Review Article

A review of fresh produce outbreaks, current interventions, food safety concerns and potential benefits of novel antimicrobial sodium acid sulfate

Abstract

This article provides a comprehensive literature review of the growing significance that foodborne pathogens have on the produce supply and the steps that are taken to reduce them. The numbers of illnesses that are caused by contaminated produce are rising steadily. Three of the most common pathogens that have been seen to cause significant illness in humans through produce are *Escherichia coli*, *Salmonella spp*. and *Listeria monocytogenes*. The antimicrobial interventions, practices and antimicrobials that are currently the most commonly used by the food industry are examined. The literature shows that these antimicrobials currently in use have significant drawbacks when it comes to their role in the produce industry. Sensitivities to temperature and organic load and the production of harmful by products are some of these drawbacks. There is a need for a new antimicrobial that can be used in the produce processing industry. One that maintains its efficacy through the temperature, pH, and organic load changes that are experienced during produce processing. Sodium acid sulfate is a potential contender for this role. It has not previously been used or extensively studied as an antimicrobial, but is already deemed generally recognized as safe (GRAS) product by the Food and Drug Administration (FDA). The use of an antimicrobial that can withstand the varying conditions that the produce industry constantly has is imperative to reducing the number of foodborne illness caused every year by contaminated produce.

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Intoducton

Fresh produce consumption

The amount of fresh produce consumed worldwide has risen steadily over the past several years.[1] Consumers are becoming more aware of their health and nutrient intake and therefore choosing to consume more natural and healthy foods, namely fresh produce including, fresh or minimally processed fruits and vegetables. Not only are these great go-to snacks for adults, but parents are also shifting from offering their children foods that have been highly processed like potato chips or fast food to fresh fruits and vegetables. In addition to the numerous health benefits that fresh produce has to offer, they are also an easy to eat, grab-and-go snack for busy lifestyles. An increase in the use of fresh fruits and vegetables in restaurants, hotels, fast food chains and catering services is worth mentioning as well.

Fresh produce is known to be an excellent source of nutrients such as polyphenols, vitamins, dietary fiber, proteins, carbohydrates, and minerals.[2–5] Another benefit of its consumption is that fresh produce has been known to reduce the risk of chronic diseases, lower cholesterol, and reduce the risk of birth defects.[6] Overall, fresh fruits and vegetables are a part of a healthy diet.[7] For these reasons, doctors and other healthcare providers are pleading the case of the importance of consuming fresh produce to their patients for the numerous benefits that can come from them. There have also been campaigns and other efforts made by government agencies to promote the consumption of fresh fruits and vegetables.[8] Since obesity and other health problems are becoming more prevalent here in the United States, more attention is being brought to the benefits of consuming healthy food, in an effort to prevent these issues from occurring rather than treating them when they do.

Consumers want to meet the standards of healthy living and the consumption of fresh produce fits perfectly into that standard. In addition to the benefits fresh produce provides to nutritional state, consumers are looking for more ready-to-eat (RTE) foods such as fresh produce because they feel they do not have adequate time to cook meals at home and the demand for convenience is a growing factor as well.[9,10] Fresh produce is affordable for most families and provides a way for them to meet this healthier standard that the world is moving towards, without having to exert much effort. Along with this increase in popularity and consumption, foodborne illnesses associated with fresh produce are also increasing.[1]

Foodborne illness associated with fresh produce

The Food and Drug Administration (FDA) is tasked with the responsibility of ensuring that the fresh fruits and vegetables (both imported and domestic) that are consumed in the United States are safe. With a signature from President Obama on January 4th, 2011, the FDA implemented what is known as the Food Safety Modernization Act (FSMA) which was the most sweeping reform of food safety laws in the United States in over 70 years. There are seven rules within FSMA, one of which being the Produce Safety Rule which is in place to ensure that farms are taking steps to improve produce safety on the farm level. Prior to the implementation of this rule, there was no regulatory standard that growers were required to follow; there were only voluntary guidance documents that they were strongly encouraged to follow. No matter the size of the farm, precautions and reduction of food safety risks can be implemented. However, the farm can never be considered an absolute zero risk, so minimizing these risks is the ultimate goal of the FSMA Produce Safety Rule.

