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Current approaches for reconditioning process water and its use in food manufacturing operations

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Water is perhaps the most critical component in the processing of most food products. Supplies of water that is suitable for use in food processing operations are becoming limited. Three aspects of water as they relate to food processing will be discussed: water as a vehicle for various foodborne disease agents (bacterial, viral and parasitic); an overview of wastewater treatment processes, including the agents used in the final phase to disinfect water; and approaches to reconditioning food plant processing water for reuse within the food processing plant and in other areas of food production. Although the potential for the use of reconditioned water is vast, actual applications are currently very few.

By virtue of its physical and chemical properties, water is utilized as a major and essential component of many food processing operations. It is used as the vehicle for washing, heating and cooling as well as for the clean up and sanitization of equipment and facilities. Water is also an ingredient and the vehicle used to incorporate food ingredients such as NaCl and/or vinegar (acetic acid) in the processing of cured or pickled products. However, water is a limited resource and its initial costs and waste disposal represent a significant expenditure. All of the water that is available for human use is present on the planet right now and, of the total water present, only 1% is freshwater[1]. This supports the requirement for its prudent use by food processors either by developing processing operations that utilize less water yet achieve equivalent results[2], or by reconditioning water (treating used water in some fashion; see Glossary for definitions) and then recycling it within the food processing plant.

In view of the need for a safe, reliable and affordable supply of water by the food processing industry, information on and interest in the reconditioning and recycling of water are both increasing. Although there are microbiological and chemical safety concerns about using such water, recent research from this laboratory has demonstrated that reconditioned water can be used in certain meat slaughter operations. Pig carcasses that were processed using reconditioned water for scalding, dehairing and polishing contained similar levels of various pathogens and total aerobic flora as carcasses that were processed using potable water[3]. The purpose of this review article is to discuss: first, the microbial pathogens that are known to occur in water, and then consider which species can be introduced into the food; second, the various water treatment processes and the steps being used to control water quality; and finally, those areas of food processing and preparation where reconditioned water has been successfully utilized.

Waterborne microbial pathogens

Water can and often does represent a universal source and vehicle of essentially all foodborne bacterial, viral and protozoan pathogens[4]. For certain bacteria such as the *Aeromonas hydrophila* group[5] and bacteria of the genus *Vibrio*[6], the aquatic environment, whether freshwater or marine, appears to be their natural reservoir. The presence of bacteria of the genus *Salmonella* or the

Table 1. Examples of etiological agents and gastroenteritis outbreaks associated with drinking water in the USA in 1985–1995

Agent	Source of water	Location [city and/or state(s)]	Number of cases in outbreak	Ref.
Cryptosporidium spp.	Municipal	Milwaukee, WI	>400 000	14
Giardia lamblia	Chlorinated but unfiltered drinking water	Various states (MS, NY, VA, CO, AL, VT)	741	15
Hepatitis A	Individual and community wells	PA	25	15
Norwalk virus	Ice	Philadelphia, PA	191	16
Shigella sonnei	Well, lake	AL, PR, TX	2733 (over a 3-year period)	16
Escherichia coli O157:H7	Community well	MO	243	11
Campylobacter jejuni	Lake	OK	250	16
Salmonella spp.	Lake, well	MS, UT	70	16

sporeforming bacterium *Bacillus cereus* in ground water reflects incidental contamination from feedlot run-off (rain run-off from feedlot areas, which enters ground water), from contact with raw sewage, or from soil. In addition, the presence of a bacterium such as *A. hydrophila* in cooked foods can be an indicator of improper handling. For example, Hunter *et al.*[7] described the isolation of *A. hydrophila* from refrigerated cooked tripe. Detection of this relatively heat-sensitive bacterium in a fully cooked product could reflect contamination from contact with cooling water after the cooking step.

The major human pathogenic bacteria that have been associated with water (drinking, surface or waste water) include: *Aeromonas* spp., *Campylobacter* spp., *Clostridium perfringens*, *Escherichia coli* including the verotoxin-producing O157:H7 serotype, enterococci, *Helicobacter pylori*, *Legionella* spp., *Listeria monocytogenes*, *Plesiomonas shigelloides*, *Pseudomonas aeruginosa*, *Salmonella* spp., *Shigella* spp., *Vibrio* spp. and *Yersinia enterocolitica*[4,8–11]. The major human viruses occurring in water are: adenovirus, coxsackievirus, echovirus, enterovirus, hepatitis, Norwalk virus, poliovirus and reovirus[4]. Protozoan parasites that occur in water are *Cryptosporidium parvum*, *Giardia lamblia*[4,12] and *Entamoeba histolytica*[13].

