

Mitigating Foodborne Illness Through Improved Water Quality: A Review of Causes, Challenges, and Solutions

Sofia R. Meller, Neel Naglapur, Yoshi Sarkar, & Sarah E. Terwilliger

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Abstract

From the commonly known “food poisoning” Norovirus, to the deadly pathogen Salmonella, foodborne illness, facilitated by poor water quality, impacts millions of lives every year. Throughout production and processing, food is consistently exposed to water, and the presence of illness-causing pathogens raises concerns for public safety. In an attempt to propose a feasible and effective solution to this issue on the federal level, a comprehensive literature review was conducted assessing areas of current research regarding foodborne illness policy and mitigation. Libraries such as EBSCOhost and Google Scholar were utilized to compile information from research articles; these articles were used to compare various solutions, from widely used technologies to newly developed methods, on criteria such as cost, energy-efficiency, and overall efficacy. A three-part, integrated solution was recommended. First, sand filtration of microorganisms can be conducted on farms and agricultural facilities during the harvesting process to prevent the transfer of bacteria that can proliferate in shipment. Second, nanofiltration in public water systems is energy-efficient, thus making it cost-effective and a system that can be implemented on a large scale. Lastly, comprehensive consumer education regarding safe food handling practices is essential to prevent these illnesses on the level of consumers themselves. The findings of this literature review emphasize the magnitude of foodborne illness, and by extension the critical need for improved water quality management and greater consumer education. By implementing the integrated solutions discussed, it is possible to both address current issues regarding public health and significantly contribute to a future with reduced incidence of foodborne diseases, thus contributing to a healthier and safer society.

Introduction

Foodborne illness is a major issue of public health, affecting millions of lives annually. The Centers for Disease Control and Prevention (CDC) reports that 48 million people in just the United States are impacted by foodborne illness every year, 3,000 of which die from it (Centers for Disease Control and Prevention, 2019). Foodborne illnesses are often caused by contamination from pathogens such as bacteria, viruses, and parasites. Poor water quality catalyzes the spread of foodborne illness; regarding the water used to grow and process food specifically, there are numerous opportunities for contamination. For instance, water used during irrigation can carry pathogens that impact crops prior to the harvesting process. Further down the line, water in processing facilities used to wash meat can transfer pathogens to and

from equipment and food (Hall, 2016). Because of the impact water has on foodborne illness, it is essential to preserve the quality of this water throughout the entire process, from the field to the dining table. Standard treatment in public water facilities removes the majority of these contaminants. However, these treatments are not consistent across cities, states, or countries, leaving a gap that results in millions impacted by foodborne illness yearly (Illinois Department of Public Health, n.d). Increasing the quality of water in public water systems is essential to protecting lives—locally, nationally, and globally.

In this literature review, the issue of foodborne illness through contaminated water will be addressed to present a multifaceted solution. First, this paper explores the transmission of foodborne pathogens through livestock and produce. Livestock can harbor harmful bacteria that contaminate water sources through runoff, while produce can be directly exposed to contaminated water during irrigation and processing. Second, the paper reviews current solutions and ongoing research in the field, including methods like sand filtration and nanofiltration. Lastly, the paper presents a comprehensive solution recommendation, integrating sand filtration at agricultural sites, nanofiltration in public water systems, and consumer education programs. By doing so, this review aims to answer the question of how poor water quality contributes to the incidence of foodborne illness. Furthermore, it evaluates options to improve water quality in order to reduce foodborne illnesses and improve public health.

Problem Statement

The objective of this literature review is to examine the impact of poor water quality on the incidence of foodborne illnesses during the production, processing, and consumption of food. By synthesizing current findings across multiple databases, this review attempts to (1) analyze the pathways through which contaminated water contributes to the contamination of food, (2) address current regulations on water quality on both the federal and national level, and (3) offer feasible recommendations that can help reduce the prevalence of foodborne illnesses, thus protecting public health.