The FDA places an emphasis on the fact that they aim to prevent these safety issues from occurring rather than treating them after they do. Therefore, each year, work is conducted to estimate the number of foodborne illness that occurred in that year and what pathogens were the cause of those illnesses. This is done to direct the FDA and the food industry, as well as individuals who are involved in it, to take steps and implement policy to reduce this number and prevent foodborne illnesses from occurring in the years to come. Every year, as many as 1 in 6 Americans become sick with a foodborne illness by consuming food products that are contaminated with foodborne pathogens.[11] The number one cause of these foodborne illnesses is fresh produce.[12,13] Fresh produce is believed to account for 26% of the total economic loss caused by foodborne illnesses, costing $39 billion dollars, annually in the United States alone.

Though already the number one cause, foodborne illnesses and outbreaks caused by fresh fruits and vegetables are still on the rise 1. Foodborne illnesses can be classified as an outbreak whenever there are two or more cases of the same illness that were likely caused by consuming the same food product. This is in exception to when an illness with Clostridium botulinum occurs, in which case, a singular occurrence is considered to be an outbreak. In the time between 2003 and 2012 it was estimated that around 194,000 foodborne illnesses were caused by FDA-regulated fresh produce products compared to the time period between 1996 and 2014 when there were only 173 outbreaks that occurred that related to fresh produce.[14] The most common and well known types of produce involved in these outbreaks include lettuce and sprouts, however foodborne pathogen contamination is not limited to these commonly associated types of produce and has been seen across all categories.[15]

Contamination of fresh produce with foodborne pathogens can occur at virtually any phase of production or processing.[16] Most foodborne pathogens that are associated with fresh produce are enteric or fecal in origin.[17] Many food-producing animals such as cattle, chickens, pigs, and turkey are sources of foodborne pathogens. Some pathogens that these animals are known to harbor include: Campylobacter species, non-Typhoidal serotypes of Salmonella enterica, Shiga toxin-producing strains of *Escherichia coli*, and *Listeria monocytogenes*.[18] Soil is known to harbor pathogens which can make humans become ill, for weeks,[19] and improperly composted animal manure or domestic or wild animal encroachment can introduce these pathogens into the soil.[20] Therefore, produce has a high risk of being contaminated before it is even harvested. Water is also a known to harbor pathogens, and cause contamination. An example of this would be irrigation water, contaminated with animal feces, being used to irrigate a produce crop field. Equipment used for harvesting, sorting, cleaning, transporting or packing the produce can also be a source of contamination.[21] During the washing process at a processing facility, any contamination that may be present on any of the produce will likely be spread to the other produce unless an adequate antimicrobial sanitation step is in place.

The processing and production cycle for many food products include some type of pathogen control step. Whether it be in the processing facility or by the consumer at home, food products are usually cooked to a certain temperature or otherwise handled in a manner that has been proven to control or minimize contamination risk. This however, is not the case for fresh produce. Fresh produce is commonly known as a minimally-processed food, which can be defined as a commodity which is eaten raw and has not received an approved treatment to reduce pathogenic bacteria, their spores or toxins, to a safe level.[22] The main cause for such a large number of illnesses being attributed to fresh produce is likely due to the fact that there is most commonly no cooking or other kill step. This means that any pathogens that are present on the produce at the time the consumer purchases it are highly likely to be consumed. Therefore, the steps taken by both producers and processers are potentially the only protective steps in place that prevent the consumer from ingesting any foodborne pathogens that may be present.

