Disinfection of Dairy and Animal Farm Wastewater with Radiofrequency Power

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ABSTRACT

Radiofrequency (RF) power was investigated as a new, physical (nonchemical), thermal process to disinfect wastewater from dairy and animal facilities. Samples ($n = 38$) from 8 dairy, 2 calf, and 3 swine facilities in California were collected over a 3-yr period and characterized for their dielectric properties, chemical composition, and suitability for thermal processing using RF power. To establish efficacy for disinfection, selected samples were inoculated with high levels (10^6 to 10^9 cfu/mL) of bacterial pathogens such as *Salmonella* sp., *Escherichia coli* O157:H7, and *Mycobacterium avium* ssp. *paratuberculosis* and processed with an RF prototype system. The capabilities of RF power as a method for thermal disinfection of wastewater were demonstrated when bacteria pathogens were completely and rapidly (<1 min) inactivated when temperatures of 60 to 65°C were achieved. Furthermore, RF technology can be used for large-scale, batch or continuous and portable applications, allowing significant improvements in energy-use efficiencies compared with conventional thermal (surface heating) technologies. Therefore, RF power has potential as an alternative to disinfect dairy/animal farm wastewater before recycling.

(Key words: disinfection, wastewater, radiofrequency power)

Abbreviation key: FCC = Federal Communication Commission, MAP = *Mycobacterium avium* ssp. *paratuberculosis*, RF = radiofrequency.

INTRODUCTION

Background on Radiofrequency Power

Radiofrequency (RF) power is a physical method of electromagnetic energy input that heats a product uni-

formly throughout its volume leaving no chemical residues. The process operates with electrical power that generates a rapidly oscillating electric field between 2 parallel electrodes (RF cavity) where the material to be processed is placed. Dipole and induced dipole molecules in the material continuously align and reorient themselves to the changing electric field, causing friction that converts to heat. In an overall 2-step process, electrical power is first converted to RF power, which is in turn converted into thermal power. Energy-use efficiency for the overall process depends on both power conversion steps.

Industrial RF heating applications of foods have been studied since the 1940s. During the 1960s and 1970s, other applications followed including frozen foods (Jason and Sanders, 1962) and fruit juices (Demeczky, 1974). The use of RF heating was further investigated during the 1980s and 1990s to include postbaking drying operations of cookies and crackers (Mermelstein, 1997), pasteurization of sausage emulsions in a continuous-flow operation (Houben et al., 1991), and processing fresh fruits and vegetables (Nelson et al., 1994; Orsat et al., 2001). Most of the previous work demonstrated RF heating to be superior in energy-use efficiency over surface heating (>50% for RF vs. 10 to 15% for surface heating). Today, industrial uses of RF have been limited to Federal Communication Commission (FCC)-assigned frequencies (13.56, 27.12, and 40.68 MHz), a restriction that has resulted in most RF applications being based upon older-generation power tube electronics. Despite the early potential for success, large-scale uses are somewhat restricted by the current cost of RF systems (i.e., \$2000 to \$2500 per kW). Nevertheless, research using conventional frequencies and conventional RF power systems, particularly for food and agricultural applications, continues to be studied (Orsat et al., 2003; Piyasena et al., 2003). At UC Davis, both thermal and nonthermal processes based on RF power have been investigated since 1998 for various applications (Lagunas-Solar, 2003) including disinfection and disinfestation effects on various commodities (Lagunas-Solar et al., 2003, 2005a; Lagunas-Solar and

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Essert, 2003). The development and evaluation of innovative approaches for the design and engineering of high-power, high-efficiency, and lower cost RF systems are also underway.

