARVESTING EQUIPMENT

Current cleaning and sanitation practices

Routine cleaning and sanitizing of harvesting and field-packaging or packing utensils, tools, and equipment (which typically is conducted daily) are practiced by fresh produce harvesting operations as an essential component of good agricultural practices *(36, 62, 80, 179)*. Studies investigating cleaning and sanitizing techniques for various types of equipment used in food processing and manufacturing facilities are plentiful in the literature. However, publicly available evaluations of cleaning and sanitizing methods and techniques for equipment used to harvest and pack produce in the outdoor field setting are limited. Most published information describing cleaning and sanitizing methods for harvesting equipment comes from the cooperative extension system operated through U.S. land grant universities in partnership with federal, state, and local governments *(25, 76, 131, 143, 153)*. Many of these resources provide valuable, practical information and guidance on choosing a sanitizer product and appropriate product concentrations, mixing and applying chemical sanitizers, verifying labeled or selected doses, calibrating application equipment, and identifying niches and difficult-to-access equipment areas that may harbor pathogens.

Current routine cleaning and sanitizing practices for harvesting equipment generally follow a four- or five-step process and may occur in the cropped field itself or, in some cases, on perimeter farm roads. Cleaning includes activities such as removal of debris and residual cull product; application of cleaning agents (e.g., detergents); brushing, scrubbing, or wiping; and medium- to high-pressure spraying with water multiple times *(141)*. Solutions used during cleaning activities may include detergents, surfactants, water conditioners, and sanitizers or disinfectants *(25, 131, 141, 143, 153)*. Routine cleaning activities typically focus on visible and readily accessible surfaces that have direct contact with product or are adjacent to product-contact surfaces *(20)*. Within the context of this review, adjacent areas on harvesting equipment include many locations, especially on mobile harvesting and field-packing equipment, that are in close proximity, next to, or above food-contact surfaces during actual harvest operations, during preoperational staging, or during location-to-location movement. Examples include support footings, ladders next to conveyors, and various hoses and quick-connect couplers. During movement, staging at fields, and daily harvest operations, these surfaces are often sites of soil accumulation and may be very close to or overhang food-contact surfaces. At the end of each harvest pass within a field, the rough ground and rocking motion of the harvest unit as it maneuvers may cause this soil and crop residue to fall onto food-contact areas. On occasion, the forces on the structure may also be strong enough to cause water that is trapped in hollow spaces and may contain *Listeria* to leak out and potentially contaminate these surfaces during a daily operation.

Harvesting equipment cleaning is typically followed by sanitizing of food-contact and adjacent non food-contact surfaces, which may or may not be followed with a final rinse. "To sanitize" is defined in the U.S. Code of Federal Regulations *(35)* as "to adequately treat food-contact surfaces by a process that is effective in destroying vegetative cells of microorganisms of public health significance, and in substantially reducing numbers of other undesirable microorganisms, but without adversely affecting the product or its safety for the consumer." Following cleaning, harvesting equipment is sanitized by spraying or wiping with chemical sanitizers such as ammonium- or chlorine-based products. Nonchemical methods such as UV light and thermal techniques may also be used to sanitize equipment surfaces *(118, 141, 143)* but are not typical for mechanized harvesting and mobile field-packing equipment, including robotic harvest aides.

In addition to harvesting in the outdoor environment, cleaning and sanitizing of food-contact surfaces and adjacent areas on harvesting equipment also play prominent roles in food safety for produce grown in hoop or shade houses and in controlled environment agriculture facilities. Following a *Salmonella* Typhimurium outbreak at a controlled environment agriculture operation in summer 2021, in their investigation report the FDA *(169)* recommended improved procedures for cleaning and sanitizing equipment. Research conducted in shade-house produce production operations investigated bacterial transfer from contaminated produce crops to bins and clippers used in harvesting, and bacteria were recovered from bins and clippers up to 8 days after inoculation *(127)*. Because of the indoor setting, controlled environment agriculture systems do not have the benefit of UV light exposure and may require enhanced vigilance during cleaning and sanitation of harvesting equipment to avoid contamination.

Pathogens posing a contamination risk to harvesting equipment in the field

Numerous studies of human pathogens in various produce growing regions have revealed their presence and, in some instances, persistence in produce growing environments *(1, 12, 38, 64, 66, 68, 154, 155, 163, 178, 190)*. In their review of foodborne illness outbreaks occurring from 2010 through 2017, Carstens et al. *(28)* reported 228 outbreaks, 85 of which were multistate outbreaks in which fresh produce was the confirmed source of contamination. Pathogenic bacteria involved in the multistate outbreaks attributed to fresh produce consumption included Shiga toxin-producing *Escherichia coli* (STEC), *Salmonella*, and *L. monocytogenes* *(28)*. Of these three pathogens, *L. monocytogenes* is of major concern because of its ubiquitous presence and ability to survive and grow in the agricultural environment under conditions that are hostile to competing microorganisms (i.e., low water activity, wide pH range, and low temp-

eratures) *(26, 163, 190)*. *L. monocytogenes* is a facultative anaerobe that occurs naturally in the environment in soil and on plants and in the intestines of humans, other mammalian species, and birds *(32, 100, 104, 107, 147, 163, 165)*. Although not directly informative to the prevalence of *L. monocytogenes* in specialty crop production soils, Liao et al. *(100)* detected *Listeria* spp. in 31% of 1,004 soil samples in a survey of U.S. topsoil taken from natural environments that are minimally disturbed by human contact.

A systematic review of studies investigating *Listeria* spp. and *L. monocytogenes* prevalence and persistence in the produce supply chain revealed the greatest prevalence of *Listeria* spp. in outdoor production and natural environments *(163)*. Investigations of the produce production environments in New York State reported more frequent isolation of *L. monocytogenes* and *Listeria* spp. than of *Salmonella* and STEC *(155)*. In New York State, *Listeria* isolation in the produce production environment was highly associated with soil moisture and proximity to water and pastures *(32)*. Gorski et al. *(64)* tested environmental samples from San Benito and Monterey Counties, California (a major produce growing region) for *Salmonella* prevalence and found that 2.6% (16 of 617) of soil and sediment samples were positive for this pathogen. In another study, 5% of 2,460 samples of manure-amended soil taken from 19 organic farms in California, Maine, Maryland, and Minnesota tested positive for *L. monocytogenes (130)*. In their study of five farms in New York State, Strawn et al. *(155)* reported finding STEC at approximately equal frequency in soil, water, feces, and drag swabs, whereas *L. monocytogenes* and *Salmonella* were detected more frequently in water samples. A study of *L. monocytogenes* distribution within a single farm in New York State revealed that the pathogen persisted on or was repeatedly introduced to the farm over the course of the growing season *(68)*.

Risk factors for pathogen transfer to and persistence on harvesting equipment in the production environment

Although studies surveying the microbial condition of food-contact surfaces in the outdoor production environment have not been published, studies that included surveillance and monitoring of food-contact surfaces in produce packinghouses have revealed pathogen survival on inanimate surfaces in indoor environments *(53, 94, 116, 137)*. When considering the potential for cross-contamination of product from contaminated equipment surfaces, the microbial hazards in the field may have overlapping similarities to those encountered in controlled environment agriculture and indoor manufacturing and processing environments. However, equipment may be differentially exposed to microbial hazards in indoor and outdoor environments. Microbial hazards in the outdoor environment differ from those in indoor environments primarily in exposure frequency and a reduced ability to control exposure or provide protection. In addition to more frequent contact with and less control over contamination sources in the outdoor setting, surfaces of equipment used outdoors also have increased exposure to environmental conditions such as radiation and desiccation that may adversely affect human pathogen survival and persistence *(95, 149, 163, 181)*.

Environmental conditions

When equipment comes into contact with pathogen-contaminated soil, plants, water, insect vectors, bioaerosols, etc., and is not properly cleaned and sanitized prior to subsequent use, pathogens may persist or grow and can be transferred to harvested crops *(21, 93, 144, 162)*. Depending on the environmental conditions such as temperature, the availability of moisture, and presence of organic matter, human pathogens can survive on field equipment surfaces for varying lengths of time *(111, 181, 182)*. Among potential sources of contamination for harvesting equipment, animal feces, soil, and plant debris appear to be the primary ones *(12, 77, 126, 155)*. Contaminated water *(1, 13, 38, 50, 66, 164, 177)* or detergents *(33, 142, 187)* used in cleaning activities also pose a contamination risk for equipment, as do cleaning tools, which may be contaminated *(148)*. When harvesting equipment is stored outdoors between uses, additional opportunities exist for contamination due to climatic factors such as wind blowing dust onto the equipment or due to contact with various pathogen carriers (e.g., rodents and other pests). Wind may transfer contaminants to equipment in the production environment, and an understanding of normal wind direction and speed can allow harvesters to determine whether unusual circumstances warrant additional preventive measures. When equipment is stored in proximity to animal feeding or holding operations, even small-scale operations, flies may be attracted to the harvesting equipment, especially when crop residues and water remain between uses.

Although some human pathogens such as *L. monocytogenes* are ubiquitous in the environment, others are normally not prevalent but are introduced to cropland soil by manure amendments, animal feces, or flooding *(14, 71, 81, 82, 122, 127, 185)*. Numerous field studies have revealed that pathogens may persist in soil for extended periods of time *(81, 82, 122, 185)*. Depending on field conditions and soil type, soils may encrust equipment in varying degrees during harvesting, and contaminated soil can introduce pathogens onto harvested product.

Risk factors for isolation of *Listeria* spp., *Salmonella*, and pathogenic *E. coli* in soil include soil type, soil properties, soil amendments, temperature, wind speed, animal presence, proximity to water, precipitation, and irrigation *(10, 68, 78, 83, 85, 101, 102, 105, 113, 119, 123, 124, 126, 127, 129, 133, 177, 178)*. Environmental conditions may also affect pathogen survival. Wind and high temperatures may desiccate pathogens on food contact surfaces, affecting their ability to survive *(94, 181)*. Other environmental conditions

such as freeze-thaw cycles and low nutrient availability also affect pathogen survival *(83, 120, 170)*.

Bardsley et al. *(10)* reported that *Salmonella* survived longer in clay-loam soils than in sand-loam soils. When manure was applied to produce farms in New York State within 1 year before sampling, *L. monocytogenes* was detected significantly more often in terrestrial (soil and drag) samples than in fields where manure was never applied *(177)*. In a 2-year survey of manure-amended soil from 19 organic produce farms in California, Maine, Maryland, and Minnesota, 1 (0.04%) of the 2,460 samples was positive for *E. coli* O157, 7.3% were positive for non-O157 STEC, 1.1% were positive for *Salmonella*, and 5.0% were positive for *L. monocytogenes (130)*. Twenty-five percent of soil samples taken from Iowa fields were positive for *Salmonella* 1 year after application of contaminated poultry manure *(71)*. Soil samples collected from West Coast fields in which sheep grazed on cover crops contained *E. coli* strains closely related to strains isolated from sheep fecal samples and were detected through 139 days postgrazing *(126)*.

The presence of nearby sources water or water from rainfall or irrigation also can influence *L. monocytogenes* isolation in produce fields *(68, 129, 176–178)*. Pires et al. *(129)* reported that increased soil moisture and precipitation were associated with higher levels of *E. coli* in manure-amended soils on organic produce farms. The odds of detecting *L. monocytogenes* in soil samples collected from spinach fields on New York State farms were 25 times greater at 24 h after a rain or an irrigation event than at 6 to 8 days after such events *(178)*. Terrestrial samples taken from New York produce farms within 3 days of irrigation were 27 times more likely to be positive for *L. monocytogenes* than were samples taken 10 days after irrigation *(177)*. In a study of *L. monocytogenes* distribution in two fields on a New York State produce farm, the likelihood of isolating the pathogen increased for soil samples as proximity to streams increased and for drag samples when samples were collected within 5 days of rainfall *(68)*. These findings suggest that wet soils have a higher probability of pathogen presence following precipitation or irrigation. Thus, the potential for contamination increases for such equipment as heavy mechanized harvesters (i.e., used for tender leaf commodities) that may sink in the furrows and contact the soil on the planted bed. Enhanced cleaning and sanitation procedures should be considered after events that introduce moisture because these conditions are associated with increased soil deposits on equipment.