Common types of pathogens of concern in produce

The most common type of biological hazard related to fresh produce are viruses followed by bacteria and then parasites.[23] Although there are more than 250 known pathogens,[24] a select few can be named as ones which cause a significant number of illnesses. Of the up to 47.8 million foodborne illness cases that occur annually in the United States, 9.4 million cases, 55,961 hospitalizations, and 1,351 deaths can be attributed to a select group of 31 foodborne pathogens; of which 59% were caused by viruses, 39% by bacteria, and 2% by parasites.[23] These contaminated produce products can either be domestically or locally grown, or they can be imported products. Outbreaks have occurred in produce from both sources. Out of all of the total produce-associated outbreaks, sprouts, leafy greens, melons, tomatoes, berries, herbs, cucumbers and green onions accounted for 85 percent of the implicated commodities.[14]

Viruses

Viruses are microorganisms that are very small and are shed in the feces, meaning they are spread by the fecal-oral route.[25] They are unable to replicate without a living host, meaning that their numbers cannot increase during storage.[26,27] These microorganisms can also live in humans and be spread by blood contact or other bodily fluids. For example, if a worker with a virus (such as Hepatitis A) cuts themselves and then has contact with food products, the product could become contaminated and cause further contamination and/or illness in the consumer. The symptoms associated with ingestion of foodborne viruses range in severity from mild diarrhea to hepatitis, severe neural diseases, flaccid paralysis, with even rare events of myocarditis, respiratory disease or hemorrhagic fever.[28] Viruses most commonly cause acute gastroenteritis in humans. Common symptoms of this include abdominal pain and cramps, diarrhea, vomiting, fatigue, and sometimes headaches and fever. What consumers commonly consider to be a case of the stomach flu is typically the result of illness caused by a virus, namely, norovirus. Fresh produce can become contaminated with viruses by contaminated soil, irrigation water, or by organic fertilizer used in the field 26. Viruses are unique in that they are resistant to interventions that would eliminate the contamination of other pathogens, such as bacteria. Viruses can withstand drastic temperatures from freezing to 60°C and are resistant to treatments such as chlorination.[29]

Common types of illness causing viruses are, noroviruses (NoV), hepatitis A virus (HAV), rotavirus, astrovirus and enteric adenoviruses, of which NoV was by far the major causative agent of human foodborne viral illness.[30, 31] Norovirus is expected to be responsible for 58% of all foodborne illnesses that occur domestically in the United States, more than 5.5 million cases annually 23. HAV is the leading cause of acute viral hepatitis, and is responsible for 1.5 million reported cases and tens of millions of infections each year.[32]

In 2003, green onions were implicated in a large outbreak of hepatitis A virus (HAV).[33] Cruise ships have a long running history with foodborne outbreaks, especially those which are caused by viruses due to their ability to replicate without a host. 217 passengers aboard a cruise ship were victim to a gastroenteritis outbreak that occurred in fresh produce due to contamination with Norwalk virus in 1990.[34] The CDC reported a multi-state outbreak of Hepatitis A linked to frozen strawberries in 2006. This outbreak was responsible for 143 illnesses and 56 hospitalizations across 9 states. The CDC also reported a multi-state outbreak of Hepatitis A causing 162 illnesses and 71 hospitalizations across 10 states, linked to pomegranate seeds in 2013.

The detection of viruses within the fresh produce industry is lacking and until recently, there was no data available documenting the prevalence of NoV within this industry.[31] The lack of detection methods has reduced the efficiency of eliminating this food safety risk from our produce supply. However, in the last several years, detection and extraction of this hazard has been studied.[35,36] Further studies are necessary to continue to develop better practices for reducing and eliminating the risk that viruses pose to the integrity of our produce supply.

Parasites

The least common cause of foodborne illness is parasites. However, it is likely that the number reported are only a small portion or percentage of the actual cases due to the fact that there are only 10 parasites in the FoodNet surveillance system, and the majority of parasites are non-notifiable meaning that physicians are not obligated nor required to report illnesses that are caused by them.[37] Infection with parasites can come from a variety of animals including contaminated cattle, sheep, goats, poultry, fish, and shrimp, and they can also come from contaminated soil or water.[38] Parasites are usually spread to humans when we consume their host,[39] by fecal-oral route which means human-to-human or animal-to-human, or by drinking contaminated water.[40,41] Common parasites of concern for causing human illness include Cryptosporidium, Giardia and Cyclospora. These three, specifically, have been associated with numerous cases of diarrheal illness in humans.[42] Other symptoms associated with illnesses caused by parasites include abdominal cramps, bloating, weight loss and malabsorption.[40]