Thus, it is evident that essentially any and all waters can contain agents that are capable of causing disease in humans. However, despite this potential, relatively few of these agents cause disease in developed countries, undoubtedly because of widespread and adequate water treatment facilities and extensive water chlorination. Some recent US waterborne gastroenteritis outbreaks are described in Table 1. Outbreaks of shigellosis in industrialized countries such as the USA tend to be caused more often by food than by water; however, shigellosis remains largely waterborne in developing countries[17]. In general, many of the waterborne outbreaks reviewed by Cannon *et al.*[16] and Herwaldt *et al.*[15] were small and involved relatively few individuals. However, exceptions can be dramatic and illustrate that the occurrence of any problems or errors during water treatment can affect many people; examples include outbreaks caused by *E. coli* O157:H7 and Norwalk virus, which affected many individuals per outbreak[11,14,16]. For instance, it was estimated that ~400 000 individuals suffered from watery diarrhea caused by *Cryptosporidium* spp. in Milwaukee, WI, USA[14]. In the USA, the emerging pathogen *E. coli* O157:H7 caused one of the larger waterborne outbreaks of bacterial origin in recent years[11], with 243 cases being recorded.

In addition to being the vehicle for various pathogens and thus a primary disease vector, water can also contain high levels of potentially toxic chemicals such as nitrate, sodium hydroxide (high pH), fluoride–copper and ethylene glycol[18]. As will be discussed below, tertiary treatment can be used to reduce and/or eliminate various chemical contaminants.

Water represents a physical vehicle for protozoan parasites and viruses: that is, they cannot grow in water, but are simply carried in it. In contrast, bacteria in water can respond in different and complex ways depending on various exogenous factors, including temperature and the presence of metals, minerals and organic materials, which can serve as nutrients or inhibitors. Among the different bacterial responses that occur are growth, injury, survival, and transition to the viable but non-culturable state.

Growth on low substrate levels

Extensive studies have indicated that the growth of bacteria such as *A. hydrophila* and *P. aeruginosa* can be stimulated by the addition of low levels (10–25 μg carbon/liter) of different organic compounds in different water samples. The classes of compound that stimulate growth include amino acid mixtures, long-chain fatty acid mixtures and carbohydrates[19]. The concentration of nutrients in different water samples that support bacterial growth can be measured by determining assimilable organic carbon[20] or the coliform growth response[21].

Survival

Various bacteria including *A. hydrophila*, *Vibrio* spp. and *E. coli* O157:H7 have been observed to survive for long periods in sea water or river water[11,22]. Low temperature (5°C) appears to be a major contributing factor to the survival of *Vibrio* spp. and *A. hydrophila*[23].

Table 2. Waste-water clean-up procedures and their functions[a,b]

Treatment	Procedures	Function of the procedure
Primary or physical	• Filtering solids • Sedimentation • Flocculation • Centrifugation	Physical removal of large suspended solids and some microorganisms
Secondary or biological	• Activated sludge: aeration, clarification, and aerobic digestion • Trickling filter: trickling filtration and clarification • Anaerobic lagoon • Spray irrigation	Reduction of BOD and COD, and removal of TSS and TOC; removal of most microorganisms
Tertiary or chemical	• Disinfection • Nitrogen and phosphorus removal • Chemical removal of SS by coagulation and filtration	Removal of organic and inorganic material and dissolved solids

[a]Any of the listed procedures within a treatment category can be used either individually or in various combinations
[b]Adapted from Refs 18, 29 and 30
BOD, COD, SS, TOC and TSS, see Glossary

However, the presence of other bacteria can have an influence on survival; for example, Warburton *et al.*[5] observed that the presence of *P. aeruginosa* enhanced the survival of *A. hydrophila*, whereas *A. hydrophila* can have an inhibitory effect on other bacteria found in water. Toze *et al.*[24] observed that on culture media, *A. hydrophila* can inhibit the growth of *Legionella* spp., and suggested that, ultimately, the presence of *A. hydrophila* could make it difficult to isolate legionellae from various water sources, such that the water would be erroneously deemed to be free of *Legionella* spp.

Injury

Bacteria are injured or sub-lethally damaged by stresses in the environment such as high temperature, metals, inorganic compounds, acids and sanitizers (e.g. chlorine). Injured cells are unable to form colonies on selective culture media, whereas uninjured or 'normal' cells can. Terzieva and McFeters[25] reported that *E. coli*, *Campylobacter jejuni* and *Y. enterocolitica* were injured when exposed to agricultural surface water, possibly owing to the presence of various chemicals such as pesticides, herbicides and fertilizer residues. As expected, there were more injured cells in water held at 16°C than in that held at 6°C.