Various goals were used as guidelines for assessing potential solutions. The National Institute of Food and Agriculture, also known as NIFA, has established multiple goals concerning food safety. These are (1) ensuring a safe food supply, (2) improving citizens' health through nutrition, (3) reducing childhood obesity, and (4) improving food quality. In regards to the first goal, by examining how poor water quality contributes to foodborne illnesses and studying solutions to improve water quality, this review supports efforts to improve the safety of the food supply. Cleaner water in agriculture reduces the risk of contamination, thus reducing overall foodborne illnesses. Although the second goal is not directly related, the use of uncontaminated water helps ensure that produce and other food products remain free from harmful pathogens. Similarly, concerning the third goal, improving water quality in food production also supports the availability of safe produce. Access to uncontaminated food products encourages healthier eating habits in children, supporting efforts to combat childhood obesity. Lastly, the fourth goal presented by NIFA is related to water quality because the quality of food is dependent on the water it is processed with. If the water itself is contaminated, food quality cannot be upheld (National Institute of Food and Agriculture, 2010).

Furthermore, the United Nations Sustainable Development Goals (SDGs) are a set of global objectives created in order to address pressing issues and protect these lives. According to the World Health Organization (WHO), around two billion people worldwide use a contaminated source of drinking water. When harmful substances like chemicals and waste products are introduced into water systems, they degrade the quality of the water present. This polluted water enables the growth of harmful microorganisms, leading to increased foodborne illness.

Achieving SDG 3, Good Health and Well-Being, is intrinsically linked to water quality. Contaminated water enables the spread of foodborne pathogens, undermining efforts to reduce mortality rates. Ensuring access to safe water, and by extension safe food, is vital to preventing illness and supporting overall health for all. By addressing water pollution, SDG 6, Clean Water and Sanitation, directly supports efforts to reduce the incidence of foodborne illnesses with a goal of increasing clean water and sanitation. It prioritizes improving water quality, which is critical for preventing the spread of pathogens that contribute to foodborne illnesses.

Methods

A comprehensive search was conducted using various academic search engines and library databases. Two main databases, EBSCOhost and Google Scholar, were used to review over 40 articles. These articles concerned water quality both domestically and internationally, viral and bacterial pathogens in food and water, and methods used in water filtration systems.

Some keywords used when searching in these databases included “foodborne illness,” “water quality,” “filtration”, “pathogens”, and “food production”. Various source types were used, including peer-reviewed research articles, government organizations, and review papers. The primary limitation set was the timeframe; all articles were published in the past 30 years.

In addition to utilizing online databases, Matthew Lohr, the Virginia Secretary of Agriculture, was spoken to. He discussed the pathogen *Escherichia coli* and its prominence in produce such as lettuce. Virginia’s primary agricultural commodity is poultry, so the local possibilities of foodborne illness and their potential solutions in poultry farms were contrasted, then assessed on a domestic level. Additionally, Dr. Monica Ponder, Virginia Tech’s Assistant Professor for the Department of Food Science and Technology, was spoken to. With her, the differences in infection versus intoxication, hazards in food safety, biological hazards, and water contamination were discussed.

Background

Meat and Dairy

Water is essential to all life. The average amount of water used between 2014 and 2016 in the US livestock sector was 72,650 billion gallons of water per year. This amount of water could supply the daily water needs of the entire U.S. population for about 6.5 years, considering the average daily consumption is about 300 billion gallons (Water Science School, 2018) Additionally, water is essential for hydration, digestion of food, and absorption of nutrients in humans. Unfortunately, water can be contaminated with pathogens and other things such as nitrates, bacteria, organic materials, and suspended solids (Casteel, 2001). Some foodborne

illnesses found in meat and dairy products stem from pathogens that can be found in this drinking water. These include *Toxoplasma gondii*, *Salmonella enterica*, and *Campylobacter* (Minnesota Department of Health, 2022).