Equipment design, construction, and surface cleanability

Three features of equipment that have an impact on a pathogen's ability to persist are the design, construction materials, and surface cleanability. These three features are interdependent both in how they relate to each other and in how they affect the microbial safety of equipment used in produce harvesting operations. How equipment and tools are designed and constructed affect the likelihood of attachment or entrapment of pathogens and subsequent persistence or growth on equipment surfaces *(29, 108)*. Food safety guidelines have typically provided guidance addressing how design and construction of equipment used in a packing or processing facility affect the microbial safety of produce *(80, 166, 167, 179)*. The majority of published academic studies have been focused on equipment design and construction and the steps needed when food processing and packing equipment used in facilities becomes contaminated and leads to cross-contamination of product *(17, 26, 29, 98, 137, 144)*. Although food safety is most certainly taken into account by equipment manufacturers, any food safety research related to harvesting equipment design, construction, and cleanability typically has been conducted in-house by food companies and/or the equipment manufacturers and has not appeared in peer-reviewed publications. However, although produce harvesting equipment is used differently and in different settings compared with food processing equipment, much relevant information can be obtained from studies on how equipment design and construction affects equipment cleanability and, ultimately, the microbial safety of the food *(108)*.

Equipment design

Of all the equipment and tools used in produce harvesting, hand-held tools used to cut and trim produce crops have been the most frequently studied. In particular, the device used to harvest and field core head lettuce has been the subject of several studies *(45, 161, 188)*. During field coring of lettuce, the core is cut out of the lettuce head with a knife that has a flat cutting blade at one end and a coring ring at the other end. This practice was first introduced in the 1990s to reduce costs by removing waste product in the field before transport and processing. To evaluate pathogen transfer from contaminated soil to lettuce via the field coring knives, Taormina et al. *(161)* inoculated the knives by exposing them to soil containing two levels of *E. coli* O157:H7 (2.72 and 1.67 log CFU/g). After inoculation, the contaminated knives were used repeatedly to cut and core 10 lettuce heads, resulting in *E. coli* O157:H7 transfer to 10 and 5 consecutively cored heads for the two bacterial levels, respectively.

In two other studies, Dev Kumar et al. *(45)* and Zhou et al. *(188)* further explored the contamination of field coring knives that were being used by industry at that time. In both studies, rough welding joints on commercially available knives provided a favorable site for bacterial pathogen attachment. Once attached, bacterial cells were resistant to removal with a chlorine solution, a sanitation step commonly used by industry. Both groups of researchers designed and constructed modified coring knives, creating prototypes without a welding joint or with a smoothed, polished welding joint between the cutting blade and the coring ring.

When subjected to the same contamination and subsequent sanitation as used for the commercially available knives, the prototypes retained significantly less *E. coli* O157:H7 between the cutting blade and the coring ring than did the commercially available knives with the rough welding joint. These findings are consistent with studies in which enhanced bacterial attachment to weld zones on food processing equipment was found *(29, 106)*.

Concerns about problematic construction such as roughness and fractures of welding joints also apply to other harvesting equipment such as mechanized harvesters and field-packing platforms. The Produce Safety Rule requires seams on food-contact surfaces of equipment to be either "smoothly bonded or maintained to minimize accumulation of dirt, filth, food particles, and organic material" *(168)*. Other design features such as right angles and hollow structures (e.g., legs, conveyors, and framing) add difficulty to cleaning and may harbor pathogens when water and debris are collected in these structures *(17, 167)*. In 2021, a study on the deep cleaning of harvesting equipment was conducted by a select group of produce processing and harvesting companies in collaboration with industry organizations and academic extension faculty and facilitated by an industry vendor *(37)*. The study findings included several areas on a mechanical harvester (e.g., difficult-to-reach and hidden locations beneath belts, cog wheels, framework, cutting surfaces, bearings, support components, and tunnel flaps) as "at-risk" for contamination that would benefit from hygienic design improvements. The study authors called for more testing and further coordination between harvesting operations and equipment manufacturers "to enhance hygienic design and sanitation processes."

Materials used in construction

Equipment used in harvesting fresh produce may be constructed with a variety of materials such as stainless steel, aluminum, plastics, wood, textiles, silicone, and rubber. Many of these materials have been the focus of research on the ability of human pathogens to survive on surfaces *(29, 31, 43, 58, 72, 94, 111, 136, 171, 181)*. The properties and characteristics of materials impact pathogen survival on food-contact surfaces, especially the ability to form biofilms *(89)*.

Wood has generally been considered more conducive to pathogen survival, especially in moist and/or soiled conditions, than other surfaces such as stainless steel *(9, 181)*. Over the past several decades, the produce industry has moved away from the use of wood to construct rigid, solid food-contact surfaces in favor of other materials, including metals and plastics. Collectively the research related to the microbial safety of wood is inconclusive, as revealed in an extensive review by Aviat et al. *(2)*. These authors cited numerous studies comparing wood and plastic cutting boards that produced conflicting findings regarding microbial counts over time under various conditions. In a study of *E. coli* transfer from wood, corrugated fiberboard, newly manufactured plastic, and reused plastic to apples, wood performed better than did the other three materials for limiting both pathogen survival on the material and transfer to the apples *(3)*. In a study comparing *E. coli*-contaminated onions held in either wooden or plastic storage containers, no detectable *E. coli* was found on onions after 6 weeks of storage, leading the investigators to conclude that no difference in inherent risk existed between the two types of containers *(134)*. In contrast, stainless steel is considered one of the most hygienic materials for construction of food-contact surfaces and is frequently used in the construction of harvesting equipment *(8, 9, 18, 61, 171, 173)*. Food-contact surfaces such as conveyor belts and curtain tails on harvesting equipment may be constructed with soft and flexible materials such as textiles, rubber, or rubber-like materials. Research findings related to pathogen persistence on specific materials indicate pathogen growth and survival may depend on environmental factors such as moisture, ambient temperature, and relative humidity *(31)*. Overall, the most common finding among the majority of studies was that consistent, properly administered cleaning methods significantly reduced bacterial contamination on food-contact surfaces.

Surface cleanability

In addition to the design and the type of material used to construct harvesting equipment, the condition of food-contact surfaces and of the overall equipment also affects the ability to clean and sanitize effectively. Decades of food industry research has indicated that microbial adhesion to surfaces, when it occurs, requires only small amounts of food sediment to provide nutrients and makes bacteria more resistant to cleaning and sanitation *(59, 75, 140)*. Bacterial attachment to surfaces also is affected by properties of both the material to which the bacteria adhere *(145)* and the bacteria themselves *(72, 180)*. Once they are transferred to equipment, bacteria modify their physiology and morphology to better adhere to a surface *(72)*. As part of the physiological changes that enhance attachment, some pathogens can form biofilms, an extracellular polymeric substance, as a means of protection from harsh environmental conditions *(27, 99, 114)*. It is not within the scope of this review to cover the vast body of research published on biofilm formation on food-contact surfaces in the food industry; thorough reviews by Carrascosa et al. *(27)*, Li et al. *(99)*, and Mevo et al. *(114)* have been recently published. Recent approaches to address biofilm contamination on equipment surfaces include novel methods to prevent bacteria from attaching, to disperse (chemically or enzymatically) and remove established biofilms, or to kill resident bacteria in the biofilms *(8, 49, 186)*. However, physical forces applied during cleaning are very important for biofilm removal prior to sanitation.

Two surface conditions frequently evaluated in investigations of bacterial attachment to food-contact surfaces are surface topography and surface roughness. Surface topography generally refers to the material's local deviations from a flat plane and includes defects such as crevices and pits. Roughness of a surface is quantifiable as the measure of total spaced irregularities *(41, 74, 75)*. Surface topography and roughness affect the ability of microorganisms to adhere or attach to a surface, and current research findings suggest that these features are more relevant to biofilm formation than is the specific material used to construct the surface *(88)*. Surfaces with rough or worn topography are more difficult to clean than smooth or unworn surfaces, creating opportunity for pathogen contamination *(18, 173)*. For stainless steel, both the average surface roughness in the vertical direction and the shape of any defect (e.g., sharp narrow or deep scratches) affected bacterial retention and cleanability; wider surface defects were easier to clean than sharp scratches *(18)*. Verran et al. *(173)* reported that a greater force was required to remove bacterial cells on surfaces that had been damaged from use than on unused surfaces, even for defects with dimensions smaller than the average size of the bacterial cell. Addition of detergent to the water spray reduced the amount of force required to remove the bacteria *(173)*.

Despite evidence that surface topography and roughness affect cleanability, numerous studies of how roughness and topography influence bacterial adhesion often have produced conflicting findings. A more complete understanding of how the surface topography of materials commonly used in the manufacture of harvesting equipment affects bacterial adhesion would be useful for developing surfaces engineered to reduce bacterial attachment. Stainless steel is one of the most researched materials, often studied in relation to *Listeria* attachment. Studies of *L. monocytogenes* adhesion to stainless steel have produced inconsistent findings; some researchers have reported a strong correlation between adhesion and surface roughness *(29, 43)*, whereas others did not *(69, 136)*. Crawford et al. *(41)* credited the discrepancies of findings among studies to the lack of a consistent, comprehensive topographical characterization of surfaces at the nanoscale. They noted that most studies of surfaces have included analysis of only one aspect of the surface topography (i.e., average or root mean roughness measured as the typical height variation of the surface) instead of a collection of measurements that would better describe the many aspects of surface roughness.

CONTAMINATION PREVENTION AND CONTROL MEASURES

Cleaning and sanitation practices overview

Best practices for harvesting equipment, from the FDA *(168)* Produce Safety Rule and the Codex Alimentarius *(36) Code of Hygienic Practice for Fresh Fruits and Vegetables* to commodity-specific food safety guidelines, include routine cleaning and sanitizing of food-contact surfaces. Cleaning and sanitizing of harvesting equipment are the primary means of preventing bacterial transfer from equipment to harvested crops during daily operations. When equipment is not cleaned and sanitized appropriately and/or in a timely manner, human pathogens may remain on the equipment and may transfer to produce crops during harvesting operations *(103)*. Determination of where and when harvesting equipment should be cleaned and sanitized (e.g., before use, after use, or between fields) is also crucial to ensuring that this equipment is not a source of contamination in the field. Because chemicals used in cleaning and sanitation may pose a hazard to harvested and unharvested crops, the location in which these activities occur must be chosen to prevent inadvertent contamination. Decisions about cleaning and sanitation timing should be based on sound standards of care for the microbial safety of the crop and must not be compromised by expediency. Decisions on cleaning and sanitation frequency and preoperational recleaning and sanitizing must take into consideration factors such as weather, rain events, adjacent land hazards, vector activity, and other issues that enhance the risk of pathogen presence and the risk of equipment contamination.

Sanitation standard operating procedures (SSOPs) should be clearly written and easy to follow with a clearly defined scope that addresses the range of applications, the equipment and products to be used, the people responsible for the cleaning procedures, and detailed cleaning instructions *(84)*. The SSOPs for any given piece of equipment should be customized for each component (e.g., conveyor belt) with consideration of the materials used in its construction, accessibility for cleaning (such as conveyor lifts), type and complexities of joints and product transfer points, and frequency of breakdown or dissembling. Cleaning procedures for harvesting equipment depend on the properties of the component being cleaned such as the material with which it was constructed, its structure, and where it is located on the equipment, including its height from ground level. Cleaning and sanitizing compounds and solutions may react with equipment materials and coatings, causing corrosion and degradation *(47)*. Aside from the equipment itself, other considerations in establishing SSOPs for cleaning and sanitizing harvesting equipment include the chemicals used in these activities (e.g., appropriate use, disposal, and storage of these agents to prevent crop contamination), the type and condition of soil fouling the equipment (e.g., dry or wet soil), and the hardness (i.e., calcium and magnesium concentrations) of the water used for cleaning.

Unlike the food processing and manufacturing industry where periodic deep cleaning of equipment is essential to prevent product contamination from established persistent bacterial strains, the fresh produce industry does not typically perform periodic deep cleaning of harvesting equipment *(57)*. Although equipment surfaces require cleaning and

sanitation in both harvesting and processing operations, major differences exist in the equipment settings. In food processing and manufacturing settings, equipment is indoors and typically fixed in place *(20, 98)*; in contrast, harvesting equipment is used outdoors, where it is continually being transported between fields. The ever-changing routine of harvesting operations requires more strategic planning for both periodic and risk-based deep cleaning (observation of environmental conditions necessitating a preventive intervention) to occur, especially with regards to where and when equipment can be disassembled. However, even in food processing and manufacturing environments, deep cleaning of equipment requires timing considerations because it necessitates cessation of operations and interferes with product output *(20, 141)*.

The 2021 deep cleaning of harvesting equipment workgroup study included a seven-step deep cleaning process that revealed at-risk areas on the equipment and indicated that disassembly of the equipment for deep cleaning was essential for reducing or eliminating the bacterial load in hard-to-reach niches on the equipment *(37, 57)*. Although deep cleaning requires longer downtime than routine cleaning, some form of periodical deep cleaning is critical to prevent pathogen persistence (i.e., biofilm formation) on equipment used for harvesting and field-packing operations *(57)*.