In 2003, cilantro was the suspected culprit for 11 Cyclospora illnesses.[43] In 2013 the CDC reported a rather large parasite outbreak caused by Cyclospora. This outbreak was responsible for 631 illnesses, of which 49 ill persons required hospitalization. There were 25 states involved in this outbreak, and fresh produce was determined to be the source of infection. In 2018, a fresh salad mix sold at McDonald's was the source of Cyclospora illness for 511 people across 16 states, of those infected, 24 required hospitalization.[44] Also in 2018, fresh vegetable trays, contaminated with Cyclospora were the cause of illness for 250 people from 4 states, 8 of those infected required hospitalization.[45]

Bacteria

Bacteria are single-celled microorganisms that are capable of multiplying within or outside of a host. Bacteria are able to replicate and multiply very quickly under optimal conditions, up to once every 20 minutes. Bacterial pathogens are generally transmitted to food products by contaminated soil, animal feces, humans, contaminated water or equipment.[21] Symptoms of a bacterial infection in humans can be as minor as abdominal pain and diarrhea or become much more serious such as life threatening hemolytic-uremic syndrome (HUS) which can occur with infection of *E. coli* 0157:H7. Bacteria have evolved and adapted over time, giving them the ability to survive and multiply in what would previously have been an inhospitable environment.[46] This makes bacterial pathogen research extremely important as frequent new interventions are necessary to inhibit and control bacterial growth. When thinking of bacterial pathogens that are of major concern in the produce industry there are three that are of extreme significance, shigatoxin producing *Escherichia coli* (*E. coli*), *Salmonella spp*., and *Listeria monocytogenes*.[47–49] There have been numerous outbreaks caused by these pathogens associated with fresh produce over the past several years.

Escherichia coli

E. coli belongs to the family Enterobacteriaceae and is a gram-negative rod-shaped bacterium that has many different strains. Some strains live inside the gastrointestinal tract of humans and do not cause problems, because they are non-pathogenic. However, there are some strains, which live in animals such as cattle and sheep that are released in their feces and sometimes cause contamination in food products. These strains have the ability to release toxins in human's digestive tract when they are consumed, causing potentially deadly consequences to those infected. These bacteria are able to contaminate our fresh produce supply in many different ways. Animal feces contaminated with these bacteria can cause further contamination in the soil, feed, and water.[50] Since produce is grown in the soil, it can become contaminated from the earliest stages of production. Contaminated irrigation water is another potential source and, finally unsanitary, human handling and contact with contaminated equipment pose a risk for the integrity of our produce.

Shiga toxigenic *E. coli* (STEC) are of particular concern because of their threat to human health. Among STECs, there are a specific group known as "the big 6" which have been especially prevalent in the outbreaks of the past two decades, O26, O45, O103, O111, O121, and O145. Another major STEC strain is *E. coli* O157:H7. This strain along with "the big 6" has been listed as zero tolerance pathogens by the United States Department of Agriculture (USDA), meaning that there are not to be any single cells of these in any food product. This is in part because of the extremely low infectious dose that can be observed with *E. coli*, as it only takes approximately 100 cells to make a person sick.[51] It is estimated that each year STECs are responsible for more than 112,000 foodborne illnesses, posing an economic burden of more than 27 million dollars in medical costs.[52] For some food products, there are heat or cook steps that have been shown to reduce or eliminate contamination with STECs. However, in the case of fresh produce there is no cook step making reduction and elimination of this bacterium more difficult. The symptoms of an STEC infection include abdominal pain, cramps, and diarrhea which can sometimes turn bloody. In more serious cases, consumption of STECs can cause a person to develop hemolytic-uremic syndrome (HUS) or hemorrhagic colitis, especially in individuals who are immunocompromised and are not able to fight against the pathogenic infection.[53,54] Complications from any of these symptoms have the potential to cause death.