The viable but non-culturable state

Bacteria exposed to environmental stresses such as low temperature, nutrient depletion, hypochlorite or sea water can enter a condition known as the viable but non-culturable state[26] (VNC). Cells in this condition are not detected by culturing on regular/ordinary laboratory culture media, but can be detected using special techniques such as culture in chick embryos or an ileal loop assay[27]. The VNC state has been described for various waterborne human pathogens including *Legionella pneumophila*, *Campylobacter* spp., *Vibrio* spp., *E. coli*, *Salmonella enteritidis*, *Shigella* spp. and *A. hydrophila*[27]. Although initially described for Gram-negative bacteria, the VNC state has also been observed in Gram-positive bacteria such as *Streptococcus faecalis*, *Micrococcus flavus* and *Bacillus subtilis*[28]. The ramifications of the VNC condition, particularly for waterborne bacteria, cannot be assessed by readily available methods at this time, but there is little doubt that bacteria in this condition would escape detection by most common methods except direct microscopic examination, and thus water could be erroneously judged to be pathogen-free and safe to use and consume.

Water treatment processes

Waste-water treatments can be classified as primary (physical), secondary (biological treatment of organic wastes) or tertiary (chemical). Waste water that has undergone all three types of treatments and met all finished-product standards required by the governing agency is classified as potable. Treated waste water that does not meet all the standards for potable water or that has been partially treated is termed reuse, recycled or reconditioned water (see Glossary for definitions). An overview of the more commonly used procedures for waste-water treatment and their functions is listed in Table 2. As indicated in the table, disinfection usually occurs during tertiary treatment. In addition, various inorganic and organic contaminants are removed during the tertiary treatment phase, generally by the use of specific treatment methods[18]. These special methods must be customized for each individual water condition and include ferric sulfate coagulation, alum coagulation or lime softening to remove lead or silver, ferric sulfate coagulation to remove inorganic mercury, and ion exchange to remove nitrate.

Table 3. Disinfectants used in the treatment of waste water[a]				
Disinfectant	**Active form**	**Mode of action**	**Advantages**	**Disadvantages**
Chlorine Hypochlorite Chloramines Chlorine dioxide	Available chlorine	Oxidizing agent; combines with cell membrane and causes cell death	Low cost; bacteriostatic at proper levels	Not effective against all bacteria, protozoan parasites and enteric viruses; must maintain a proper residual chlorine level; activity affected by pH, temperature, water hardness and the presence of organic material, especially amines
Reducing oxygen Ozone Hydrogen peroxide Perozone (ozone + hydrogen peroxide)	O_3 (peroxygen)	Strong oxidant; forms free radicals within the cell, causing cell death	Most effective against bacterial pathogens; effective against protozoan parasites and viruses	Costly; toxic to humans; reacts with Mn and Fe to yield a precipitate, thus reducing its effectiveness
Radiation	Penetrating UV, sun and irradiation wavelengths	Disrupts nucleic acids, causing mutations and death		
Sunlight ($\lambda = 400–750$ nm)			No cost	Visible light needs a pigment for adsorption; needs large surface area; poor penetration; seasonal variation; not effective for coliphages
UV light source ($\lambda = 10–350$ nm)			Effective when used with a chemical disinfectant	Turbidity inhibits penetration; contact time too short to inactivate coliphages; poor penetration
Irradiation (gamma or electron beam; $\lambda = 10^{-1}–10^{-4}$ nm)			Effective against all pathogens	Costly
Competitive inhibition	Algae or non-pathogenic bacteria	Depletion of nutrients or production of inhibitory metabolites	No chemical additives; low cost	Process is slow

[a]Adapted from Refs 26, 31 and 32

Although chlorine has historically been the disinfectant of choice for water treatment in developed and developing countries, recent concerns about the formation of organochlorine compounds and their potential toxicity have prompted interest in the use of other compounds and treatments to inactivate any remaining microorganisms. Some of the currently available disinfectants that are used in waste-water treatment are listed in Table 3. The table also indicates the active form, mode of action, and advantages and disadvantages of each disinfectant.