Application of RF Power in Wastewater Management

Since the advent of modern wastewater management and use in the United States in the early 1800s (Metcalf and Eddy, 1991), treated municipal wastewater effluents have been used in irrigation of agricultural and recreational land as a means to conserve water resources. Water reclamation and reuse is often an alternative to disposal, especially in those areas where surface water has limited capacity to absorb contaminants. The solid phase resulting from processing municipal wastewater (i.e., sludge) contains organic matter and nutrients that are useful in fertilization of agricultural land; thus, its use in improving productivity while simultaneously providing alternatives to disposal in place of incineration or landscaping (filling). These practices are now generally accepted mostly due to existing guidelines (EPA, 1992, 1993, 2003) that established minimum standards for both reclaimed water and sewage sludge from concentrated animal feeding operations. Today, most reclaimed water produced in the United States is of high quality. However, although recycling continues to be beneficial, it raises concerns because of the nature of potential microbial and chemical contaminants. Furthermore, nutrients from livestock and poultry manure (i.e., phosphates and nitrates) have been identified as key sources of water pollution (Ribaudo et al., 2003).

Several types of waterborne zoonotic disease agents are likely to be present in wastewater. Many bacterial pathogens such as *Campylobacter jejuni*, *Salmonella typhimurium*, and *Escherichia coli* have relatively high infectious doses; therefore, thousands of viable organisms are needed to initiate infections in humans (Robinson, 1981; Black et al., 1988). On the contrary, protozoan pathogens such as *Cryptosporidium parvum* and *Giardia lamblia* have very low infectious doses (Rendtorff, 1954; DuPont et al., 1995) and only a few viable organisms may initiate diseases in humans. Moreover, these protozoa are characterized for their cysts and particularly the relative resistance of their oocysts to chemical disinfectants (Sterling, 1990).

Besides human pathogens, the presence of organic matter (as N and P sources) and inorganic contaminants in sludge (i.e., As, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Se, and Zn) are well known and are viewed as potential human and environmental health hazards. The accu-

mulation of trace elements in land applications is ultimately detrimental for agriculture because excessive levels may decrease productivity, cause economic losses, and increase liability risks.

Wastewater is produced on most livestock and poultry farm facilities worldwide. Disposal is often not an option, whereas recycling is an attractive and advantageous alternative. Currently, wastewater is collected, stored, and often separated into liquid and solid phases before reuse without effective treatment against human pathogens or chemicals. The liquid phase, which contains nutrients, is used in irrigating adjacent agricultural fields, whereas the solid phase is usually used as field fertilizers or as commercial animal feed supplements. In California, legislation was considered by the House of Representatives in August 2003 to mandate reprocessing of dairy/animal farm wastewater for disinfection as a condition for recycling. However, fulfilling the anticipated regulatory and operational needs require that an appropriate, practical, and economically viable technical solution is available. For the farm application, none of the methods used extensively in the processing of municipal wastewater (i.e., chemical disinfection, ozonation, ultraviolet radiation) are likely alternatives due to economic or logistical constraints. Therefore, the general objectives of this work were to determine the applicability of RF power technology for processing wastewater and project its use in the livestock and poultry farm environ.

MATERIALS AND METHODS

Sample Collection

Samples (38 total, 19 to 38 L each) of raw and filtered wastewater were collected from 8 dairy and 5 animal farm facilities (2 calf, 3 swine) operating in Tulare County, California. These facilities ranged in size from 25 (swine facility) to 100 animals (calf facility), and from 600 to 2800 dairy cows. Samples were collected in winter, late spring, and summer from May 2000 to June 2003. Collections (38 total) were done from several on-farm locations and points of operation including flush alleys, after sump areas, before and after solid separation, and from small pond separators as well as large manure lagoons. The samples were used to measure RF properties of wastewater and to determine any potential change on their response to RF fields that could be due to variations in physical and chemical characteristics. Representative subsamples (n = 28) for microbial and chemical analyses were taken from the original samples, and disinfection effects were studied

with inoculated subsamples over the entire collection period (May 2000 to June 2003).