Significant STEC outbreaks are common, and are typically widespread, especially in the case of produce. In 2011 there was a significant case in which a rare strain of *E. coli* O104:H4 caused a large outbreak of diarrhea and hemolytic-uremic syndrome (HUS), resulting in and 4,074 illnesses and 50 deaths in Germany.[55] There was a multi-state outbreak causing 276 illnesses and 3 deaths in which *E.*

coli O157:H7 implicating spinach was found to be the cause in the United States in 2006.[56] Romaine lettuce contaminated with *E. coli* 0157:H7 was the cause of illness for 62 people from 16 states and the District of Columbia, according to the CDC. Joint efforts from the CDC and FDA were used to find the source of this outbreak. Illnesses began between October 2018 and December 2018 for this outbreak and the Public Health Agency of Canada identified people ill with the same DNA fingerprint of bacteria in Canada.

In addition to the impact of "the big 6" and *E. coli* O157:H7, other strains of *E. coli* have been known to cause illnesses and deaths, as was seen in the 2011 case of *E. coli* 0104:H4. Research is needed to continue improvement on the area of reducing and eliminating STECs and other types of *E. coli* from our produce supply. The impact of this pathogen is significant and improvements are needed to reduce the number of illnesses and deaths that result from it every year.

Salmonella spp.

Salmonella spp. is a gram-negative, facultative anaerobe that does not have the ability to form spores. Despite this, it does have the ability to adapt to stressful environments for survival in non-ideal conditions. An example of this type of adaptation is the formation of biofilms.[57] Biofilms can be explained simply as groups of bacteria that attach to surfaces and are difficult to kill or remove as they are protected by an extracellular polymeric substances (EPS) matrix.[58,59] Like *E. coli*, Salmonella is also a member of the Enterobacteriaceae family and has peritrichous flagella, making it motile.[60] Salmonella is composed of six subspecies containing over 2,700 serotypes, with more being discovered each year, all of which are presumed to be pathogenic. Salmonella accounts for approximately half of all produce-associated outbreaks in the United States.[61] Salmonella has been linked to cantaloupe, sprouts, raw almonds, mangos, peppers and tomato-related outbreaks.[62] This bacterium grows best at temperatures of 35 to 40C, however, certain serotypes are able to grow at other temperatures if the correct media is used. It has been estimated that one million foodborne illnesses and approximately 130 outbreaks annually in the United States are the result of non-typhoidal Salmonella.[63]

According to the CDC, most individuals who become infected with Salmonella will become symptomatic with diarrhea, fever, and abdominal cramps within 12 to 72 hours of infection. An illness with Salmonella will typically last anywhere from four to seven days, usually not requiring treatment. However, sometimes the diarrhea that Salmonella can cause becomes severe enough to require the person infected to be hospitalized. Other illnesses that Salmonella infection can cause include typhoid fever, food poisoning, gastroenteritis and enteric fever. Those who are most susceptible to Salmonella illness are those who are immunocompromised, children and the elderly. The illness that is associated with infection with *Salmonella spp*. can also be referred to as Salmonellosis.

In 2008, an outbreak of Salmonella Saintpaul which through trace back implicated contaminated jalapeno and serrano peppers, affected 1500 people, of which 21% were hospitalized and two died.[64] In 2003, 166 probable cases and 29 laboratory confirmed cases of gastroenteritis caused by Salmonella braenderup contaminated iceberg lettuce occurred in the United Kingdom, originating from a single producer in Spain.[65] A 2005 outbreak associated with tomatoes broke out across 21 states in the U.S causing 459 illnesses.[66] The Centers for Disease Control and Prevention reported a multi-state outbreak of Salmonella Typhimurium and Salmonella Stanley that was linked to cantaloupes in 2012. This outbreak affected a total of 261 individuals, 228 of which were caused by Salmonella Typhimurium and 33 were caused by Salmonella Stanley. This outbreak spread across 24 states and was the cause of 94 hospitalizations and 3 deaths. In 2008 a multi-state outbreak of infections with Salmonella Litchfield was linked to cantaloupes. This outbreak caused illnesses in 51 people across 16 United States, and 9 ill people were identified in Canada, according to CDC data.