Livestock infections commonly occur through drinking water. One way *T. gondii* and other pathogens transmit into water is through fecal contamination. An example of this is the feline fecal matter, containing contaminants of *T. gondii* oocysts, a thick-walled spore containing zygote (Must et al., 2017). As cats are commonly found on farms and in barns, they pose a great risk for water contamination. *T. gondii* oocysts, essentially fertilized eggs, can be consumed by animals and reproduce in their digestive systems. This occurs through the maturation of the parasite. After infection, *T. gondii* cells invade animal host cells and begin to multiply. After a certain number of rounds of replication, they form tissue cysts in the intracellular tissue of the infected individual. *T. gondii* tissue cysts are concealed from the immune system and can thus continue to live. Once animals are slaughtered or milked, *T. gondii* oocysts persist in their products (Slana et al., 2021). The three major meat-producing animals that harbor *T. gondii* are swine, cattle, and poultry (Guo et al., 2015). These products are consumed at high rates by human populations, demonstrating the potential impact of pathogen presence.

Another pathogen that can be highly detrimental to humans is *Salmonella*. Every year it infects roughly 1.35 million Americans with salmonellosis (United States Food and Drug Administration, 2023). *Salmonella* can commonly be found in different types of surface waters, like lakes, rivers, and ponds (Liu, 2018). Surface water is a primary source for irrigation water in agriculture (USDA Economic Research Service, 2022). Irrigation water can be used for many things, including livestock feed and water (Heinke, 2020). Ingesting this water orally is one way that *Salmonella* is transmitted to livestock. *Salmonella* is also present in the water that is used for poultry processing (Hamidi, 2014).

Dairy-producing animals play a significant role as vectors in the transmission of foodborne illnesses to humans. These animals—including cows, sheep, and goats—are highly susceptible to pathogenic infections. For example, due to current dairy husbandry practices, sheep and goats raised for milk production are highly susceptible to *T. gondii* infections.

However, various types of milk display different levels of infection; sheep show a much higher prevalence to *T. gondii* infection than goats (48% vs 30%) (Tzanidakis et al., 2012). Furthermore, certain pathogens are found at higher levels for other animals. Cows, for instance, are highly susceptible to *Campylobacter*. It is important to note that when animals are infected with *Campylobacter*, they often don't show any clinical signs, making it more difficult to eliminate (Taghizadeh et al., 2022). *Campylobacter* was found in approximately 24.9% of bulk milk tanks or milk filters in the US. Operations with higher cow populations, specifically greater than 100, in comparison to operations with 30-99 cows, were found to have significantly higher rates of transmission (Del Collo et al., 2017). Overall, these dairy-producing animals serve as a primary method of foodborne illness transmission to humans.

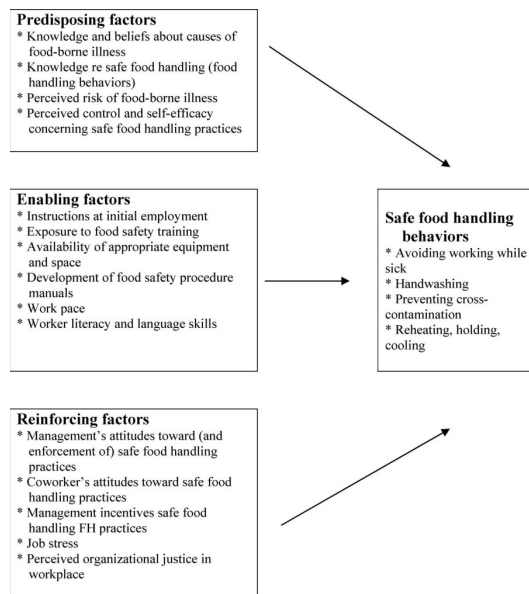
Water is used throughout the livestock facility process; it can be used for washing, cleaning, waste disposal, chilling, scalding, and more. One broiler chicken requires somewhere between 3.5 to 10 gallons of water to be processed (Food Northwest, n.d.). Another common

example of water use in processing is in the harvesting of goat meat. Water is used to wash the goats before they are slaughtered; then, after their parts are harvested, they use various wash combinations determined by the type of meat. The aforementioned process does not include the water used in packaging (Kannan, 2021). It is important to note that in most commercial processing facilities, the water quality is regulated. If municipal water is used then the water quality must comply with the National Primary Drinking Water Regulations (NPDWR). The NPDWR does regulate microorganisms in water used in processing and has a small window for allowance (United States Environmental Protection Agency, 2024).