Microbial and Chemical Composition of Wastewater

Dairy wastewater samples ($n = 28$) collected during May and June 2000 were used to characterize their microbiological and chemical composition. Standard methods of microbial and chemical assays were used, as described below. The latter information was useful in establishing the range of conditions to be met in efficacy disinfection tests with RF power, as well as to determine possible variations in wastewater composition likely to affect its RF behavior (i.e., ability to induce thermal effects). A certified analytical laboratory (Mid State Laboratories, Visalia, CA) performed both microbial and chemical assays using standard procedures or methods approved by AOAC (AOAC, 2000). Microbial assays included total and gram-stained bacteria counts, and chemical assays included pH, total dissolved solids, electrical conductivity, and concentrations (ppm) of calcium, sodium, magnesium, boron, chlorine, bicarbonates, sulfates, and nitrates.

RF Research Systems

A transversal electromagnetic cell (model TC3020A; Amplifier Research, Souderton, PA) was used to study the RF behavior of the 38 diverse wastewater samples collected. In addition, all RF-induced thermal disinfection experiments were conducted with a research-prototype RF system (parallel-plate cavity) developed and constructed at the UC Davis Crocker Nuclear Laboratory. Design, engineering, and operating details of these systems are given in Lagunas-Solar et al. (2005a). The operating version of the RF research prototype is shown in Figure 1. The RF treatment cavity consists of 2 parallel metallic Al plates (46×60 cm; 2.5 cm thick) connected to a Cu-coil resonance inductor and to a capacitor-matching network (not shown), all of which were designed and fabricated at UC Davis Crocker Nuclear Laboratory. The RF system uses a synthesized RF signal generator (model 6060B, 10 kHz to 1050 MHz; Gigatronics Inc., San Ramon, CA) and a 2.5-kW wideband RF amplifier (model TCCX 2500P, 10 kHz to 250 MHz; Instruments for Industry Inc., Ronkonkoma, NY), to deliver RF energy to an enclosed (RF-shielded) cavity. The system includes several diagnostic devices including RF power meters (model 4391A; Bird Electronic Corp., Cleveland, OH), and an oscilloscope (model 54610B, 500 MHz; Hewlett Packard, Palo Alto, CA) for electric field measurements in the RF cavity. Thermocouples (off-line measurements) and a fiber optic system

(model UMI-4; FISO Technologies, Quebec, Canada) for online measurements were used to profile the treated samples during processing. A digital computer provided data acquisition and storage capabilities.

Determination of RF Properties of Wastewater

The efficiency and reproducibility of RF energy to be converted to thermal energy (i.e., RF behavior) was tested on wastewater samples collected from different dairy and animal farm facilities, from May and June 2000 ($n = 28$) to June 2003 ($n = 10$). A plastic container holding the sample (100 mL) was positioned in the transversal electromagnetic cell and RF power was applied at a selected frequency over a range of 0.2 to 125 MHz. At each frequency interval of 0.5 to 1 MHz, the absorbed RF power was determined using RF power meters, and the RF energy-use efficiency for each sample was determined as a fractional absorbed power vs. frequency relationship. The relationships for each wastewater sample were then compared to ascertain the homogeneity of RF behavior between samples from different facilities, locations, and times of operation. Those tests also provided information on the potential seasonal variations in wastewater composition that could have affected its ability to absorb RF power. Finally, those samples were used and treated under the same RF cavity configuration (Figure 1) to measure the heating rate ($^{\circ}\text{C}/\text{min}$) of wastewater under various RF power levels and frequency of operation. This information was valuable in determining throughput capacity for processing wastewater with RF power applied at a selected single band or with a narrow band of frequencies and at different power levels.

Preparation of Inoculated Wastewater Samples

American Type Culture Collection strains of *Salmonella typhimurium* (ATCC # 14028), *Escherichia coli* O157:H7 (ATCC # 43895), and isolates of *Mycobacterium avium* ssp. *paratuberculosis* (MAP) were provided by the UC Davis School of Veterinary Medicine Dairy Food Safety Laboratory. On the day of RF-processing experiments, 100-mL aliquots of the wastewater samples were added into a 275-mL polystyrene culture flask (75-cm^2 culture area; Corning, Acton, MA) and inoculated as described below with each specific pathogen. Control samples were prepared exactly as the treated samples but were not exposed to RF processing. For the experiments with MAP, the wastewater was autoclaved before inoculation to facilitate recovery and quantification of this organism.