Listeria monocytogenes

Listeria monocytogenes (*L. monocytogenes*) is a major foodborne pathogen of concern in the United States.[47] This pathogenic bacterium is a facultative anaerobe that is able to survive with, or without oxygen. It is a Gram-positive, non-spore-forming, rod,[67] that has the ability to grow at temperatures as low 1°C. Most bacteria can survive at this temperature, but do not have the ability to grow, making *L. monocytogenes* of great concern for the food industry.[68] *L. monocytogenes* causes an illness known as listeriosis, which causes symptoms including, fever and diarrhea like most other foodborne illness, but this particular bacterium also has the ability to cause headaches, stiff neck, confusion, loss of balance, and in pregnant women, miscarriage, stillbirth, premature delivery and newborn infections. The groups of individuals who are most commonly infected are pregnant women, newborns, elderly and those with weakened immune systems.[69,70] According to the Centers for Disease Control and Prevention, approximately 1,600 people become sick with listeriosis every year, and of these about 260 die. Listeriosis ranks third in the total number of deaths caused by foodborne bacterial pathogens.

Contaminated diced celery, an ingredient that was being used in chicken salad served in hospitals in Texas, was the cause of a *L. monocytogenes* outbreak in 2010 70. An outbreak lasting from October 2014 to February 2015 in the United States was caused by *L. monocytogenes* contaminated whole apples.[71] This outbreak caused 35 illnesses across 12 states; 34 of the affected were hospitalized and seven died. A major outbreak occurred due to the consumption of contaminated cantaloupes originating from Jensen Farms in Colorado, in 2011 in the United States was the cause of 147 illnesses, 33 deaths, and one miscarriage.[72]

Other pathogens of concern

Other pathogens that have caused illnesses in humans through fresh produce include Shigella spp., Yersinia spp., Staphylococcus aureus and Clostridium spp.[73,74] Outbreaks with these have been seen and reported by the CDC. However, the number of illnesses and outbreaks caused by these is limited in comparison to shigatoxin producing *E. coli*, *Salmonella spp*., and L. monocytogenes.

Current Interventions

Producers

Farms currently use what are known as Good Agricultural Practices (GAPs) to insure the safety of the produce they grow. These practices are in place to reduce bacterial survival and growth by minimizing the situations that allow this. Some examples of GAPs include worker training programs, water monitoring, testing and treatment, manure and compost management, wildlife and animal monitoring, and sanitation programs. Other regulatory guidelines that are commonly followed by farmers and other producers are Global Food Safety Initiative schemes including USDA GAPs and PRIMUS which provide an extra level of protection to the consumer with their required third party audits. These audits maintain a level of integrity within the farm as they must meet the standards set forth by the audit scheme in order to gain the approval of the auditor and ultimately the regulatory body.

Processors

Processors in the produce industry focus on the implementation of hazard analysis critical control points (HACCP) in addition to the use of various chemical wash treatments to reduce the number of both pathogenic and spoilage organisms that may be present on the produce. The most common practice that processors employ in regards to fresh produce is a dump tank wash.[75] This usually is a large metal container that contains a wash solution where produce is added in and agitated for a certain amount of time to reduce the likelihood of consumers purchasing a contaminated product. The problem with this is that it is not always effective.

During the produce wash cycle, the produce is in a tank that uses a continuous production process. The water within the tank is reused throughout the day. If the antimicrobial used is sensitive to organic load, pH, temperature or other factors, the efficacy of the wash could be compromised the more that it is used. Therefore, water disinfection is an extremely important step in produce processing, as contaminated water brought forth by an antimicrobial that is unable to withstand the conditions of produce processing, has been found to be a contributing factor to human foodborne diseases.[76] Furthermore, even though consumers are known to sometimes wash their produce at home with tap water, it is not a reliable way to completely remove or eliminate pathogens from the produce as there is no antimicrobial involved; and this practice has the potential to cause cross-contamination of food contact surfaces, utensils and other food items.[77] An antimicrobial that is insensitive to organic load and other factors that are common within the produce industry is needed in order to improve the safety and integrity of the produce supply.