Cleaning and sanitizing methods

Current routine cleaning and sanitizing practices for harvesting equipment generally follow a four- or five-step process *(141, 143)*. Cleaning and sanitizing of equipment surfaces are two distinct processes that combine mechanical action such as scrubbing, spraying, scraping, etc., with chemicals or technologies (e.g., heat or radiation) to remove and/or kill contaminants on the equipment *(23)*. The cleaning process involves chemicals (detergent type and concentration), contact time, temperature, and mechanical action *(23)*. Surfaces must be cleaned before they are sanitized because surface cleanliness greatly affects sanitizer effectiveness; soil and product extracts (e.g., from cut surfaces or rotting or damaged products) can interfere with sanitizer efficacy *(45, 73, 90, 141, 143, 158)*. Even trace amounts of soil or plant residues may protect bacteria on surfaces from sanitizer treatment *(91, 92)*.

The specific methods used to clean a surface significantly impact its cleanliness as does the nature of the material fouling the equipment (e.g., soil residues or plant material). Some residues such as soil may partially or fully dissolve in water, whereas others require detergents or physical removal *(18, 141, 171, 173)*. Boyd et al. *(18)* found that cleaning of fouled unpolished stainless steel with brushes removed substantially more of the fouling material than did spray cleaning. Verran et al. *(171, 173)* reported that cleaning with detergent produced better results than did spray cleaning with only water. A study by Lambrecht et al. *(96)* revealed that detergents in foam form used with a low-pressure applicator were also more efficacious than conventional cleaning methods and reduced the potential for cross-contamination from pathogen dispersal in aerosols and droplets. Cleaning of stainless steel with a nonionic detergent and simulated manual cleaning techniques resulted in a 2-log reduction in attached bacteria *(173)*. Selection of appropriate cleaning tools (e.g., brushes) and application procedures (e.g., foaming) is essential, recognizing that different equipment, surfaces, and environments may require different strategies.

Numerous factors should be considered when choosing specific cleaning and sanitizing agents, far more than could be adequately addressed here. Although below we briefly discuss general categories and select research findings, others researchers have more thoroughly addressed these factors in relation to cleaning and sanitizing equipment used indoors in packing and processing operations, and much of this information is also relevant for harvesting equipment *(25, 141, 143)*. Cleaning agents or detergents typically contain numerous chemical components such as surfactants, water conditioners, fillers, and oxidizing agents, that play specific roles (e.g., controlling the pH) in the cleaning process *(141, 143)*. The primary role of detergents is to facilitate penetration, breakdown, and suspension of soil with mechanical action, which prevents redeposition on the equipment surface *(23, 189)*. Knowledge of the type of soil fouling the equipment is critical for choosing the correct cleaning agent(s) (i.e., acidic or alkaline) because agents with the wrong pH can hinder soil removal *(143)*. A surfactant works by reducing the adhesive forces between a contaminant and the equipment surface *(143, 189)*. Water conditioners prevent buildup of mineral deposits, mainly in the form of calcium and magnesium, which may affect the overall chemistry of the cleaning agent and may be detrimental to equipment performance and maintenance *(143)*.

Sanitation is affected by contact time, concentration of the active chemical, treatment frequency, applied force, and treatment temperature *(15, 23, 54, 55, 63, 141, 143)*. Operators of harvesting equipment should consider each of these factors when developing plainly and concisely written SSOPs, including the appropriate tools and equipment needed to conduct each procedure. In their evaluation of commercial equipment sanitizing processes used in food manufacturing, Cai et al. *(23)* reported that sanitizer contact time was the most important predictor of *L. monocytogenes* reduction on surface materials such as high-density polyethylene, epoxy, stainless steel, and Buna-N rubber. Use of sanitizers in foam form also enhances efficacy by increasing contact time compared with liquid sanitizers *(96)*. Solution temperature affects the sanitizing efficacy of select sanitizers (e.g., lower temperature slows the oxidizing effect of hypochlorous acid), their safe use, and their ability to corrode *(141, 143)*. Fagerlund et al. *(54)* tested commercially

available sanitizer performance on conveyor belt material and reported that when sanitizer concentration, the number of follow-up treatments, exposure time, and temperatures were increased over the typical standard daily cleaning and sanitizing process recommended by the manufacturers, *L. monocytogenes* biofilm removal improved from a maximum 1.8-log reduction to a >5.5-log reduction.

Because chemical sanitizers are most commonly used to reduce microbes on produce harvesting and packing equipment, the correct selection and use of sanitizing agents is vital for preventing cross-contamination of product during harvesting and field-packing operations. Chemical sanitizing agents approved for use on food-contact surfaces include halogens (e.g., chlorine- and iodine-based products), ozone, peroxides (e.g., peracetic acid [PAA]), and quaternary ammonium compounds (QACs) *(15, 141)*. Although some researchers have reported that for QACs, higher minimum inhibitory concentration are needed to kill some *L. monocytogenes* strains *(51, 160)*, these strains appear to be killed at equal efficacy as those killed by lower MICs *(16)*. Although these findings support the need for use of appropriate sanitizer concentrations, current evidence is not sufficient to advise against the use of QAC-based sanitizers. In numerous studies of sanitizer efficacy against foodborne pathogens under various conditions (frequently in the presence of food residues), sanitizer efficacy depended on the target microorganisms *(73, 89, 90, 93, 140, 183)*. Many researchers have investigated sanitizer efficacy against *L. monocytogenes*, which is a key environmental pathogen due to its ability to readily attach to surfaces and the frequency at which it has been identified as both a transient and resident contaminant in food pro-cessing facilities *(26, 112, 152, 156)*. The efficacy of sanitizers (e.g., PAA, QACs, chlorine, or chlorine dioxide) commonly used against *L. monocytogenes* biofilms has been variable, depending on the materials being investigated, the specific *L. monocytogenes* strain, and the degree of biofilm develop-ment *(34, 73, 79, 90)*. However, researchers have consistently emphasized the importance of timely and thorough cleaning of food-contact surfaces before sanitation to further optimize sanitizer efficacy and reduce biofilm formation.

Biofilm control

A finding common to many studies is that pathogens attached to equipment, especially in the form of biofilms, are much more difficult to eliminate than those present as individual cells *(60, 90, 140, 183)*. As they mature, biofilms become more difficult to remove *(54, 90, 183)*. *L. monocytogenes* may not form true biofilms but often co-occurs with biofilm producers such as *Pseudomonas* and *Burkholderia (159)*. Korany et al. *(90)* reported that the efficacies of QACs, chlorine, chlorine dioxide, and PAA were much lower against *L. monocytogenes* cells that have been attached for 7 days than against cells attached for only 2 days.

Driven largely by the food manufacturing, meat, dairy, and medical industries, research into new sanitizing technologies and/or chemicals with enhanced efficacy against biofilms has increased over the past decade. Several publications have provided comprehensive reviews of these innovative and promising approaches to sanitation, which include use of visible and UV light, proteins, cold plasma and plasma-generated compounds, electric currents, natural products, nanoparticles, nanomaterials, nanobubbles, peptides, bacteriophages, and low-frequency high-intensity ultrasound *(5, 6, 42, 67, 114, 121, 138, 144, 175)*. The mechanisms of action behind these novel approaches to sanitation are based on increasing the bacterial cell membrane permeability, disrupting bacterial communication via quorum sensing (quorum quenching), promoting bacterial cell lysis, degrading components of the biofilm matrix, and/or inhibiting enzyme activity or protein synthesis—all of these mechanisms may facilitate the disruption and dismantling of biofilms or bacterial cell death *(114, 138, 144)*.

A hurdle approach to biofilm control or elimination by use of a combination of sanitizing treatments or technologies has frequently been more effective against biofilms than a single antimicrobial intervention alone *(114, 132, 138, 174)*. For example, ultrasound treatment plus 30 s in 1 ppm of chlorinated water reduced *E. coli* O157:H7 counts below the limit of detection (1.10 CFU/cm^2) on the coring ring blade and welding joint of lettuce coring knives *(188)*. Rafeeq and Ovissipour *(132)* reported a synergistic effect of ultrasound and nanobubbles against *E. coli* O157:H7 and *Listeria innocua* on spinach leaves that surpassed the efficacy of either treatment alone. In other cases, bacteriophage addition or treatments that dismantle or dissolve the biofilm matrix (e.g., quorum quenching) in combination with sanitizing agents have effectively reduced pathogens in biofilms on food-contact surfaces *(42, 138)*. However, in the "real world" the persistence of pathogen communities and biofilms is often due to contamination in equipment locations that are not reached by chemicals in niches or harborage sites *(112)*. Use of specific chemicals targeting biofilms is often ineffective because the liquid or gaseous chemicals cannot reach the target organisms in hollow areas. In these cases, removal of persistent pathogen communities and/or biofilms will require equipment disassembly and enhanced mechanical cleaning rather than use of specialized chemicals *(23)*.

Validation and verification of cleaning and sanitizing processes

In the *Validation of Cleaning Processes* guide for inspectors of the pharmaceutical industry, the FDA *(168)* states "the test of any validation process is whether scientific data shows that the system consistently does as expected and produces a result that consistently meets predetermined specifications." In a similar way, for the produce industry, cleaning and sanitizing procedures as outlined in a harvesting company's

SSOP should be validated or drawn from scientifically valid studies subject to peer review to ensure these procedures accomplish what they are intended to accomplish, meaning these cleaning and sanitizing procedures should have predictable outcomes when repeatedly implemented. The FDA did not include equipment SSOP validation requirements in the Produce Safety Rule *(168)*, however harvesting companies must validate their SSOPs or identify established studies as specifically suitable validations as part of their food safety program and risk management strategies. In addition to equipment-specific SSOP validation, companies supplying or manufacturing cleaning technologies, equipment, and chemicals may provide validation of their products. These documents are useful as supplementary validation resources but, as noted by Fagerlund et al. *(54)*, may not be adequate for effective cleaning of a specific piece of equipment. Because specific aspects of the equipment and the environment in which it is used may differ from a chemical manufacturer's validation procedure, the manufacturer's product validation should not be solely relied upon without some form of verification of the SSOPs by a harvesting company or a qualified third-party agent.

In the produce industry, it is a fairly common practice to visually inspect equipment to ensure it is in a condition appropriate for entering the field and contacting crops. Visual inspections of harvesting equipment are typically performed prior to harvesting to verify that the equipment is clean and field ready. When equipment is visually inspected, personnel doing the inspection typically follow a written standard procedure and record their findings. Inspection records can be shared with cleaning crews to provide essential feedback on the quality of their work. However, although essential, visual inspection is subjective (i.e., dependent on human senses and worked-related experience) and should not be solely relied on as evidence that the equipment has been thoroughly and appropriately cleaned and sanitized and is ready to harvest crops in the field *(115)*. Best practices for ensuring harvesting equipment is field ready include making quantitative or qualitative measurements demonstrating the hygienic state of the equipment.

Numerous quantitative and qualitative methods are available to assess cleaning and sanitation efficacy (i.e., by measuring equipment surface hygiene), many of which are already routinely used in produce packing and processing facilities *(86, 137)*. For harvesting equipment, frequent movement and constant use during harvesting season necessitates timely cleaning and sanitation verification. This timing is generally before movement to the next location or the next day of harvesting; retrospective microbiological testing may be problematic for linking multiple crops or locations when an out-of-compliance result is obtained. The time constraints associated with harvesting equipment generally rule out the use of swab and plate microbial techniques, which require ≥ 24 h to get results. Thus, hygienic assessment options may be limited to rapid methods that produce results in minutes or, at the most, a few hours. For decades, the food industry at large has commonly used ATP-based assays for rapid assessment of equipment cleaning. These assays produce light (bioluminescence) when ATP (an energy-bearing molecule found in living organisms) is detected *(115)*. The ATP detected on equipment surfaces could be from soil or plant residues or from microorganisms, and the intensity of the light emitted is used to estimate the ATP concentration *(115)*. In a tofu manufacturing facility, Sogin et al. *(150)* compared ATP bioluminescence monitoring of food-contact surface cleanliness with microbiological enumeration and reported that the two methods agreed on site cleanliness status only 75.1% of the time. Although these data support the value of ATP testing, they should not be misinterpreted as suggesting that ATP testing can verify sanitation; ATP testing can be used to only verify cleaning. Multiple experiences in practice have indicated that ATP testing works well on many food-contact surfaces but very poorly in general on surfaces such as brushes and rollers.