Figure 1. University of California, Davis radiofrequency (RF) research prototype system (2.5 kW; 0.3 to 125 MHz) showing the RF cavity (lower left, foreground) with fixed (bottom) and variable electrode (top); RF amplifier (top right, background); online accessories (background tabletop: joulemeters, oscilloscope, and RF signal generator); and computer system (right, foreground). The fiber optic system for online thermometry is shown on top of computer system.

Escherichia coli O157:H7 and *S. typhimurium* were incubated overnight in trypticase soy broth at 37°C, to an approximate concentration of 10^9 cfu/mL. The broth cultures were centrifuged, washed, and resuspended to approximately 10^9 cfu/mL in 10 mM sodium phosphate buffer (pH 7.3). The inocula were then diluted 1:100 in wastewater resulting in an approximate final concentration of 10^7 cfu/mL.

The isolate of MAP was grown in Middlebrook 7H9 medium supplemented with mycobactin J (2 mg/L), Tween 80, and Middlebrook oleic acid, albumin, dextrose, and catalase enrichment media (Becton Dickinson, Sparks, MD), until the optical density at 540 nm reached approximately 1.15, equivalent to approximately 10^8 cells/mL. The broth culture was centrifuged, washed with PBS, and resuspended in PBS to yield an inoculum concentration of approximately 10^8 cells/mL. Because of the lower broth concentration of MAP (and its slow growth rate), the inoculum was then diluted 1:100 in autoclaved dairy wastewater resulting in a final concentration of 10^6 cfu/mL.

RF Disinfection Effects in Wastewater

The biocidal effects of RF processing on normal flora (i.e., total bacteria, gram-negative, coliform) and on various inoculated bacteria pathogens in wastewater were measured in a series of experiments ($n = 47$). Freshly inoculated samples (100-mL each, in triplicate, treated the same day) were processed within a temperature range of 50 to 90°C. Treatment temperatures were measured online using fiber-optic transducers (center, top, bottom locations) that were precalibrated with secondary wastewater samples with thermocouple-based thermometry placed at the same locations. The temperature profile in samples indicated homogeneous heating (within $\pm 1^\circ\text{C}$) in all regions. As the absorption of RF allows for rapid heating, limited power (40 to 500 W) was used to lengthen times of processing (2 to 5 min) and to allow precise temperature determinations during processing. At the completion of the RF heating phase, all samples were cooled passively (without intervention) at 20 to 22°C.

Immediately after cooling, the wastewater samples were diluted with sterile water and 50 μL of both diluted and undiluted samples (controls and RF-treated) were plated using a spiral plater (model RGB; Microbiology International, Frederick, MD) in duplicate onto the appropriate agar for the bacteria to be recovered. For estimates of surviving *E. coli* O157:H7, sorbitol MacConkey agar was used with only the sorbitol nonfermenting colonies counted. Rainbow *Salmonella* agar was used as the selective media for *Salmonella* spp. with only the black colonies counted and used to estimate *Salmonella* levels (cfu/mL). The bacterial colonies were counted using a Protocol plate counter (Microbiology International). For the experiments using MAP, appropriate dilutions were spirally plated onto Middlebrook 7H10 agar plates supplemented with mycobactin J, in duplicate. The plates were incubated in sealed plastic bags for 1 to 3 wk at 37°C and the resulting microcolonies counted using a dissecting microscope at 40 $\times$ magnification (Smith et al., 2003).