Uses of reconditioned and/or recycled water in food processing

Water represents a major component in the processing and preparation of food products, particularly for fresh and processed red-meat and poultry operations. For example, in the USA, each broiler carcass processed requires ~20 liters of water. If this figure is multiplied by ~5000 million, the number of broilers processed yearly, then the annual requirement is 100 000 million liters of water. In geographic areas where water resources are limited, food processors can make prudent use of these resources in one of two ways: develop processing operations that utilize less water to achieve the same result[2], or recondition water (treat used water in some fashion to reduce its BOD, COD and microbial content and then recycle it within the plant). When water that has not been completely treated (reconditioned water) is used, both its chemical and microbiological content must be considered. Reusing water saves not only on the initial water costs but also on the cost of disposal because sewage fees are based on both the volume and the TSS, BOD and COD of the effluent.

Despite the tremendous potential for using recycled or reconditioned water in food processing and preparation plants, there is relatively little published information in this area. A review of the literature has indicated that reconditioned or recycled water is currently used or has the potential for use in the food industry as shown in Table 4. Reuse water can be utilized in a very wide range of unit operations. As mentioned above, poultry processing uses large quantities of water, and a great deal of research has been directed towards the reconditioning of water from these plants; several different

Table 4. Uses of reconditioned and/or recycled water in food processing and preparation		
Unit operation	**Water description or treatment**	**Ref.**
Pig carcass washing	Secondary treatment plus chlorination	3
Poultry chiller water	Flocculation and chlorination	33
	Perlite filtration and ozonation	34
Poultry processing water	Scalder water reused directly; reconditioned by removal of grease and/or bacteria for other processing	35
Chicken giblets and neck processing	Filtration through diatomaceous earth, followed by chlorination	34
Poultry scaler and brine chiller water	Microfiltration	33
Poultry carcass washing	Diatomaceous earth filtration and ozonation	36
Processed meat cooling solutions (brine or propylene glycol)	Recycled	a
Egg washing water	Recycled with alkaline detergent and sanitizer added	37
Butter washing water	Recycled	38
Cannery cooling water	Recycled after additional chlorine added	39
Washing leafy vegetables	Recycled from previous batch after settling and filtration; some blanch water is added along with some fresh water	40
Reuse of stillage water in the mashing of grain	Recycled	41
Sugar-beet processing	Recycled	2
Washing of peas	Recycled	2
Wheat-starch processing	Recycled	2
Hydrocooling of cucumbers	Recycled with addition of chlorine dioxide	42
Cucumber pickling brines	Recycled with additional NaCl	43
Sweet-cherry processing brines	Filtration, treatment with activated carbon, and addition of SO_2 and lime	44
Surimi processing brine	Recycled after removal of proteins	45
Citrus irrigation	Secondary treatment plus chlorination	46
Aquaculture of catfish	Maturation pond water	47

[a] A.J. Miller, unpublished

treatments have been investigated (Table 4). Additional research is needed in other meat processing operations.

The treatments currently employed to recondition water for reuse in food operations vary. Some only remove suspended food particles using filtration or flocculation, whereas others simply reduce or eliminate the bacterial content of the water, primarily through the use of chlorine or ozone.

Although the last two examples listed in Table 4 illustrate the use of reconditioned water in food production as opposed to processing or preparation, the water quality can still influence the quality of the food product. For instance, crop irrigation using reconditioned water (treated municipal waste water) can alter the mineral content of the product[46]. In the case of aquaculture of catfish, van den Heever and Frey[47] determined that when the coliform count of the water (treated waste water) was below 10^4cfu/ml, the fish produced were pathogen-free.

Although the primary force driving the use of reconditioned water is economic, there are certain concerns and hazards associated with the practice. As is evident from Table 4, none of the studies utilized complete treatment (primary, secondary and tertiary). In fact, most generally limit treatment to primary treatment. The most critical concerns and hazards associated with using reconditioned water are microbiological. Without an adequate disinfection step, fresh food products processed with reconditioned and/or recycled water are exposed to increased levels of both pathogenic and spoilage bacteria. Furthermore, if the treatments used to recondition the water fail to remove most or all of the organic material, such material can serve as a nutrient source for microbial growth. Research in this laboratory indicates that reconditioned water from a local pork processing plant's water treatment facility contains sufficient nutrients to support the growth of *A. hydrophila*[48], *Salmonella* spp., *Vibrio* spp.[49], *P. aeruginosa* and *E. coli*

(K. Rajkowski, unpublished). This research also supports the importance of maintaining residual chlorine levels to prevent the growth of any remaining bacteria not removed by treatment.

Conclusions

In conclusion, there is potential for the use of reconditioned water in the preparation and processing of various food products. At present, relatively few food processing operations employ reconditioned water. Each use has to be considered on an individual basis and the microbiological safety and quality of each food evaluated. Treatments for each reconditioned water operation must be tailored to the food product and the processing operations involved.

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