Although ATP testing is widely used in produce packinghouses and processing facilities, little published information is available that describes the performance of these tests in those settings. Ruiz-Llacsahuanga et al. *(137)* examined the accuracy of ATP-based assays for assessing the hygiene of equipment used in apple packing facilities and reported no significant association between ATP-based rapid test results and plate counts of aerobic bacteria, *Enterobacteriaceae,* coliforms, and *E. coli*. In a laboratory study, Corbitt et al. *(39)* evaluated the ability of ATP bioluminescence alone or in combination with the cellular marker adenylate kinase (an enzyme involved in ATP production) to detect broccoli and potato residues on stainless steel surfaces. ATP plus adenylate kinase performed better for detecting either vegetable than did ATP bioluminescence alone. Lane et al. *(97)* concluded, based on their laboratory study, that ATP bioluminescence measurement is an appropriate tool for measuring leafy green residues and bacterial contamination on stainless steel or high-density polyethylene plastic surfaces; however, ATP testing does not detect low levels of bacteria and therefore is never appropriate as a tool to verify sanitation. Recently published cleaning and sanitation verification assays include a more sensitive version of the ATP assay that detects total adenylates: ATP, ADP, and AMP *(7)*. Other innovations include paper biosensors combined with a smartphone for detecting and measuring ATP *(24)*. Although ATP-based testing is an appropriate tool for verifying the cleanliness of harvesting equipment, it should be supplemented by periodic evaluation of total bacterial counts to verify sanitation practices. Recently adopted industry recommended practice is to start with weekly microbiological swabs or agar contact-press plates to build a history of performance for cleaning and to reduce this testing frequency based on use, environment, season, and data-informed experience.

Cleaning the cleaning tools

The condition and suitability of the tools and equipment used in cleaning and sanitizing are often overlooked. In a 1998 microbiological survey of food manufacturing plants in the United Kingdom, 47% of cleaning tools tested positive for *L. monocytogenes (70)*. The potential to cross-contaminate food-contact surfaces is significant when cleaning tools are not routinely cleaned and sanitized. Inappropriate design of cleaning tools may lead to inadequate contact with surfaces such as sharp angles or curves. Cleanliness of the cleaning tools is receiving more attention in food safety programs, as indicated by the recent addition to food safety schemes approved by the Global Food Safety Initiative, and is also influencing tool design and cleaning and maintenance protocols and schedules *(148)*.

Studies in packing, processing, and retail establishments provide examples of how cleaning equipment can become sources of contamination when not properly maintained. In a microbial survey of fresh-cut vegetable production plants, Lehto et al. *(98)* reported a mean aerobic plate count of 80 CFU/cm^2 and a mean *Enterobacteriaceae* count of 49 CFU/cm^2 on the surface of floor cleaning equipment. Conveyors, floors, and gloves had elevated aerobic plate counts (50 to 72 CFU/cm^2) even after they had been cleaned *(98)*.

Cloths and squeegees may be used to wipe debris and dirt from equipment surfaces during harvesting and field-packing activities. In their survey of 30 produce retail environments, Burnett et al. *(22)* swab sampled squeegees and other floor cleaning tools; at one retail location 33 of 180 sampled tools were positive for *L. monocytogenes* and 1 tool was positive for *Salmonella*. Cleaning cloths (n = 1,132) used to clean surfaces in preparation for service of ready-to-eat foods in U.K. foodservice and retail establishments had higher aerobic plate counts and higher levels of *Enterobacteriaceae*, *E. coli*, and *Staphylococcus aureus* than did the surfaces they were used to clean *(139)*. Kusumaningrum et al. *(93)* also reported high levels of *Salmonella* and *S. aureus* on regular and microfiber cleaning cloths but not on disposable cloths treated with antibacterial agents, which had no detectable contamination. Cleaning cloth material may hence affect cleaning efficacy and cross-contamination of surfaces being cleaned *(61)*.

Tools used to clean harvest equipment may spread contamination to equipment surfaces. Goulter et al. (65) reported transfer of bacteria from contaminated cleaning water to surfaces wiped with cloths that had been dipped in the contaminated water. Water containing QACs prevented bacterial transfer but did not stop transfer of bacterial spores to surfaces via the wiping cloths. Squeegees used to remove condensation from overhead pipes in a food manufacturing facility had extensive *Listeria* contamination when used to wipe inoculated pipe surfaces *(109)*. Sanitizer alone was able to remove only 1 to 2 log CFU/in^2 (6.45 cm^2) from squeegee blades, but the bacterial levels were further reduced by 3 to 4 log CFU/in^2 after an extensive cleaning regimen was implemented. Tools and equipment such as those evaluated in these studies *(22, 61, 65, 93, 98, 109, 139)* are used for cleaning harvesting equipment. In contrast to tools used indoors, tools used to clean harvesting equipment may have significant exposure to UV light between cleanings; nonetheless, each cleaning tool should be routinely cleaned and sanitized at a frequency that is appropriate for how it is used and stored. Observations reported by a workgroup during the deep cleaning of harvesting equipment *(37)* indicated that much greater attention and emphasis on the physical condition of cleaning tools, especially brush heads, is warranted.

Equipment storage

As noted above, during harvesting season, harvesting and field-packing equipment are typically moved between harvesting locations and remain outdoors, uncovered either overnight or when not in use counter seasonally. When harvesting equipment is removed from storage after an extended period such as counter seasonally, the preoperational SOPs should include preventive maintenance, deep cleaning, sanitation, and verification of the hygienic state before use in harvesting activities. Storage of equipment uncovered outdoors leaves it vulnerable to microbial contamination from pests, blowing dust and dirt, and moisture, which supports pathogen growth and biofilm formation *(68)*. When harvesting equipment is cleaned and sanitized immediately after use and then subsequently remains inactive outdoors—whether overnight or for several days or months between uses—this down time provides opportunities for microbial contamination. Use of coverings or portable storage structures for inactive equipment is a possible preventive measure. The time between cleaning and sanitizing activities and equipment use can be decreased by performing those activities immediately before harvesting operations, which reduces the potential for microbial contamination during down time; however, this order of operations may not always be logistically possible. As an alternative, design and construction of equipment incorporating antimicrobial materials would support sanitation maintenance when equipment is both operating and inactive.

New materials and coating technologies

Research focusing on how to maintain surfaces in a sanitary state with less frequent cleaning and sanitizing activities has been largely driven by medical applications but has also become increasingly important to the food industry as more activities become automated. Automated processes typically involve more surfaces that are then available for potential bacterial contamination, increasing the opportunity for cross-contamination of product *(11)*. Surfaces constructed with materials that have antifouling or

antimicrobial properties can more easily be maintained in a sanitary state. Similar to innovative sanitation technologies, research on antifouling and antimicrobial surfaces has mainly focused on equipment used in food processing and manufacturing. Several reviews have been recently published that have summarized and explained the various innovative materials and methods and the unique challenges in food industry applications *(11, 44, 128)*.

Innovative antimicrobial and antifouling materials include additives incorporated into the structural materials themselves, modified material surfaces, or surface coatings that have antibacterial activity (antimicrobial) or that prevent soil and bacterial adhesion (antifouling) *(4, 8, 11, 31, 40, 46–48, 56, 117, 172, 184)*. Chaitiemwong et al. *(31)* reported enhanced *L. monocytogenes* reduction on wet conveyor belt material containing antimicrobial additives compared with wet conveyor belt material without additives. Ban et al. *(8)* modified stainless steel by creating nanoscale pores in the material surface coupled with a Teflon coating to form a self-cleaning surface that reduced *E. coli* O157:H7 and *Salmonella* populations by 2.1 to 3.0 log CFU/cm^2, respectively, compared with untreated or noncoated stainless steel. Surface coatings range from permanent to temporary (e.g., food-safe oil-based coatings) *(4, 11)*. Awad et al. *(4)* evaluated a food-safe oil-based slippery coating for stainless steel surfaces and reported that the oil coating, which filled surface grooves and cavities, suppressed bacterial adherence and biofilm formation. Metal-based coatings such as titanium, silver, copper, and zinc on food-contact surfaces act as antimicrobials by reducing retention and enhancing the removal of bacteria from the coated surfaces *(11, 172)*. Many antimicrobial coatings work in synergy with sanitizing treatments, resulting in enhanced bactericidal effects *(46, 47)*. Other coatings exploit material properties such as hydrophobicity or hydrophilicity that inhibit or minimize bacterial adhesion *(56, 184)*. Rechargeable coatings containing antimicrobial N-halamines (a halogenated nitrogen compound) can renew their antimicrobial effect by reloading from a halogen (chlorine, bromine, or iodine) source *(11)*. Cossu et al. *(40)* evaluated a novel rechargeable antimicrobial polymer that prevents biofilm formation over repeated exposures and helps inactivate existing biofilms upon contact. The polymeric material is recharged with bleach during cleaning with mechanical sonication. Although few, if any, of these novel technologies are at a state where they could be applied to preharvest equipment, this area may, in the long term, yield approaches that could be valuable for preharvest food safety.

CONCLUSION

Equipment and tools used in harvesting produce crops can harbor and transfer human pathogens present in the outdoor environment in which they operate. Environmental conditions affect the risk of contamination by microbial hazards in the produce production environment where the equipment is operating. For example, numerous studies have provided evidence that contamination risk is higher when the soil is wet (i.e., after rainfall or irrigation). Use of harvesting equipment in the field too soon after irrigation or precipitation may increase the risk of cross-contamination.

The fast-paced, time-sensitive nature of harvesting produce crops in an outdoor environment presents distinctive challenges for maintaining equipment in a sanitary condition. When food-contact and other exposed surfaces or internal hollow areas on harvesting equipment frames and at fractures in welded areas become contaminated, pathogens can be transferred to harvested product. Research and development efforts across industries are producing new, practical, and cost-effective materials and techniques for maintaining harvesting equipment in a sanitary state during and after use. Equipment operators can take practical steps to minimize cross-contamination between food-contact surfaces, areas adjacent to food-contact surfaces, and the produce crops. Cleaning and sanitizing equipment in a timely manner using appropriate methods and techniques are the keys to preventing microbial contamination of produce crops during harvesting activities. Equipment operators should have a basic understanding of the chemistry and mechanisms underlying their sanitation processes and the efficacy of these treatments against biofilms. Well-written SSOPs should provide work crews with clear and concise instructions regarding the methods and tools for cleaning and sanitizing harvesting equipment. Although the FDA did not include monitoring requirements in the Produce Safety Rule, harvesting companies must validate equipment SSOPs and verify cleaning and sanitation procedures as part of their food safety programs and risk management strategies. When equipment is not in use, the practicality of storage—covered or uncovered, indoors or outdoors—to minimize the risk of contamination is worth consideration.

Continued attention to equipment design and construction and use of enhanced hygienic practices are also fundamental to the produce industry's commitment to provide consumers with safe, nutritious products. Applied research on the efficacy of harvest equipment sanitation (e.g., with various chemicals, for various dwell times, and under various environmental conditions) will be valuable for establishing cleaning and sanitation performance criteria and identifying situations in which harvest equipment sanitation differs substantially from findings for sanitation in other environments (e.g., packinghouses and processing facilities).