Despite this being established, negligence or other confounding variables can still contaminate water with pathogens. If the water used at any point is contaminated, the impacts are devastating. Processing operations all over the world are reusing water in an effort to cut costs and be more environmentally conscious, which can quickly make issues arise; if the water is contaminated, instead of just contaminating one batch of product, all the batches would be contaminated till the water gets cycled out. Since microorganisms and pathogens are able to survive in water for extended periods of time, they are highly linked to outbreaks (Meneses et al., 2017). Also since water is used so often in processing the impact of its quality is often underestimated. This can lead to various issues that can fester foodborne illness. Some examples of this are water mismanagement, maintenance issues, food safety, and quality of products (Bhagwat, 2019).

Figure 1

Factors contributing to safe food handling behaviors



Note. Predisposing, Enabling, and Reinforcing factors of PRECEDE-PROCEED Framework as applied to worker behaviors related to safe food handling in the food service environment (Mitchell et al., 2007).

Crops and Produce

Nearly half of all foodborne illnesses are linked to fresh produce (The Interagency Food Safety Analytics Collaboration (IFSAC) et al., 2023). As a leading cause of foodborne illness, infected produce can be examined to explore the detrimental effects of pathogen presence in food. Due to its high water content and the inability to completely sterilize produce, it is likely a primary vector of foodborne illness in the United States. In the annual CDC Foodborne Illness source attribution, it was found that 75% of cases of *Salmonella* came from sources of fruits, seeded vegetables, and other produce and meats. Over 80% of *E. coli* cases were linked to vegetable row crops and beef (The Interagency Food Safety Analytics Collaboration, 2023). This contamination can happen through various modes of infection, such as contamination in handling, water activity, and agricultural leaching.

Handling

Yu et al. (2022) indicates that three factors influence the safety of processed produce: post-harvesting processes in facilities, employee handling practices, and consumer handling in personal kitchens. Results of this study showed that when participants cross-state were presented with a survey concerning food safety and handling practices associated with fresh produce, less than 10% of participants had sufficient knowledge relating to the U.S. Food and Drug Administration food code. After R. E. Mitchell et al. assessed the predisposing, enabling, and reinforcing factors, safe food handling behaviors were established.

When nationally recognized experts in food microbiology, epidemiology, food safety education, and food safety policy were identifying and ranking food-handling and consumption behaviors associated with the 13 major pathogens, behaviors related to food safety temperatures were ranked of primary importance in preventing illness from *Clostridium perfringens*. Hillers et al. (2003) ranked the use of a thermometer to cook foods adequately of primary importance for *Salmonella* species and *E. coli*. Both food safety temperatures and use of thermometers are inferred in *Figure 1* under the decided Safe food handling behaviors.

Water Activity

When considering pathogenic growth in produce, a core contributor is water activity. Water activity is the humid surroundings and available water in the processed produce. In states that have consistently high humidity, the environment encourages the growth of most pathogens. Foods with lower water activity (abbreviated aw)—under 0.85—inhibit pathogenic growth, affecting food safety (Balsamo Jr. et al., 2024). Not to be confused with water content or liquid content, water activity measures the moisture of a product. Few microorganisms can reproduce in low-water activity environments, therefore these products are generally qualified as safe in set conditions. Despite this, *Salmonella* was proven to reproduce and survive in foods with low water activity for long periods (Ma et al., 2023). These studies add to the understanding that although ideal water activity for pathogen reproduction is greater than or equal to 0.85, exceptions are found in some of the most documented infectious pathogens (Balsamo Jr. et al., 2024). *Salmonella*'s ability to persist in typically unideal environments for pathogen growth creates a large challenge in the food industry. The pathogenicity of the bacteria is due to its virulence factors, which enable the bacteria to easily infect and cause

disease in hosts. The ease with which *Salmonella* can spread creates a necessity for sanitary procedures in produce processing and control measures for foods with a low water activity (Morasi et al., 2022).