Antimicrobials

Chlorine

The most commonly used chemical additive within the produce industry to remove bacterial contaminants from produce is chlorinated water (50–200ppm).[78,79] However, chlorine has limited effectiveness when it is applied to fresh produce due to a number of reasons, such as, reduced efficacy after rinsing, potential cross-contamination, and sensitivity to temperature and organic load.[56] One study found that treatment of cantaloupe with 200ppm chlorine reduced aerobic place counts by less than 1 log and did not delay visible spoilage.[80] Chlorine loses its effectiveness whenever it is in the presence of nitrogenous compounds of foods and can result in the formation of halogenated organic compounds.[81] There are other potentially harmful byproducts produced when chlorine interacts with organic material such as chloramines, trihalomethanes and other organochlorine compounds which is of major concern due to their health implications and the possibility of them causing cancer in humans.[82] Because of this, there have been a rising number of consumer safety concerns about the use of chlorine as an antimicrobial, and alternatives to chlorine have been and continue to be investigated.

Chlorine dioxide

An alternative option to chlorine is chlorine dioxide,[83] and it has shown to be more tolerant of organic matter;[84,85] as well as pH than chlorine.[86] An additional benefit that chlorine dioxide has over chlorine is the fact that it does not react with ammonia to form carcinogenic bi-products.[87] This antimicrobial has been approved by the FDA for the treatment of produce wash water. In a laboratory experiment, it was found that the use of 3ppm chlorine dioxide at a 5-minute treatment time, reduced *L. monocytogenes* by more than 5 logs on apples.[88] However, the amount of total aerobic mesophilic and coliform bacteria was not reduced, but increased after a wash with this antimicrobial.[89] This indicates that chlorine dioxide alone is incapable of ensuring microbiological quality of fresh produce.

Peroxyacetic acid

Another common antimicrobial that is employed by the produce industry is peroxyacetic acid (PAA). The maximum residue of PAA in produce wash water has been set at 80ppm by the FDA.[90] This is a limitation because there have been studies which have shown that this is not sufficient in achieving a desirable microbial reduction. A laboratory study using PAA to reduce *L. monocytogenes* from apples found that in order to achieve a 1 Log reduction, an 80-second wash time is required 91. This is not efficient for use in a dump tank wash and therefore the use of PAA is not ideal for use in a commercial produce processing environment.

Ozone

One antimicrobial substance that is a strong oxidizer is ozone. Ozone has been approved for use as a direct food additive both in liquid state and gaseous phase for treatment, storage, and processing of foods in 2001 by the FDA 92. There is no residue left behind by ozone and it is a broad-spectrum antimicrobial effect. The efficacy of ozone as an antimicrobial is not affected by the pH of the solution 93. When 3ppm ozonated water is used, Log reductions times of *L. monocytogenes* and *E. coli* O157:H7 were seen to be about 20 seconds.[91] The problem with the use of ozone as a produce dump tank antimicrobial is that it is highly reactive with organic matter. Also, off ozone gas, worker safety, and economical issues make ozone impractical for use in the produce wash industry.

Essential oils

Essential oils, also known as natural oils, are concentrated hydrophobic liquids that contain volatile chemical compounds from plants. They are becoming more and more popular amongst families for their healing, relaxation, and cleansing properties. Their use in the food industry as both an antimicrobial and as an anti-spoilage agent has been investigated 56. Log reductions of Salmonella typhimurium by using 1000ppm myrtle oil was investigated on tomatoes and iceberg lettuce and found to be similar to that of chlorine. [94] Another study by Gundez et. al was also conducted looking into the use of 100 ppm oregano oil to reduce Salmonella typhimurium from tomatoes and the result was a 2.68 log reduction.[95]

However, this process would not be feasible in the food industry due to both productivity and organoleptic reasons. Although some oils may possess the ability to inactivate certain bacteria, more research is necessary to determine which oils are most effective on each specific bacterium. Essential oils are not ideal for use in the produce industry, or the food industry in general, because of the amounts required and the significant cost that comes along with using them. The oils themselves are expensive to produce, making the financial impact they would impose on the produce industry to employ them in processing extensive.