REFERENCES

1. Antaki, E. M., G. Vellidis, C. Harris, P. Aminabadi, K. Levy, and M. T. Jay-Russell. 2016. Low concentration of *Salmonella enterica* and generic *Escherichia coli* in farm ponds and irrigation distribution systems used for mixed produce production in southern Georgia. *Foodborne Pathog. Dis.* 13:551–558.
2. Aviat, F., C. Gerhards, J. J. Rodriguez-Jerez, V. Michel, I. le Bayon, R. Ismail, and M. Federighi. 2016. Microbial safety of wood in contact with food: a review. *Compr. Rev. Food Sci. Food Saf.* 15:491–505.
3. Aviat, F., I. le Bayon, M. Federighi, and M. Montibus. 2020. Comparative study of microbiological transfer from four materials used in direct contact with apples. *Int. J. Food Microbiol.* 333:108780.
4. Awad, T. S., D. Asker, and B. D. Hatton. 2018. Food-safe modification of stainless steel food-processing surfaces to reduce bacterial biofilms. *ACS Appl. Mater. Interfaces* 10:22902–22912.
5. Axelsson, L., A. Holck, I. Rud, D. Samah, P. Tierce, M. Favre, and C. F. Kure. 2013. Cleaning of conveyor belt materials using ultrasound in a thin layer of water. *J. Food Prot.* 76:1401–1407.
6. Bai, X., L. Xu, A. K. Singh, X. Qiu, M. Liu, A. Abuzeid, T. El-Khateib, and A. K. Bhunia. 2022. Inactivation of polymicrobial biofilms of foodborne pathogens using epsilon poly-L-lysin conjugated chitosan nanoparticles. *Foods* 11:569.
7. Bakke, M., and S. Suzuki. 2018. Development of a novel hygiene monitoring system based on the detection of total adenylate (ATP+ ADP+AMP). *J. Food Prot.* 81:729–737.
8. Ban, G., Y. Li, M. M. Wall, and S. Jun. 2020. A nanoengineered stainless steel surface to combat bacterial attachment and biofilm formation. *Foods* 9:1518.
9. Bang, J., A. Hong, H. Kim, L. R. Beuchat, M. S. Rhee, Y. Kim, and J. H. Ryu. 2014. Inactivation of *Escherichia coli* O157:H7 in biofilm on food-contact surfaces by sequential treatments of aqueous chlorine dioxide and drying. *Int. J. Food Microbiol.* 191:129–134.
10. Bardsley, C. A., D. L. Weller, D. T. Ingram, Y. Chen, D. Oryang, S. L. Rideout, and L. K. Strawn. 2021. Strain, soil-type, irrigation regimen, and poultry litter influence *Salmonella* survival and die-off in agricultural soils. *Front. Microbiol.* 12:590303.
11. Bastarrachea, L. J., A. Denis-Rohr, and J. M. Goddard. 2015. Antimicrobial food equipment coatings: applications and challenges. *Annu. Rev. Food Sci. Technol.* 6:97–118.
12. Belias, A., L. K. Strawn, M. Wiedmann, and D. Weller. 2021. Small produce farm environments can harbor diverse *Listeria monocytogenes* and *Listeria* spp. populations. *J. Food Prot.* 84:113–121.
13. Bell, R. L., J. A. Kase, L. M. Harrison, K. V. Balan, U. Babu, Y. Chen, D. Macarisin, H. J. Kwon, J. Zheng, E. L. Stevens, J. Meng, and E. W. Brown. 2021. The persistence of bacterial pathogens in surface water and its impact on global food safety. *Pathogens* 10:1391.
14. Bergholz, P., L. K. Strawn, G. Ryan, S. Warchocki, and M. Wiedmann. 2016. Spatiotemporal analysis of microbiological contamination in New York State produce fields following extensive flooding from Hurricane Irene, August 2011. *J. Food Prot.* 79:384–391.
15. Berk, Z. 2018. Food process engineering and technology. Third Edition. Academic Press, London.
16. Bolten, S., A. S. Harrand, J. Skeens, and M. Wiedmann. 2022. Nonsynonymous mutations in *fepR* are associated with adaptation of *Listeria monocytogenes* and other *Listeria* spp. to low concentrations of benzalkonium chloride but do not increase survival of *L. monocytogenes* and other *Listeria* spp. after exposure to benzalkonium chloride concentrations recommended for use in food processing environments. *Appl. Environ. Microbiol.* 88:e0048622.
17. Bouvier, L., C. Cunault, C. Faille, H. Dallagi, L. Wauquier, and T. Bénézech. 2021. Influence of the design of fresh-cut food washing tanks on the growth kinetics of *Pseudomonas fluorescens* biofilms. *iScience* 24:102506.
18. Boyd, R. D., D. Cole, D. Rowe, J. Verran, A. J. Paul, and R. H. West. 2001. Cleanability of soiled stainless steel as studied by atomic force microscopy and time of flight secondary ion mass spectrometry. *J. Food Prot.* 64:87–93.
19. Brar, P. K., and M. D. Danyluk. 2013. *Salmonella* transfer potential during hand harvesting of tomatoes under laboratory conditions. *J. Food Prot.* 76:1342–1349.
20. Brouillette, R., and T. Steffensmeier. 2018. The importance of periodic equipment cleaning. *Food Saf. Mag.* Available at: https://www.food-safety.com/articles/ 5653-the-importance-of-periodic-equipment-cleaning. Accessed 27 June 2022.
21. Buchholz, A. L., G. R. Davidson, B. P. Marks, E. C. D. Todd, and E. T. Ryser. 2012. Quantitative transfer of *Escherichia coli* O157:H7 to equipment during small-scale production of fresh-cut leafy greens. *J. Food Prot.* 75:1184–1197.
22. Burnett, J., S. T. Wu, H. C. den Bakker, P. W. Cook, D. R. Veenhuizen, S. R. Hammons, M. Singh, and H. F. Oliver. 2020. *Listeria monocytogenes* is prevalent in retail produce environments but *Salmonella* is rare. *Food Control* 113:107173.
23. Cai, S., D. M. Phinney, D. R. Heldman, and A. B. Snyder. 2020. All treatment parameters affect environmental surface sanitation efficacy, but their relative importance depends on the microbial target. *Appl. Environ. Microbiol.* 87:e01748-20.
24. Calabretta, M. M., R. Álvarez-Diduk, E. Michelini, A. Roda, and A. Merkoçi. 2020. Nano-lantern on paper for smartphone-based ATP detection. *Biosens. Bioelectron.* 150:111902.
25. Callahan, C. 2020. A guide to cleaning, sanitizing, and disinfecting for produce farms. Burlington. Available at: https://blog.uvm.edu/cwcallah/2020/03/30/clean-sanitize-disinfect/. Accessed 7 March 2022.
26. Carpentier, B., and O. Cerf. 2011. Review—persistence of *Listeria monocytogenes* in food industry equipment and premises. *Int. J. Food Microbiol.* 145:1–8.
27. Carrascosa, C., D. Raheem, F. Ramos, A. Saraiva, and A. Raposo. 2021. Microbial biofilms in the food industry—a comprehensive review. *Int. J. Environ. Res. Public Health* 18:2014.
28. Carstens, C. K., J. K. Salazar, and C. Darkoh. 2019. Multistate outbreaks of foodborne illness in the United States associated with fresh produce from 2010 to 2017. *Front. Microbiol.* 10:2667.
29. Casarin, L. S., A. Brandelli, F. de Oliveira Casarin, P. A. Soave, C. H. Wanke, and E. C. Tondo. 2014. Adhesion of *Salmonella* Enteritidis and *Listeria monocytogenes* on stainless steel welds. *Int. J. Food Microbiol.* 191:103–108.
30. Centers for Disease Control and Prevention. 2022. *Listeria* outbreak linked to packaged salads produced by Dole. Available at: https://www.cdc.gov/listeria/outbreaks/packaged-salad-mix-12-21/details.html. Accessed 17 April 2022.
31. Chaitiemwong, N., W. C. Hazeleger, and R. R. Beumer. 2010. Survival of *Listeria monocytogenes* on a conveyor belt material with or without antimicrobial additives. *Int. J. Food Microbiol.* 142:260–263.
32. Chapin, T. K., K. K. Nightingale, R. W. Worobo, M. Wiedmann, and L. K. Strawn. 2014. Geographical and meteorological factors associated with isolation of *Listeria* species in New York State produce production and natural environments. *J. Food Prot.* 77:1919–1928.
33. Chapman, P., B. M. Forde, L. W. Roberts, H. Bergh, D. Vesey, A. V. Jennison, S. Moss, D. L. Paterson, S. A. Beatson, and P. N. A. Harris. 2020. Genomic investigation reveals contaminated detergent as the source of an extended-spectrum-β-lactamase–producing *Klebsiella michiganensis* outbreak in a neonatal unit. *J. Clin. Microbiol.* 58:e01980-19.
34. Chavant, P., B. Gaillard-Martinie, and M. Hébraud. 2004. Antimicrobial effects of sanitizers against planktonic and sessile *Listeria monocytogenes* cells according to the growth phase. *FEMS Microbiol. Lett.* 236:241–248.
35. Code of Federal Regulations. 1986. Title 21 food and drugs, §110.3 definitions. Available at: https://www.ecfr.gov/current/title-21/chapter-I/subchapter-B/part-110/subpart-A/section-110.3. Accessed 2 March 2022.

36. Codex Alimentarius. 2003. Code of hygienic practice for fresh fruits and vegetables. Available at: https://www.fao.org/fao-who-codexalimentarius/sh-proxy/en/?lnk=1&url=https%253A%252F%252Fworkspace.fao.org%252Fsites%252Fcodex%252FStandards%252FCXC%2B53-2003%252FCXC_053e.pdf. Accessed 7 April 2022.

37. Commercial Food Sanitation. 2021. Periodic deep cleaning study of harvesting equipment. Available at: https://assets-us-01.kc-usercontent.com/ceb3f9ae-dd7c-00e0-c929-c0700175e55b/3cd896eb-c06d-4ba3-b872-26e2f8b18ae6/Harvester%20-%20White%20Paper%20Periodic%20Deep%20Cleaning%20Study%20of%20Harvesting%20Equipment%202022.03.14.pdf. Accessed 9 March 2022.

38. Cooley, M. B., B. Quiñones, D. Oryang, R. E. Mandrell, and L. Gorski. 2014. Prevalence of Shiga toxin producing *Escherichia coli*, *Salmonella enterica*, and *Listeria monocytogenes* at public access watershed sites in a California Central Coast agricultural region. *Front. Cell. Infect. Microbiol.* 4:30.

39. Corbitt, A. J., N. Bennion, and S. J. Forsythe. 2000. Adenylate kinase amplification of ATP bioluminescence for hygiene monitoring in the food and beverage industry. *Lett. Appl. Microbiol.* 30:443–447.

40. Cossu, A., Y. Si, G. Sun, and N. Nitin. 2017. Antibiofilm effect of poly(vinyl alcohol-co-ethylene) halamine film against *Listeria innocua* and *Escherichia coli* O157:H7. *Appl. Environ. Microbiol.* 83:e00975-17.

41. Crawford, R. J., H. K. Webb, V. K. Truong, J. Hasan, and E. P. Ivanova. 2012. Surface topographical factors influencing bacterial attachment. *Adv. Colloid Interface Sci.* 179–182:142–149.

42. Cristobal-Cueto, P., A. García-Quintanilla, J. Esteban, and M. García-Quintanilla. 2021. Phages in food industry biocontrol and bioremediation. *Antibiotics (Basel)* 10:786.

43. Das, J., J. A. Chase, M. L. Partyka, E. R. Atwill, and B. Linke. 2020. An insight into surface topographical parameters and bacterial adhesion: a case study of *Listeria monocytogenes* Scott A attachment on 304 stainless steel. *J. Food Prot.* 83:426–433.

44. DeFlorio, W., S. Liu, A. R. White, T. M. Taylor, L. Cisneros-Zevallos, Y. Min, and E. M. A. Scholar. 2021. Recent developments in antimicrobial and antifouling coatings to reduce or prevent contamination and cross-contamination of food contact surfaces by bacteria. *Compr. Rev. Food Sci. Food Saf.* 20:3093–3134.

45. Dev Kumar, G., L. Zhu, M. C. Siemens, K. Nolte, N. Brassill, D. V. Rios, R. Galvez, J. M. Fonseca, and S. Ravishankar. 2019. Modified coring tool designs reduce iceberg lettuce cross-contamination. *J. Food Prot.* 82:454–462.

46. Di Cerbo, A., A. Mescola, R. Iseppi, R. Canton, G. Rossi, R. Stocchi, A. R. Loschi, A. Alessandrini, S. Rea, and C. Sabia. 2020. Antibacterial effect of aluminum surfaces untreated and treated with a special anodizing based on titanium oxide approved for food contact. *Biology (Basel)* 9:456.

47. Di Cerbo, A., A. Mescola, G. Rosace, R. Stocchi, G. Rossi, A. Alessandrini, S. Preziuso, A. Scarano, S. Rea, A. R. Loschi, and C. Sabia. 2021. Antibacterial effect of stainless steel surfaces treated with a nanotechnological coating approved for food contact. *Microorganisms* 9:248.

48. Di Cerbo, A., F. Pezzuto, and A. Scarano. 2016. Cytotoxic and bacteriostatic activity of nanostructured TiO_2 coatings. *Polish J. Microbiol.* 65:225–229.

49. Dou, F., K. Huang, and N. Nitin. 2021. Targeted photodynamic treatment of bacterial biofilms using curcumin encapsulated in cells and cell wall particles. *ACS Appl. Bio Mater.* 4:514–522.

50. Draper, A. D., S. Doores, H. Gourama, and L. F. Laborde. 2016. Microbial survey of Pennsylvania surface water used for irrigating produce crops. *J. Food Prot.* 79:902–912.

51. Duze, S. T., M. Marimani, and M. Patel. 2021. Tolerance of *Listeria monocytogenes* to biocides used in food processing environments. *Food Microbiol.* 97:103758.