All samples were assayed in duplicate. Results were expressed as colony-forming units per milliliter and disinfection effects were calculated as $\log_{10}$ reduction values. Because the assay method has a lower limit of detection of 400 cfu/mL, measured results were expressed accordingly. However, 2 separated groups containing all of the specific-growth plated samples were kept at room (20 to 22°C) and at refrigeration (0 to 2°C) temperatures, and examined daily for up to 21 d to detect any surviving fraction of the added bacteria pathogens. As no colony growth was detected, $\log_{10}$ reductions were also calculated (extrapolated) using the initial inoculation levels.

Data Analyses

All results presented here were obtained from replicated experiments. Wastewater microbial and chemical characteristics were assayed in all samples collected from May to June 2000 ($n = 28$) from 3 swine, 2 calf, and 8 dairy farms. Results were averaged and standard deviations (SD) were calculated. Radiofrequency disinfection results for gram-negative bacteria ($n = 29$), *Salmonella* spp. ($n = 6$), *E. coli* O157:H7 ($n = 6$), and MAP ($n = 6$) were also obtained from duplicated assays of original or inoculated subsamples and reported as $\log_{10}$ reduction values. Temperatures reported in this work had a standard error of $\pm 1^\circ\text{C}$ both for thermocouple and fiber optic-based thermometry, and frequency (MHz), RF power levels (W), and energy-use efficiencies had errors of ± 0.05 MHz, ± 3 W, and $\pm 10\%$ respectively.

RESULTS

The microbial and physical-chemical characteristics of wastewater samples taken from swine, calf, and dairy

farm operations are summarized in Table 1. As expected, total microbial loads are high (10^6 to 10^8 cfu/mL) and include gram-negative bacteria (10^6 to 10^7 cfu/mL) as well as coliforms (10^6 cfu/mL). Depending on how such unprocessed wastewater is used, potential public and environmental risks are possible with such microbial loads. Results of chemical analyses are also presented and show some similarity, as in most cases, chemical composition varied within a narrow range.

The RF behavior of wastewater samples (shown in Figure 2) indicates that the RF properties of the different wastewater samples were similar even over a wide range of operating frequencies (0.3 to 125 MHz). Furthermore, these data show that wastewater has a uniform response to RF due to its consistent chemical and physical properties (i.e., composition, concentration of suspended/dissolved matter, turbidity, and specific heat) despite the diversity of source, time, location, and operating conditions. Therefore, a single frequency or a selected narrow band of frequencies could be used to operate an RF system to process wastewater. New RF systems could be designed to operate with maximum overall energy-use efficiency ($>80\%$), which is a distinct advantage over conventional surface-heat (pasteurization) technologies.

Results of wastewater disinfection levels (i.e., $\log_{10}$ reduction) are summarized in Table 2, including disinfection of *Salmonella* spp., *E. coli* O157:H7, and MAP. For all bacteria pathogens, RF thermal processing of wastewater reaching 60 to 65°C controlled inoculum levels of up to 10^8 cfu/mL, and no colony growth was detected in any of the assayed samples after a 21-d observation period. These results indicate that the RF thermal process is capable of providing high disinfection levels for bacteria pathogens. In addition, approximate 2 $\log_{10}$ reduction effects for all other microorganisms present in wastewater, including gram-positive (data not shown) and other gram-negative bacteria were determined. Radiofrequency processing was demonstrated to be effective in controlling MAP at thermal levels of 60 to 65°C.

The relationship of RF disinfection levels and temperature is shown in Figure 3, in which both measured and extrapolated $\log_{10}$ reduction values are indicated. Measured $\log_{10}$ reduction values are influenced by the limit sensitivity (400 cfu/mL) of the assay method, whereas extrapolated values are reported because long-term incubation showed no viable or surviving colonies after processing. The extrapolated values were expressed as $\log_{10}$ reduction levels based upon the original inoculum concentrations used in these experiments.

Temperatures effective for bacteria control were achieved rapidly, and time varied as a function of power

Table 1. Microbial and physicochemical characteristics of collected wastewater samples (n = 28) from dairy and animal farm operations in Tulare County, California (May to June 2000).