Agricultural Leaching

As agricultural practice intensifies and increasingly promotes mass production over safety, crops are at risk of processes like agricultural leaching, which exacerbates foodborne illness. Agricultural leaching is when fertilization, pesticides, organic additives, and other chemicals are washed out of the soil and carried into other systems, polluting them and impacting the growth of other organisms (Hadas et al., 1999). This leaching runoff is responsible for many environmental issues, such as accelerating the eutrophication process so severely that sunlight is unable to penetrate aquatic environments; this leads to the contamination of agricultural products, causing foodborne illness (Daniel et al., 1998). One study used livestock manure (seen increasingly in modern agricultural practices) to evaluate the leaching of *Salmonella enterica*, *E. coli*, and *Cryptosporidium parvum* oocysts in the soil (Forslund et al., 2011). The study showed the usage of manure in the soil and revealed an extended leaching and long survival time for the *E. coli* and *Salmonella* bacteriophages. *Salmonella* was found in the leachate five months after injection, while *E. coli* could be detected three and a half months after injection. From this one can infer that agricultural leaching, specifically regarding pathogens, can leave dangerous microorganisms in soil for months. These microorganisms can then infect crops and produce growing in the soil that utilizes manure as fertilizer, infecting them with foodborne illness-causing pathogens.

Policy

Passed in 1974, the Safe Drinking Water Act (SDWA) is the broadest legislation targeting water quality in the United States. It established guidelines for “public water systems,” defined as systems that provide drinking water for 25 or more or that have 15 connections and provide water for at least two months per year. Under the SDWA, the US Environmental Protection Agency (EPA) regulates water authorities on various levels, from local to federal. The EPA currently regulates over 90 water contaminants by setting caps for the maximum levels that can be present in water. These contaminants range from inorganic chemicals to radionuclides. Microorganisms—which are a significant contributor to foodborne illness—are regulated as well, including total coliforms (such as fecal coliform and the commonly known *E. Coli*) and *Cryptosporidium* (Environmental Protection Agency, 2024).

Three main rules of the SDWA apply to microorganisms, each with specific regulations that aim to reduce the transfer of these organisms through water. First, the *Surface Water Treatment Rules* include a total of five regulations passed from 1989 to 2006. Some components of these regulations are mandatory sanitary surveys for all surface water systems regardless of size, along with ensuring recycled filter backwash water undergoes direct filtration in surface water systems. In late 2006, the *Ground Water Rule* (GWR) was established, mandating routine sanitary surveys of systems with the intent to decrease fecal contamination. More recently, the EPA revised the 1989 *Total Coliform Rule* (TCR). Total coliforms are generally innocuous bacteria; however, the EPA has designated them as an accurate indicator of other pathogens in drinking water. These laws currently guide the actions of public water

systems regarding microorganisms that cause foodborne illness.

Furthermore, various water treatment policies—both successful and unsuccessful—have been implemented around the globe. India, as one example, has struggled with the spread of foodborne illnesses exacerbated by poor water quality. Approximately 150 million cases of foodborne illnesses are reported every year in this region (National Centre for Disease Control, 2017). This is due to inadequate sanitation infrastructure and poor hygiene practices; however, it is important to consider that these conditions vary widely across the country. Due to the presence of significant wealth and resource inequality in countries such as India, certain areas are disproportionately impacted by foodborne illness and are unable to recover as well.

Unfortunately, India's regulatory framework for food safety and water quality is fragmented and poorly enforced. This exacerbates existing inequalities (Sharma, 2024). By addressing systemic differences and infrastructure gaps, countries such as India can reduce the incidence of foodborne diseases.