52. Erickson, M. C., J. Y. Liao, C. C. Webb, M. Y. Habteselassie, and J. L. Cannon. 2018. Inactivation of *Escherichia coli* O157:H7 and *Salmonella* deposited on gloves in a liquid state and subjected to drying conditions. *Int. J. Food Microbiol.* 266:200–206.

53. Estrada, E. M., A. M. Hamilton, G. B. Sullivan, M. Wiedmann, F. J. Critzer, and L. K. Strawn. 2020. Prevalence, persistence, and diversity of *Listeria monocytogenes* and *Listeria* species in produce packinghouses in three U.S. states. *J. Food Prot.* 83:277–286.

54. Fagerlund, A., L. Idland, E. Heir, T. Møretrø, M. Aspholm, T. Lindbäck, and S. Langsrud. 2022. Whole-genome sequencing analysis of *Listeria monocytogenes* from rural, urban, and farm environments in Norway: genetic diversity, persistence, and relation to clinical and food isolates. *Appl. Environ. Microbiol.* 88:e0213621.

55. Fan, M., D. M. Phinney, and D. R. Heldman. 2015. Effectiveness of rinse water during in-place cleaning of stainless steel pipe lines. *J. Food Sci.* 80:E1490–E1497.

56. Fernández-Gómez, P., I. Muro-Fraguas, R. Múgica-Vidal, A. Sainz-García, E. Sainz-García, M. González-Raurich, A. Álvarez-Ordóñez, M. Prieto, M. López, M. López, P. Toledano, Y. Sáenz, A. González-Marcos, and F. Alba-Elías. 2022. Development and characterization of anti-biofilm coatings applied by non-equilibrium atmospheric plasma on stainless steel. *Food Res. Int.* 152:109891.

57. Ferreira, V., M. Wiedmann, P. Teixeira, and M. J. Stasiewicz. 2014. *Listeria monocytogenes* persistence in food-associated environments: epidemiology, strain characteristics, and implications for public health. *J. Food Prot.* 77:150–170.

58. Frank, J. F. 2001. Microbial attachment to food and food contact surfaces. *Adv. Food Nutr. Res.* 43:319–370.

59. Frank, J. F., and R. A. Koffi. 1990. Surface-adherent growth of *Listeria monocytogenes* is associated with increased resistance to surfactant sanitizers and heat. *J. Food Prot.* 53:550–554.

60. Giaouris, E., N. Chorianopoulos, P. Skandamis, and G.-J. Nychas. 2012. Attachment and biofilm formation by *Salmonella* in food processing environments, p. 157–180. *In* B. S. M. Mahmoud (ed.), *Salmonella*—a dangerous foodborne pathogen. InTech, Rijeka, Croatia.

61. Gibson, K. E., P. G. Crandall, and S. C. Ricke. 2012. Removal and transfer of viruses on food contact surfaces by cleaning cloths. *Appl. Environ. Microbiol.* 78:3037–3044.

62. Gil, M. I., M. V. Selma, T. Suslow, L. Jacxsens, M. Uyttendaele, and A. Allende. 2015. Pre- and postharvest preventive measures and intervention strategies to control microbial food safety hazards of fresh leafy vegetables. *Crit. Rev. Food Sci. Nutr.* 55:453–468.

63. Goode, K. R., D. Phinney, T. Hasting, and P. Fryer. 2018. Engineering considerations for cleaning and disinfection in the food industry, p. 1125–1174. *In* D. R. Heldman, D. B. Lund, and C. M. Sabliov (ed.), Handbook of food engineering. CRC Press, Boca Raton, FL.

64. Gorski, L., C. T. Parker, A. Liang, M. B. Cooley, M. T. Jay-Russell, A. G. Gordus, E. R. Atwill, and R. E. Mandrell. 2011. Prevalence, distribution, and diversity of *Salmonella enterica* in a major produce region of California. *Appl. Environ. Microbiol.* 77:2734–2748.

65. Goulter, R. M., J. S. Clayton, R. G. Moore, J. M. Bradshaw, J. W. Frye, E. J. Puntch, and L.-A. Jaykus. 2020. Characterizing microbial cross-contamination on large surfaces using a traditional "cloth and bucket" disinfection method. *Food Prot. Trends* 40:392–401.

66. Gu, G., Z. Luo, J. M. Cevallos-Cevallos, P. Adams, G. Vellidis, A. Wright, and A. H. C. van Bruggen. 2013. Factors affecting the occurrence of *Escherichia coli* O157 contamination in irrigation ponds on produce farms in the Suwannee River watershed. *Can. J. Microbiol.* 59:175–182.

67. Handorf, O., V. I. Pauker, T. Weihe, J. Schäfer, E. Freund, U. Schnabel, S. Bekeschus, K. Riedel, and J. Ehlbeck. 2021. Plasma-treated water affects *Listeria monocytogenes* vitality and biofilm structure. *Front. Microbiol.* 12:652481.

68. Harrand, A. S., L. K. Strawn, P. M. Illas-Ortiz, M. Wiedmann, and D. L. Weller. 2020. *Listeria monocytogenes* prevalence varies more within fields than between fields or over time on conventionally farmed New York produce fields. *J. Food Prot.* 83:1958–1966.

69. Hilbert, L. R., D. Bagge-Ravn, J. Kold, and L. Gram. 2003. Influence of surface roughness of stainless steel on microbial adhesion and corrosion resistance. *Int. Biodeter. Biodegrad.* 52:175–185.

70. Holah, J. T. 1999. Effective microbiological sampling of food processing areas. Guideline document 20. Campden & Chorleywood Food Research Association, Chipping Campden, UK.

71. Hruby, C. E., M. L. Soupir, T. B. Moorman, C. Pederson, and R. Kanwar. 2018. *Salmonella* and fecal indicator bacteria survival in soils amended with poultry manure. *Water Air Soil Pollut.* 229:32.

72. Hsu, L. C., J. Fang, D. A. Borca-Tasciuc, R. W. Worobo, and C. I. Moraru. 2013. Effect of micro- and nanoscale topography on the adhesion of bacterial cells to solid surfaces. *Appl. Environ. Microbiol.* 79:2703–2712.

73. Hua, Z., A. M. Korany, S. H. El-Shinawy, and M. J. Zhu. 2019. Comparative evaluation of different sanitizers against *Listeria monocytogenes* biofilms on major food-contact surfaces. *Front. Microbiol.* 10:2462.

74. Huang, L. 2021. Surface roughness chart: understanding surface finishes. Available at: https://www.rapiddirect.com/blog/surface-roughness-chart/. Accessed 27 June 2022.

75. Huang, Y., S. Chakraborty, and H. Liang. 2020. Methods to probe the formation of biofilms: applications in foods and related surfaces. *Anal. Methods* 12:416–432.

76. Hultberg, A., and M. Shermann. 2018. Cleaning and sanitizing tools, harvest containers and surfaces. UMN Extension. Available at: https://extension.umn.edu/growing-safe-food/cleaning-and-sanitizing-tools-harvest-containers-and-surfaces. Accessed 7 July 2022.

77. Ibekwe, A. M., S. E. Murinda, and A. K. Graves. 2011. Microbiological evaluation of water quality from urban watersheds for domestic water supply improvement. *Int. J. Environ. Res. Publ. Healt*h 8:4460–4476.

78. Ibekwe, A. M., P. J. Shouse, and C. M. Grieve. 2006. Quantification of survival of *Escherichia coli* O157:H7 on plants affected by contaminated irrigation water. *Eng. Life Sci.* 6:566–572.

79. Ibusquiza, P. S., J. J. R. Herrera, and M. L. Cabo. 2011. Resistance to benzalkonium chloride, peracetic acid and nisin during formation of mature biofilms by *Listeria monocytogenes. Food Microbiol.* 28:418–425.

80. International Fresh Produce Association. 2020. Post-harvest operations harmonized food safety standard, v. 2.0. Food safety guidelines for the fresh-cut produce industry. Fourth Edition. Available at: https://www.freshproduce.com/siteassets/files/reports/food-safety/post-harvest-operations-harmonized-standard-april-2020.pdf. Accessed 10 July 2022.

81. Islam, M., M. P. Doyle, S. C. Phatak, P. Millner, and X. Jiang. 2005. Survival of *Escherichia coli* O157:H7 in soil and on carrots and onions grown in fields treated with contaminated manure composts or irrigation water. *Food Microbiol.* 22:63–70.

82. Islam, M., J. Morgan, M. P. Doyle, S. C. Phatak, P. Millner, and X. Jiang. 2004. Persistence of *Salmonella enterica* serovar Typhimurium on lettuce and parsley and in soils on which they were grown in fields treated with contaminated manure composts or irrigation water. *Foodborne Pathog. Dis.* 1:27–35.

83. Ivanek, R., Y. T. Gröhn, M. T. Wells, A. J. Lembo, B. D. Sauders, and M. Wiedmann. 2009. Modeling of spatially referenced environmental and meteorological factors influencing the probability of *Listeria* species isolation from natural environments. *Appl. Environ. Microbiol.* 75:5893–5909.

84. Jackson, L. S., F. M. Al-Taher, M. Moorman, J. W. DeVries, R. Tippett, K. M. J. Swanson, T. J. Fu, R. Salter, G. Dunaif, S. Estes, S. Albillos, and S. M. Gendel. 2008. Cleaning and other control and validation strategies to prevent allergen cross-contact in food-processing operations. *J. Food Prot.* 71:445–458.

85. Jechalke, S., J. Schierstaedt, M. Becker, B. Flemer, R. Grosch, K. Smalla, and A. Schikora. 2019. *Salmonella* establishment in agricultural soil and colonization of crop plants depend on soil type and plant species. *Front. Microbiol.* 10:967.

86. Jones, S. L., S. C. Ricke, D. Keith Roper, and K. E. Gibson. 2020. Swabbing the surface: critical factors in environmental monitoring and a path towards standardization and improvement. *Crit. Rev. Food Sci. Nutr.* 60:225–243.

87. Killinger, K., and A. Adhikari. 2014. Assessment of sanitation techniques for tree fruit storage bins. Available at: https://www.centerforproducesafety.org/amass/ documents/researchproject/345/CPS%20Final%20Report%20Killinger.pdf. Accessed 8 March 2022.

88. Kleine, D., J. Chodorski, S. Mitra, C. Schlegel, K. Huttenlochner, C. Müller-Renno, J. Mukherjee, C. Ziegler, and R. Ulber. 2019. Monitoring of biofilms grown on differentially structured metallic surfaces using confocal laser scanning microscopy. *Eng. Life Sci.* 19:513–521.

89. Knight, G. C., and H. M. Craven. 2010. A model system for evaluating surface disinfection in dairy factory environments. *Int. J. Food Microbiol.* 137:161–167.

90. Korany, A. M., Z. Hua, T. Green, I. Hanrahan, S. H. El-Shinawy, A. El-Kholy, G. Hassan, and M. J. Zhu. 2018. Efficacy of ozonated water, chlorine, chlorine dioxide, quaternary ammonium compounds and peroxyacetic acid against *Listeria monocytogenes* biofilm on polystyrene surfaces. *Front. Microbiol.* 9:2296.

91. Kuda, T., T. Koyanagi, G. Shibata, H. Takahashi, and B. Kimura. 2016. Effect of carrot residue on the desiccation and disinfectant resistances of food related pathogens adhered to a stainless steel surfaces. *LWT - Food Sci. Technol.* 74:251–254.

92. Kuda, T., G. Shibata, H. Takahashi, and B. Kimura. 2015. Effect of quantity of food residues on resistance to desiccation of food-related pathogens adhered to a stainless steel surface. *Food Microbiol.* 46:234–238.

93. Kusumaningrum, H. D., R. Paltinaite, A. J. Koomen, W. C. Hazeleger, F. M. Rombouts, and R. R. Beumer. 2003. Tolerance of *Salmonella* Enteritidis and *Staphylococcus aureus* to surface cleaning and household bleach. *J. Food Prot.* 66:2289–2295.

94. Kusumaningrum, H. D., G. Riboldi, W. C. Hazeleger, and R. R. Beumer. 2003. Survival of foodborne pathogens on stainless steel surfaces and cross-contamination to foods. *Int. J. Food Microbiol.* 85:227–236.

95. Lakicevic, B. Z., H. M. W. den Besten, and D. de Biase. 2022. Landscape of stress response and virulence genes among *Listeria monocytogenes* strains. *Front. Microbiol.* 12:738470.

96. Lambrechts, A. A., I. S. Human, J. H. Doughari, and J. F. R. Lues. 2014. Efficacy of low-pressure foam cleaning compared to conventional cleaning methods in the removal of bacteria from surfaces associated with convenience food. *Afr. Health Sci.* 14:585–592.