	Swine farm (n = 3; 3 samples)			Calf farm (n = 2; 2 samples)			Dairy farm (n = 8; 23 samples)		
	Min	Max	Mean ($\pm$ SD)	Min	Max	Mean ($\pm$ SD)	Min	Max	Mean ($\pm$ SD)
Microbial assays ($\times 10^5$ cfu/mL)									
Total bacteria	71	71	71 (0)	327	7250	2916 (3777)	5	1492	146 (325)
Gram-negative bacteria	9	53	31 (31)	10	208	77 (113)	0.1	14	3 (3)
Lactose-fermenting bacteria	0.2	11	6 (8)	0.5	16	6 (9)	0.1	5	1 (1.5)
Physical assays									
Total dissolved solids (mg/kg)	ND ¹			646	2797	1894 (1116)	678	5376	3142 (1270)
Acidity (pH)	ND			6.9	7.5	7.2 (0.3)	7.1	9.0	7.6 (0.5)
Electric conductivity (mmho/mL)	ND			1.0	4.4	3.0 (1.7)	1.1	8.4	4.9 (2.0)
Chemical assays (mg/kg)									
Calcium	ND			2.8	7.7	4.6 (2.7)	1.0	11.2	6.3 (2.7)
Magnesium	ND			3.6	10.4	6.0 (3.8)	1.4	16.3	6.7 (3.3)
Sodium	ND			2.1	10.0	5.6 (4.0)	3.6	12	8.7 (2.5)
Boron	ND			0.2	0.3	0.23 (0.06)	0.3	1.1	0.8 (0.2)
Chlorine	ND			37	309	165 (137)	51	359	221 (96)
Bicarbonate	ND			11	33	25 (13)	8	88	47 (20)
Sulfate	ND			16	101	48 (47)	18	87	37 (22)
Nitrate	ND			<0.01	<0.01	<0.01 (0)	<0.01	<0.01	<0.01 (0)

¹ND = Not determined.

(Figure 4). This would allow either a batch or a continuous flow system to be implemented with sufficient RF (and electric) power to provide adequate throughput capabilities.

Selected low-frequency narrow bands were also tested and demonstrated to be as efficient as single frequencies, reaching in excess of 90% RF power-to-thermal conversion efficiencies when operating in the

Figure 2. Summary of radiofrequency (RF) behavior of wastewater samples (n = 38) from dairy (n = 8), swine (n = 3), and calf (n = 2) feeding facilities in Tulare County, California (May 2000 to June 2003). Samples are grouped and represented together to emphasize observed similar response to RF fields.

Table 2. Summary of results of radiofrequency-induced thermal disinfection of wastewater.

	Gram-negative bacteria (n = 29)	<i>Salmonella</i> spp. (n = 6)	<i>Escherichia coli</i> O157:H7 (n = 6)	<i>Mycobacterium paratuberculosis</i> (n = 6)
Frequency (MHz)	79 to 94	10 to 14	10 to 14	10 to 14
Temperature (°C)	63 to 66	>63	>63	>60
Inoculation level	None	1.1×10^7	8.2×10^6	3.2×10^6
Log ₁₀ reduction ¹ (measured)	4–6	>4	>4	>3.5
Log ₁₀ reduction ² (extrapolated)	NA	>7	>6	>6
Colony formation ²	None	None	None	None

¹Measured values are given considering a minimum detection level of ≥ 400 cfu/mL.

²In inoculated samples, because no colony formation was observed during 21-d of incubation and observation, a maximum control at the initial inoculation level was assumed, thus log₁₀ reduction values were calculated (extrapolated) accordingly.

0.15- to 3.0-MHz range and with product thickness of 80 to 85 mm (Figure 5). Therefore, overall energy-use efficiencies (electric or wall power to RF, and RF to thermal power) can exceed 80%, making this approach highly attractive for reduced operational costs as well as significant savings in the cost of manufacturing systems.