Bacteriophages

Bacteriophages are of interest to the food industry because of their unique properties. A bacteriophage can be described very simply as a naturally occurring virus which targets specific bacteria.[96] They are extremely specific meaning they are able to infect and kill pathogenic bacterium without damaging or destroying other cells around them. Bacteriophages are only able to replicate within their specific host organisms and this means that the more bacteria they kill, the more bacteriophages there are to kill more pathogenic bacteria. Bacteriophages are able to kill bacterial cells by attaching to the host and then inject their genome into the host cell, then the bacteriophage DNA integrates into the host cell's DNA causing eventual cell lysis and release of the bacteriophages to move on to other bacterial cells. It has been estimated that these viruses, that occur naturally, kill up to half of all of the bacteria that is produced daily. The problem with the use of bacteriophages in the food industry comes from what makes them so intriguing, their specificity. It is impossible to know exactly which types and specific strains of bacteria will be present in each food production or processing facility. Because of the numerous diverse bacteria and serotypes within these bacterial groups, developing a bacteriophage cocktail which would eliminate all risks in all facilities across the nation and world is a difficult if not impossible task.

Sodium acid sulfate

Sodium acid sulfate (SAS) is a natural food acid that can also be referred to as sodium bisulfate, bisulfate of soda or sodium hydrogen sulfate and has a chemical formula of $NaHSO_4$.[97] SAS is recognized as a generally recognized as safe (GRAS) by the FDA for use on fresh fruits and vegetables. Previously, SAS has been used in the processing of fresh fruits and vegetables because of its ability to reduce browning, specifically in fresh cut apples.[98] Other products that have benefitted from the addition of SAS include sauces, dressings, soups, prepared meals, beverages, dips, fillings, gravies, spreads and desserts. The way that SAS works or the mode of action of SAS is something that also needs further exploration. SAS is an acid, so it is known that it reduces the pH of the products it is applied to. One unique property that it has is the fact that it is able to lower pH without causing or generating a sour taste. However, there is little research available on the way that SAS is able to reduce the microbial load of the products that it is applied to. The use of SAS as an antimicrobial agent has been explored briefly and the potential it has shown already, warrants further exploration.

In addition to each of the above listed antimicrobials, there are many proprietary blends using different concentrations and mixtures of these. Other antimicrobials than these listed are also used but are not necessarily common. Continued research into antimicrobial efficacy and limitations is required to improve produce handling and decontamination practices within the food industry.

Summary

Although there are risks with many different types of fresh produce, the two that this research will be focusing on are cantaloupes and bell peppers. Both of these are increasing in popularity, meaning that there will likely be more outbreaks associated with them in the coming years. The surface of cantaloupes consist of a complex netting-like structure that provides an ideal surface for bacteria to strongly adhere.[99] Once bacteria is present on the surface of the melon, it can easily be transferred to the edible flesh when the melon is further processed by either the processor or by the consumer at home.[100] The use of bell peppers is becoming more popular among restaurants and consumers at home and so they are of importance in research today. Their skin is fragile and research is needed to evaluate not only the microbiological safety but also the quality parameters associated with the antimicrobial used as well.

It is necessary for more research to be conducted in the area of antimicrobials for use during produce processing. Eliminating the risk of contamination altogether at the farm would be the ultimate goal, but likely will never be possible due to the countless risks. From the farm to processing, there are many contact points, from the soil, to equipment, to handling, that pose a danger to the safety of our produce supply. Therefore, finding an antimicrobial that does not become inactivated by organic load or temperature is essential in reducing the number of foodborne illnesses caused by produce every year. This antimicrobial must be affordable to use by the industry and not cause a delay in processing time or any type of large disturbance to the process already in place. It must also appeal to consumers and increase the consumer's likelihood to purchase the product rather than turn them away. Since nearly all processors have similar methods of handling produce, the application of this research will only consist of a simple change of antimicrobial used. SAS has been used in the produce industry before as an anti-browning agent. However, research of its use as an antimicrobial is limited and there are a lot of questions left unanswered. SAS is comparable in price to chlorine, making it within reach to all levels of processors. It is also listed as a "safer choice antimicrobial" by the Environmental Protection Agency (EPA), which makes it more appealing to consumers. There is limited knowledge as to the microbial reduction ability of SAS and the affect that this antimicrobial has on produce quality. It is important to see the difference it has on quality compared to the industry standard, chlorine because consumers are not likely to purchase produce that does not meet the expected standard.

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Conflicts of interest

The author declares that there is no conflict of interest.

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