97. Lane, K., L. A. McLandsborough, W. R. Autio, and A. J. Kinchla. 2020. Efficacy of ATP monitoring for measuring organic matter on postharvest food contact surfaces. *J. Food Prot.* 83:1829–1837.

98. Lehto, M., R. Kuisma, J. Määttä, H. R. Kymäläinen, and M. Mäki. 2011. Hygienic level and surface contamination in fresh-cut vegetable production plants. *Food Control* 22:469–475.

99. Li, Q., L. Liu, A. Guo, X. Zhang, W. Liu, and Y. Ruan. 2021. Formation of multispecies biofilms and their resistance to disinfectants in food processing environments: a review. *J. Food Prot.* 84:2071–2083.

100. Liao, J., X. Guo, D. L. Weller, S. Pollak, D. H. Buckley, M. Wiedmann, and O. X. Cordero. 2021. Nationwide genomic atlas of soil-dwelling *Listeria* reveals effects of selection and population ecology on pangenome evolution. *Nat. Microbiol.* 6:1021–1030.

101. Litt, P. K., A. Kelly, A. Omar, G. Johnson, B. T. Vinyard, K. E. Kniel, and M. Sharma. 2021. Temporal and agricultural factors influence *Escherichia coli* survival in soil and transfer to cucumbers. *Appl. Environ. Microbiol.* 87:e02418-20.

102. Locatelli, A., A. Spor, C. Jolivet, P. Piveteau, and A. Hartmann. 2013. Biotic and abiotic soil properties influence survival of *Listeria monocytogenes* in soil. *PLoS One* 8:e75969.

103. López-Gálvez, F., L. Rasines, E. Conesa, P. A. Gómez, F. Artés-Hernández, and E. Aguayo. 2021. Reusable plastic crates (RPCs) for fresh produce (case study on cauliflowers): sustainable packaging but potential *Salmonella* survival and risk of cross-contamination. *Foods* 10:1254.

104. Lyautey, E., A. Hartmann, F. Pagotto, K. Tyler, D. R. Lapen, G. Wilkes, P. Piveteau, A. Rieu, W. J. Robertson, D. T. Medeiros, T. A. Edge, V. Gannon, and E. Topp. 2007. Characteristics and frequency of detection of fecal *Listeria monocytogenes* shed by livestock, wildlife, and humans. *Can. J. Microbiol.* 53:1158–1167.

105. Ma, J., A. M. Ibekwe, D. E. Crowley, and C. H. Yang. 2014. Persistence of *Escherichia coli* O157 and non-O157 strains in agricultural soils. *Sci. Total Environ.* 490:822–829.

106. Mai, T. L., N. I. Sofyan, J. W. Fergus, W. F. Gale, and D. E. Conner. 2006. Attachment of *Listeria monocytogenes* to an austenitic stainless steel after welding and accelerated corrosion treatments. *J. Food Prot.* 69:1527–1532.

107. Marik, C. M., J. Zuchel, D. W. Schaffner, and L. K. Strawn. 2020. Growth and survival of *Listeria monocytogenes* on intact fruit and vegetable surfaces during postharvest handling: a systematic literature review. *J. Food Prot.* 83:108–128.

108. Marriott, N. G., M. W. Schilling, and R. B. Gravani. 2018. Principles of food sanitation. Springer, Cham, Germany.

109. Martinez, B. A., A. Bianchini, J. Stratton, O. Raabe, and S. Swanson. 2021. Condensation removal practices and their potential for contributing to environmental pathogen contamination in food processing facilities. *J. Food Prot.* 84:1047–1054.

110. Matthews, K. R. 2013. Sources of enteric pathogen contamination of fruits and vegetables: future directions of research. *Stewart Postharvest Rev.* 9:1–5.

111. Maule, A. 2000. Survival of verocytotoxigenic *Escherichia coli* O157 in soil, water and on surfaces. *Symp. Ser. Soc. Appl. Microbiol.* 88(29):71S-78S.

112. Mazaheri, T., B. R. H. Cervantes-Huamán, M. Bermúdez-Capdevila, C. Ripolles-Avila, J. J. Rodríguez-Jerez, and E. González-Fandos. 2021. *Listeria monocytogenes* biofilms in the food industry: is the current hygiene program sufficient to combat the persistence of the pathogen? *Microorganisms* 9:181.

113. McLaughlin, H. P., P. G. Casey, J. Cotter, C. G. M. Gahan, and C. Hill. 2011. Factors affecting survival of *Listeria monocytogenes* and *Listeria innocua* in soil samples. *Arch. Microbiol.* 193:775–785.

114. Mevo, S. I. U., M. Ashrafudoulla, M. F. R. Mizan, S. H. Park, and S. do Ha. 2021. Promising strategies to control persistent enemies: some new technologies to combat biofilm in the food industry—a review. *Compr. Rev. Food Sci. Food Saf.* 20:5938–5964.

115. Mildenhall, K. B., and S. A. Rankin. 2020. Implications of adenylate metabolism in hygiene assessment: a review. *J. Food Prot.* 83:1619–1631.

116. Moore, C. M., B. W. Sheldon, and L.-A. Jaykus. 2003. Transfer of *Salmonella* and *Campylobacter* from stainless steel to romaine lettuce. *J. Food Prot.* 66:2231–2236.

117. Møretrø, T., and S. Langsrud. 2011. Effects of materials containing antimicrobial compounds on food hygiene. *J. Food Prot.* 74:1200–1211.

118. Morey, A., S. R. McKee, J. S. Dickson, and M. Singh. 2010. Efficacy of ultraviolet light exposure against survival of *Listeria monocytogenes* on conveyor belts. *Foodborne Pathog. Dis.* 7:737–740.

119. Murphy, C. M., D. L. Weller, M. S. Reiter, C. A. Bardsley, J. Eifert, M. Ponder, S. L. Rideout, and L. K. Strawn. 2022. Anaerobic soil disinfestation, amendment-type, and irrigation regimen influence *Salmonella* survival and die-off in agricultural soils. *J. Appl. Microbiol.* 132:2342–2354.

120. Natvig, E. E., S. C. Ingham, B. H. Ingham, L. R. Cooperband, and T. R. Roper. 2002. *Salmonella enterica* serovar Typhimurium and *Escherichia coli* contamination of root and leaf vegetables grown in soils with incorporated bovine manure. *Appl. Environ. Microbiol.* 68:2737–2744.

121. Niemira, B. A., G. Boyd, and J. Sites. 2014. Cold plasma rapid decontamination of food contact surfaces contaminated with *Salmonella* biofilms. *J. Food Sci.* 79(5):M917–M922.

122. Ongeng, D., A. H. Geeraerd, D. Springael, J. Ryckeboer, C. Muyanja, and G. Mauriello. 2015. Fate of *Escherichia coli* O157:H7 and *Salmonella enterica* in the manure-amended soil-plant ecosystem of fresh vegetable crops: a review. *Crit. Rev. Microbiol.* 41:273–294.

123. Pang, H., R. McEgan, A. Mishra, S. A. Micallef, and A. K. Pradhan. 2017. Identifying and modeling meteorological risk factors associated with pre-harvest contamination of *Listeria* species in a mixed produce and dairy farm. *Food Res. Int.* 102:355–363.

124. Park, S., B. Szonyi, R. Gautam, K. Nightingale, J. Anciso, and R. Ivanek. 2012. Risk factors for microbial contamination in fruits and vegetables at the preharvest level: a systematic review. *J. Food Prot.* 75:2055–2081.

125. Patrignani, F., L. Siroli, F. Gardini, and R. Lanciotti. 2016. Contribution of two different packaging material to microbial contamination of peaches: implications in their microbiological quality. *Front. Microbiol.* 7:938.

126. Patterson, L., N. Navarro-Gonzalez, M. T. Jay-Russell, P. Aminabadi, E. Antaki-Zukoski, and A. F. A. Pires. 2018. Persistence of *Escherichia coli* in the soil of an organic mixed crop-livestock farm that integrates sheep grazing within vegetable fields. *Zoonoses Public Health* 65:887–896.

127. Phan-Thien, K., M. H. Metaferia, T. L. Bell, M. I. Bradbury, H. P. Sassi, F. F. van Ogtrop, T. V. Suslow, and R. McConchie. 2020. Effect of soil type and temperature on survival of *Salmonella enterica* in poultry manure–amended soils. *Lett. Appl. Microbiol.* 71:210–217.

128. Pinho, A. C., and A. P. Piedade. 2020. Polymeric coatings with antimicrobial activity: a short review. *Polymers* 12:2469.

129. Pires, A., T. Ramos, P. D. Millner, J. Stover, P. Pagliari, M. Hutchinson, J. Liley, N. Rowley, P. Aminabadi, J. Baron, A. Kenney, F. Hashem, and M. Jay-Russell. 2020. Risk factors associated with *Escherichia coli* persistence in soils amended with raw manure in certified organic farming systems in four regions of USA. *J. Food Prot.* 83(Suppl. A):239.

130. Pires, A., T. Ramos, P. D. Millner, J. Stover, P. Pagliari, M. Hutchinson, J. Liley, N. Rowley, P. Aminabadi, J. Baron, A. Kenney, F. Hashem, and M. Jay-Russell. 2020. Risk factors associated with prevalence of foodborne pathogens in manured soils from USDA-NOP-certified organic farms in four regions of USA. *J. Food Prot.* 83(Suppl. A):36.

131. Produce Safety Alliance. n.d. General resource listing. Available at: https://producesafetyalliance.cornell.edu/resources/general-resource-listing/. Accessed 6 July 2022.

132. Rafeeq, S., and R. Ovissipour. 2021. The effect ultrasound and surfactants on nanobubbles efficacy against *Listeria innocua* and *Escherichia coli* O157:H7, in cell suspension and on fresh produce surfaces. *Foods* 10:2154.

133. Reed-Jones, N. L., S. C. Marine, K. L. Everts, and S. A. Micallef. 2016. Effects of cover crop species and season on population dynamics of *Escherichia coli* and *Listeria innocua* in soil. *Appl. Environ. Microbiol.* 82:1767–1777.

134. Reitz, S. R., C. C. Shock, E. B. G. Feibert, A. Rivera, L. D. Saunders, H. Kreeft, and J. Klauzer. 2016. Dry bulb onion storage in sterilized plastic crates compared to storage in old wooden boxes. Oregon State University Malheur Experiment Station annual report 2015, Department of Crop and Soil Science Ext/CrS 156. Available at: https://agsci.oregonstate.edu/article/dry-bulb-onion-storage-sterilized-plastic-crates-compared-storage-old-wooden-boxes-0. Accessed 26 June 2022.

135. Riggio, G. M., Q. Wang, K. E. Kniel, and K. E. Gibson. 2019. Microgreens—a review of food safety considerations along the farm to fork continuum. *Int. J. Food Microbiol.* 290:76–85.

136. Rodriguez, A., W. R. Autio, and L. A. McLandsborough. 2008. Effect of surface roughness and stainless steel finish on *Listeria monocytogenes* attachment and biofilm formation. *J. Food Prot.* 71:170–175.

137. Ruiz-Llacsahuanga, B., A. Hamilton, R. Zaches, I. Hanrahan, and F. Critzer. 2021. Utility of rapid tests to assess the prevalence of indicator organisms (aerobic plate count, *Enterobacteriaceae*, coliforms, *Escherichia coli*, and *Listeria* spp.) in apple packinghouses. *Int. J. Food Microbiol.* 337:108949.

138. Sadekuzzaman, M., S. Yang, M. F. R. Mizan, and S. D. Ha. 2015. Current and recent advanced strategies for combating biofilms. *Compr. Rev. Food Sci. Food Saf.* 14:491–509.

139. Sagoo, S. K., C. L. Little, C. J. Griffith, and R. T. Mitchell. 2009. Evaluation of the hygiene of ready-to-eat food preparation areas and practices in mobile food vendors in the UK. *Int. J. Environ. Health Res.*19:431–443.

140. Sanchez-Vizuete, P., B. Orgaz, S. Aymerich, D. le Coq, and R. Briandet. 2015. Pathogens protection against the action of disinfectants in multispecies biofilms. *Front. Microbiol.* 6:705.

141. Sansebastiano, G., R. Zoni, and L. Bigliardi. 2007. Cleaning and disinfection procedures in the food industry general aspects and practical applications, p. 253–280. *In* A. McElhatton and R. J. Marshall (ed.), Food safety, vol. 1. Springer, Boston, MA.

142. Schaffner, D. W., D. Jensen, C. P. Gerba, D. Shumaker, and J. W. Arbogast. 2018. Influence of soap characteristics and food service facility type on the degree of bacterial contamination of open, refillable bulk soaps. *J. Food Prot.* 81:218–225.