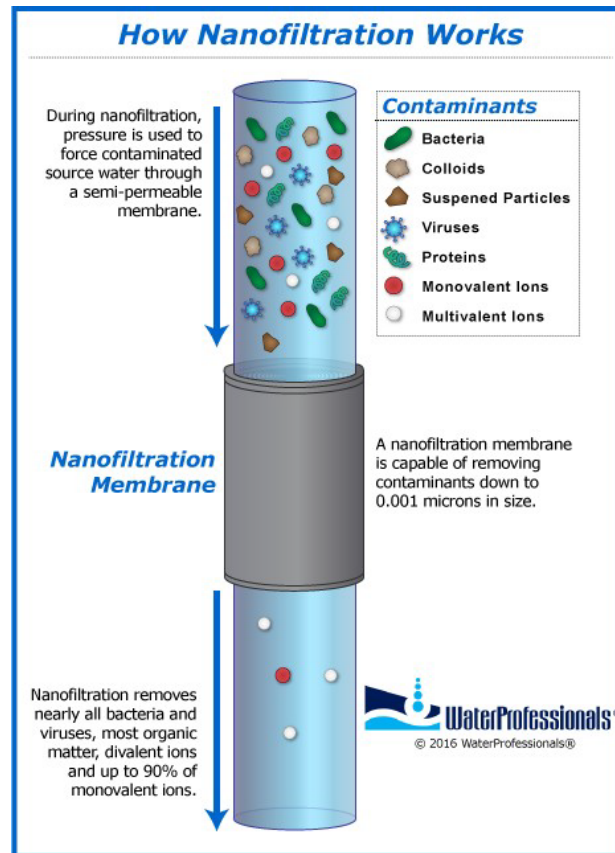
Certain countries have already made steps towards achieving systemic equality, and by extension, decreasing foodborne illnesses. For example, Denmark experienced a spike in *Salmonella* cases due to infected chicken meat approximately 35 years ago. It then adopted a *National Salmonella Control Program* that established steps in combatting this crisis—however, results were uneven (Terry, 2014). After a decade of worsened impacts, Danish farmers and policymakers came together with new methods. Chicken coops were redesigned, an integrated database that collected data from farms, slaughterhouses, and human health services was implemented, and policy initiatives were shared to the Danish population. The "From Stable to Table" campaign, for example, educated consumers about food safety practices, emphasizing the importance of proper food handling, cooking, and storage. Today, the incidence of *Salmonella* infections in Denmark has decreased dramatically due to rigorous control measures in poultry and pork production. Similar methods can be implemented in countries currently in foodborne illness crises (Wegener et al., 2003).

Current Methods

Currently, numerous methods of water filtration are used on a wide scale. The two most prominent solutions are reverse osmosis and nanofiltration; these systems utilize certain membranous designs and properties of common contaminants to effectively remove them from water. In a common treatment plant, reverse osmosis and nanofiltration membranes can be used to further filter water after physical removal of sediments. Both procedures apply high amounts of pressure to the water; this pressure causes the water molecules to pass through a semipermeable membrane, a filter that allows certain molecules to pass through them more easily than others (Kershner, 2023). These technologies have displayed effective removal of a wide range of contaminants, ensuring cleaner water output (Zhou et al., 2016).

Figure 2

Diagram displaying nanofiltration mechanism with descriptions of processes



Note. A nanofiltration membrane typically removes 50 to 90% of monovalent ions. Called the “softening membrane”, nanofiltration is often used to filter water with low amounts of total dissolved solids (*Nanofiltration*, n.d.-b).

Nanofiltration membranes can effectively remove divalent salts and larger organic molecules from water. These membranes have molecular weight cut-offs (MWCOs) of around 300-500 Dalton, a unit of molecular weight. Conversely, reverse osmosis membranes have far smaller pores and MWCOs of around 100 Daltons, providing a finer level of purification. A study analyzed the performance of various nanofiltration and reverse osmosis membranes. It found that the specific two membranes, Koch MPF-34 (nanofiltration membrane) and Toray 70UB (reverse osmosis membrane), displayed high contaminant rejection rates, making them suitable for long-term wastewater treatment applications. These systems improve water quality and are also a cost-effective alternative to traditional methods, reducing operational costs significantly (Zhou et al., 2016).

Israel has been at the forefront of applying reverse osmosis for desalination due to its water issues. According to a study, the Ashkeleon seawater desalination plant in Israel is known for being the world's largest reverse osmosis desalination facility. The facility holds a capacity of 84.5 million gallons per day(320,000) of water and ensures that the initial seawater is treated

to become potable water with a salt concentration of 30mg/L. The system's main purpose was to address Israel's lack natural supplies for its increasing water demand(Landers, 2006). China has been advancing its nanofiltration technology and becoming a leading country in this field. According to a study, China has shown insane growth in both patents and scientific publications related to nanofiltration technology. China extensively uses this technology for water purification and treatment which addresses the country's water scarcity. Government policies, such as the 12th Five-Year Special Plan, has enhanced the growth of nanofiltration membrane technology and making it a substantial component of China's strategy for environmental development(Zhai et al., 2014).

Integrating nanofiltration in water treatment protocols is pivotal in improving water quality and reducing the incidence of foodborne illness due to its ability to remove pathogens and organic matter that can compromise safety. Research conducted on Fall Lake water in Minnesota and dechlorinated potable water in Ohio demonstrated the effectiveness of nanofiltration in eliminating total organic carbon, *Bacillus subtilis*, and MS2 bacteriophage (Patterson et al., 2012). The study found that nanofiltration is effective in removing pathogens which prevents waterborne diseases such as *Cryptosporidiosis* that affected over 400,000 people in Milwaukee (Corso et al., 2003). The use of nanofiltration in water treatment systems enhances the removal of bacteria and various viruses from drinking water sources. For instance, thin-film composite nanofilters showed complete removal of microorganisms in several challenge tests (Lovins et al., 2002). Nanofiltration eliminating pathogens can contribute to the removal of *E. coli* and *Salmonella* which plays a crucial role in reducing the risks of foodborne illnesses.

Although both methods are effective at overall filtration, reverse osmosis membranes are more effective at removing pathogens and preventing diseases compared to nanofiltration. As Yang et al. (2019) reports, reverse osmosis employs a membrane to take out contaminants from water that includes bacteria and viruses. This level of filtration is efficient at eliminating disease-causing pathogens but is not as cost-effective as nanofiltration. Another study suggests that because reverse osmosis is used traditionally for dissolved solutes (salts), it can also be used to achieve the removal of viruses, like *Cryptosporidium*. Due to the semi-permeable membrane used in reverse osmosis, it has a high efficiency at removing pathogens that have different molecular sizes. Reverse osmosis systems can reach high log removal levels (LRV), indicating the effectiveness in eliminating the concentration of contaminants (Vickers, 2018). Despite all these applications and advantages, reverse osmosis technology faces setbacks such as high energy consumption and membrane fouling. Even though they are making solutions to the high energy consumption used, reverse osmosis membranes are still a less cost-efficient option for global implementation (Wenten & Khoiruddin, 2016).

Future Research

Sand filtration as a pioneering method of water filtration has gained prominence in recent years. Specifically, it has been studied as an on-farm technology, intended to mitigate the impacts of foodborne bacteria prior to its entry into a public water system. Research conducted by Marik et al. suggests the potential of iron-sand filtration technology (2019). Both foodborne illness-causing bacterias *Listeria monocytogenes* and *E. coli* were studied; however, a significant reduction of bacteria on lettuce leaves after sand filtration treatment only occurred

for *L. monocytogenes* likely due to its gram-positive properties. Previous research has established the efficiency of iron-sand filtration on the removal of gram-positive bacteria, bacteria with thick layers of the polymer peptidoglycan in their cell walls, unlike their gram-negative counterparts (Hsueh et al., 2017). However, most common foodborne illnesses are caused by gram-negative bacteria such as *E. coli*. This suggests that while sand filtration is partially successful for the on-farm mitigation of certain foodborne illness-causing bacteria, it is not a viable treatment for all bacteria on a larger scale.