143. Schmidt, R. H. 2009. Basic elements of equipment cleaning and sanitizing in food processing and handling operations. Institute of Food and Agricultural Sciences, University of Florida, Gainesville.

144. Sharma, S., S. Jaiswal, B. Duffy, and A. K. Jaiswal. 2022. Advances in emerging technologies for the decontamination of the food contact surfaces. FoSilva, S., P. Teixeira, R. Oliveira, and J. Azeredo. 2008. Adhesion to and viability of *Listeria monocytogenes* on food contact surfaces. *J. Food Prot.* 71:1379–1385.

145. Silva, S., P. Teixeira, R. Oliveira, and J. Azeredo. 2008. Adhesion to and viability of *Listeria monocytogenes* on food contact surfaces. *J. Food Prot.* 71:1379–1385.

146. Siroli, L., F. Patrignani, D. I. Serrazanetti, C. Chiavari, M. Benevelli, L. Grazia, and R. Lanciotti. 2017. Survival of spoilage and pathogenic microorganisms on cardboard and plastic packaging materials. *Front. Microbiol.* 8:2606.

147. Smith, A., E. Moorhouse, J. Monaghan, C. Taylor, and I. Singleton. 2018. Sources and survival of *Listeria monocytogenes* on fresh, leafy produce. *J. Appl. Microbiol.* 125:930–942.

148. Smith, D. L. 2019. Global Food Safety Initiative scheme audit requirements regarding cleaning tool and utensil selection and maintenance—a review. *Qual. Assur. Saf. Crops Foods* 11:603–611.

149. Smoot, L. M., and M. D. Pierson. 1998. Effect of environmental stress on the ability of *Listeria monocytogenes* Scott A to attach to food contact surfaces. *J. Food Prot.* 61:1293–1298.

150. Sogin, J. H., G. Lopez-Velasco, B. Yordem, C. K. Lingle, J. M. David, M. Çobo, and R. W. Worobo. 2021. Implementation of ATP and microbial indicator testing for hygiene monitoring in a tofu production facility improves product quality and hygienic conditions of food contact surfaces: a case study. *Appl. Environ. Microbiol.* 87:e02278-20.

151. Sreedharan, A., K. R. Schneider, and M. D. Danyluk. 2014. *Salmonella* transfer potential onto tomatoes during laboratory-simulated in-field debris removal. *J. Food Prot.* 77:1062–1068.

152. Stasiewicz, M. J., H. F. Oliver, M. Wiedmann, and H. C. den Bakker. 2015. Whole-genome sequencing allows for improved identification of persistent *Listeria monocytogenes* in food-associated environments. *Appl. Environ. Microbiol.* 81:6024–6037.

153. Stone, D., J. Kovacevic, and S. Brown. 2020. Sanitizer basics for the food industry. PNW 752. Pacific Northwest Extension Publishing. Available at: https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw752.pdf. Accessed 2 March 2022.

154. Strawn, L. K., M. D. Danyluk, R. W. Worobo, and M. Wiedmann. 2014. Distributions of *Salmonella* subtypes differ between two U.S. produce-growing regions. *Appl. Environ. Microbiol.* 80:3982–3991.

155. Strawn, L. K., Y. T. Gröhn, S. Warchocki, R. W. Worobo, E. A. Bihn, and M. Wiedmann. 2013. Risk factors associated with *Salmonella* and *Listeria monocytogenes* contamination of produce fields. *Appl. Environ. Microbiol.* 79:7618–7627.

156. Sullivan, G., and M. Wiedmann. 2020. Detection and prevalence of *Listeria* in U.S. produce packinghouses and fresh-cut facilities. *J. Food Prot.* 83:1656–1666.

157. Suslow, T. 2020. Scientifically valid corrective actions for multiple harvest shade-house production systems. Available at: https://www.centerforproducesafety.org/amass/documents/researchproject/424/CPS%20Final%20Report%20-%20Suslow%20%28Shade%20house%29_March%202020.pdf. Accessed 22 June 2022.

158. Suslow, T. V., M. P. Oria, L. R. Beuchat, E. H. Garrett, M. E. Parish, L. J. Harris, J. N. Farber, and F. F. Busta. 2003. Production practices as risk factors in microbial food safety of fresh and fresh-cut produce. *Compr. Rev. Food Sci. Food Saf.* 2:38–77.

159. Tan, X., T. Chung, Y. Chen, D. Macarisin, L. Laborde, and J. Kovac. 2019. The occurrence of *Listeria monocytogenes* is associated with built environment microbiota in three tree fruit processing facilities. *Microbiome* 7:115.

160. Taormina, P. J., and L. R. Beuchat. 2002. Survival of *Listeria monocytogenes* in commercial food-processing equipment cleaning solutions and subsequent sensitivity to sanitizers and heat. *J. Appl. Microbiol.* 92:71–80.

161. Taormina, P. J., L. R. Beuchat, M. C. Erickson, L. I. Ma, G. Zhang, and M. P. Doyle. 2009. Transfer of *Escherichia coli* O157:H7 to iceberg lettuce via simulated field coring. *J. Food Prot.* 72:465–472.

162. Todd-Searle, J., L. M. Friedrich, R. A. Oni, K. Shenge, J. T. LeJeune, S. A. Micallef, M. D. Danyluk, and D. W. Schaffner. 2020. Quantification of *Salmonella enterica* transfer between tomatoes, soil, and plastic mulch. *Int. J. Food Microbiol.* 316:108480.

163. Townsend, A., L. K. Strawn, B. J. Chapman, and L. L. Dunn. 2021. A systematic review of *Listeria* species and *Listeria monocytogenes* prevalence, persistence, and diversity throughout the fresh produce supply chain. *Foods* 10:1427.

164. Truitt, L. N., K. M. Vazquez, R. C. Pfuntner, S. L. Rideout, A. H. Havelaar, and L. K. Strawn. 2018. Microbial quality of agricultural water used in produce preharvest production on the eastern shore of Virginia. *J. Food Prot.* 81:1661–1672.

165. Truong, H. N., D. Garmyn, L. Gal, C. Fournier, Y. Sevellec, S. Jeandroz, and P. Piveteau. 2021. Plants as a realized niche for *Listeria monocytogenes. Microbiologyopen* 10:e1255.

166. U.S. Food and Drug Administration. 1998. Guidance for industry: guide to minimize microbial food safety hazards for fresh fruits and vegetables. Available at: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-guide-minimize-microbial-food-safety-hazards-fresh-fruits-and-vegetables. Accessed 7 July 2022.

167. U.S. Food and Drug Administration. 2008. Guidance for industry: guide to minimize microbial food safety hazards of fresh-cut fruits and vegetables. Available at: https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-guide-minimize-microbial-food-safety-hazards-fresh-cut-fruits-and-vegetables. Accessed 7 March 2022.

168. U.S. Food and Drug Administration. 2015. Standards for the growing, harvesting, packing, and holding of produce for human consumption. *Fed. Regist.* 80:74353–74672.

169. U.S. Food and Drug Administration. 2022. Factors potentially contributing to the contamination of packaged leafy greens implicated in the outbreak of *Salmonella* Typhimurium during the summer of 2021. Available at: https://www.fda.gov/food/outbreaks-foodborne-illness/factors-potentially-contributing-contamination-packaged-leafy-greens-implicated-outbreak-salmonella. Accessed 10 February 2022.

170. van Elsas, J. D., M. Chiurazzi, C. A. Mallon, D. Elhottova, V. Krištůfek, and J. F. Salles. 2012. Microbial diversity determines the invasion of soil by a bacterial pathogen. *Proc. Natl. Acad. Sci.* USA 109:1159–1164.

171. Verran, J., R. D. Boyd, K. Hall, and R. H. West. 2001. Microbiological and chemical analyses of stainless steel and ceramics subjected to repeated soiling and cleaning treatments. *J. Food Prot.* 64:1377–1387.

172. Verran, J., A. Packer, P. Kelly, and K. A. Whitehead. 2010. Titanium-coating of stainless steel as an aid to improved cleanability. *Int. J. Food Microbiol.* 141 (Suppl. 1):S134–S139.

173. Verran, J., D. L. Rowe, and R. D. Boyd. 2001. The effect of nanometer dimension topographical features on the hygienic status of stainless steel. *J. Food Prot.* 64:1183–1187.

174. Wang, R., Y. Zhou, N. Kalchayanand, D. M. Harhay, and T. L. Wheeler. 2021. Consecutive treatments with a multicomponent sanitizer inactivate biofilms formed by *Escherichia coli* O157:H7 and *Salmonella enterica* and remove biofilm matrix. *J. Food Prot.* 84:408–417.

175. Wang, Y., Z. Ye, and Y. Ying. 2012. New trends in impedimetric biosensors for the detection of foodborne pathogenic bacteria. *Sensors* 12:3449–3471.

176. Weller, D., S. Shiwakoti, P. Bergholz, Y. Grohn, M. Wiedmann, and L. K. Strawn. 2015. Validation of a previously developed geospatial model that predicts the prevalence of *Listeria monocytogenes* in New York State produce fields. *Appl. Environ. Microbiol.* 82:797–807.

177. Weller, D., M. Wiedmann, and L. K. Strawn. 2015. Irrigation is significantly associated with an increased prevalence of *Listeria monocytogenes* in produce production environments in New York State. *J. Food Prot.* 78:1132–1141.

178. Weller, D., M. Wiedmann, and L. K. Strawn. 2015. Spatial and temporal factors associated with an increased prevalence of *Listeria monocytogenes* in spinach fields in New York State. *Appl. Environ. Microbiol.* 81:6059–6069.

179. Western Growers. 2016. Commodity specific food safety guidelines for the production and harvest of lettuce and leafy greens. Available at: https://www.wga.com/sites/default/files/resource/files/California%20LGMA%20metrics%2001%2029%2016%20Final.pdf. Accessed 13 March 2022.

180. Whitehead, K. A., D. Rogers, J. Colligon, C. Wright, and J. Verran. 2006. Use of the atomic force microscope to determine the effect of substratum surface topography on the ease of bacterial removal. *Colloids Surf. B Biointerfaces* 51:44–53.

181. Williams, A. P., L. M. Avery, K. Killham, and D. L. Jones. 2005. Persistence of *Escherichia coli* O157 on farm surfaces under different environmental conditions. *J. Appl. Microbiol.* 98:1075–1083.

182. Wißmann, J. E., L. Kirchhoff, Y. Brüggemann, D. Todt, J. Steinmann, and E. Steinmann. 2021. Persistence of pathogens on inanimate surfaces: a narrative review. *Microorganisms* 9:343.

183. Yang, H., P. A. Kendall, L. C. Medeiros, and J. N. Sofos. 2009. Efficacy of sanitizing agents against *Listeria monocytogenes* biofilms on high-density polyethylene cutting board surfaces. *J. Food Prot.* 72:990–998.

184. Yoon, S. H., N. Rungraeng, W. Song, and S. Jun. 2014. Superhydrophobic and superhydrophilic nanocomposite coatings for preventing *Escherichia coli* K-12 adhesion on food contact surface. *J. Food Eng.* 131:135–141.

185. You, Y., S. C. Rankin, H. W. Aceto, C. E. Benson, J. D. Toth, and Z. Dou. 2006. Survival of *Salmonella enterica* serovar Newport in manure and manure-amended soils. *Appl. Environ. Microbiol.* 72:5777–5783.

186. Yuan, L., M. F. Hansen, H. L. Røder, N. Wang, M. Burmølle, and G. He. 2020. Mixed-species biofilms in the food industry: current knowledge and novel control strategies. *Crit. Rev. Food Sci. Nutr.* 60:2277–2293.

187. Zapka, C. A., E. J. Campbell, S. L. Maxwell, C. P. Gerba, M. J. Dolan, J. W. Arbogast, and D. R. Macinga. 2011. Bacterial hand contamination and transfer after use of contaminated bulk-soap-refillable dispensers. *Appl. Environ. Microbiol.* 77:2898–2904.

188. Zhou, B., Y. Luo, P. Millner, and H. Feng. 2012. Sanitation and design of lettuce coring knives for minimizing *Escherichia coli* O157:H7 contamination. *J. Food Prot.* 75:563–566.

189. Zhu, J., H. An, M. Alheshibri, L. Liu, P. M. J. Terpstra, G. Liu, and V. S. J. Craig. 2016. Cleaning with bulk nanobubbles. *Langmuir* 32:11203–11211.

190. Zhu, Q., R. Gooneratne, and M. A. Hussain. 2017. *Listeria monocytogenes* in fresh produce: outbreaks, prevalence and contamination levels. *Foods* 6:21.