Biological approaches have also been studied in order to improve water quality. For example, Aracic et al. discussed the use of whole-cell microbial biosensors for the detection of water contaminants (2015). They reported that an area of current research at the time was the use of native biota—the plant and animal life of a specific region—to reduce water contaminants while simultaneously maintaining high standards of sustainability. Separately, they found that synthetically-derived microbial biosensors, created from common laboratory strains of *E. coli*, responded to conditions such as excessive nitrogen in bodies of water. Thus, they could potentially be used as indicators of poor water quality. Continuing with biological remediation, however, Bala et al. recently found that xenobiotic substances and organic wastes in contaminated waters could be reduced by treatment with specific microorganisms such as *Bacillus*, *Pseudomonas*, and *Sphingomonas* (2022). This suggests the potential of bacterial exposure as a method of improving overall water quality.

Solutions

In order to address the issue of foodborne illness through water contamination, a multifaceted solution is necessary. This solution can be split into three primary stages. First, in-situ remediation of contaminants can be conducted using sand filtration as described by Marik et al. (2019); this method limits the amount of gram-negative bacteria that leaves a farm or production center. However, it still allows for other bacteria to continue through water systems. Thus, filtration of bacteria and pathogens is necessary in all public water systems. Due to the number and size of these systems present throughout the country, a cost-effective filtration mechanism is required. Nanofiltration membranes enable effective removal of pathogens while maintaining low costs. They are widely recognized as a more economical membrane technology, in terms of both cost and energy, in comparison to other technologies such as reverse osmosis; Wafi et al. (2019) reported nanofiltration was just as effective as reverse osmosis yet consumed 29% less energy. This means that they are more feasible for use on a wide scale. By implementing nanofiltration into the majority of water systems, further foodborne illness-causing pathogens can be removed from the common water supply before even reaching the consumer.

These methods help reduce the threat of foodborne illness as spread through public water systems, yet a significant risk is still present. This risk can only be mitigated through comprehensive consumer education, focused primarily on safe food handling practices. The United States Department of Agriculture (USDA) designated four main steps in preventing foodborne illness: (1) clean, by regularly sanitizing hands and surfaces, (2) separate, by keeping raw meat away from other foods, (3) cook, by heating raw ingredients to proper temperatures and using visual indicators such as color, and (4) chill, by refrigerating foods promptly. This four-step model helps ensure food safety at the consumer level. Supporting

further consumer education by passing food safety policies at the local level and lobbying at the federal level will increase societal understanding of these models and contribute to overall food safety.

Conclusion

Addressing the relationship between water quality and food safety, from production to processing, is essential to combatting today's public health crisis. Livestock, including meat and dairy, are heavily impacted by poor water quality; pathogens such as *T. gondii* can be consumed by livestock and their presence can persist beyond slaughtering/milking all the way to human consumption. Post-harvesting processes and employee handling for fresh produce can translate into the spread of *E. coli* and other pathogens at higher rates than on other foods. Ultimately, this has led to foodborne illnesses caused by these pathogens impacting 48 million people yearly (Center of Disease Control, n.d). In this review, numerous potential solutions to this issue were assessed and a multi-part solution targeting each step of the food handling process was recommended.

Initially, on-site remediation using sand filtration can be used to limit the discharge of bacteria from agricultural facilities, though other pathogens may still persist in water systems. Integrating nanofiltration on a wide scale in water systems can effectively remove these pathogens, reducing the risk of foodborne illness before water reaches consumers. While these methods mitigate foodborne illness risks through public water systems, significant risks still remain. Addressing these risks necessitates comprehensive consumer education, emphasizing safe food handling practices. The USDA advocates a four-step approach: regular hand and surface sanitization, separation of raw meat from other foods, thorough cooking of ingredients to proper temperatures, and prompt refrigeration of perishable items. Enhancing consumer education through local and national food safety policies will foster broader adoption of these practices, supporting overall food safety and reducing the incidence of foodborne illnesses.

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