An analysis of logistics and economic estimates for several dairy farm models, based upon the findings of the current work, is given in Table 3. These estimates are based upon a direct extrapolation of RF power consumption with needed throughput, a credible assumption as RF processing is highly dependent on electric

power and commercial systems are expected to operate consistently at the same levels of overall efficiency.

Finally, a general concept for a modular RF processing system for wastewater is shown in Figure 6. This system can be operated in a continuous-flow mode by pumping the collected wastewater and circulating it through an RF cavity. Processing throughput can be varied by proper selection of the RF cavity volume as well as by varying electrical and RF power.

DISCUSSION

Radiofrequency power technologies are being investigated for several large-scale applications in a variety

Figure 3. Measured and extrapolated radiofrequency (RF)-induced disinfection levels (log₁₀ reductions) for inoculated wastewater as a function of temperature.

Figure 4. Heating rates ($^{\circ}\text{C}/\text{min}$) for different samples of wastewater as a function of input RF power applied at 200 kHz without thermal insulation (electrode gap = 83 mm, wastewater volume = 220 mL). Energy-use efficiency increases with power as surface radiation losses are minimized.

of industrial activities including food and agriculture processing (e.g., disinfection, disinfestation) and in environmental remediation (Lagunas-Solar et al., 2005b).

For the most part, this effort is driven by the known advantages of RF processing over conventional surface-heating technologies and by the anticipated need for

Figure 5. Radiofrequency (RF) power absorption (%) as a function of operating frequency for dairy wastewater (electrode gap = 83 mm, wastewater volume = 220 mL, RF power = 10 W, no inductor). Values are indicated with standard deviations.

Table 3. Specifications and cost estimates for installation and operation of a radiofrequency thermal processing system for disinfection of dairy wastewater.

Assumptions				
Wastewater properties:	1.05 g/mL (density)	3.9 J/g/°C (specific heat)	Temperature gradient = +50°C	
Energy-use efficiencies:	Electric-to-RF power = 88%	RF-to-Thermal power = 92%		
	Overall energy-use efficiency = 81% (conventional RF = 45%)			
Heat properties:	Containment heating and radiation losses are omitted.			
Other assumptions:	Heating rate is proportional to the RF power. Temperature gradient is proportional to electric power. Wastewater per cow = 30 gallons/day (113.6 L/d). Cost of electric power = \$ 0.05/kWh. ¹			
Model dairy farm		500 cows	1000 cows	2000 cows
Daily wastewater (gallons/day)		15,000	30,000	60,000
Rate of wastewater processing (gallons/h)	8-h process	1875	3750	7500
	12-h process	1250	2500	5000
	24-h process	625	1250	2500
RF power level (kW)				
(cost estimate of RF system) ²	8-h process	450 (\$105,000)	900 (\$195,000)	1,800 (\$375,000)
	12-h process	300 (\$75,000)	600 (\$135,000)	1,200 (\$255,000)
	24-h process	150 (\$45,000)	300 (\$75,000)	600 (\$135,000)
Energy cost for all conditions:		\$0.013/gallon (\$0.0034/L)		

¹Preferential agricultural use rate.

²Include cost estimate of RF power system (\$200/kW; a variable cost) and standard accessories (RF cavity, shielding, sensors, and pumps) at \$15,000 per system (a fixed cost). Because of uncertainties, these cost estimates were rounded to the nearest tens (RF power) and nearest thousand (Cost).

an adequate technical solution to the massive challenges in material processing confronting the livestock and poultry industries.

The benefits of RF for this application include the high energy-use efficiency, reduced costs of manufacturing and operation compared with other thermal

technologies, and the physical nature of this process that gives it an environmentally friendly aspect (because no chemical residues are added and no chemical or nutritional changes are induced in the treated material). Processing with RF was selected for investigation because it allows uniform penetration and heating, us-

Figure 6. Schematic of a radiofrequency (RF) thermal processing module for disinfection of wastewater. The modular system can be used in a serial combination to achieve desired processing rates.

ing the well-known kinetics of thermal disinfection (FDA, 2000). When applied to wastewater, a material with high electrical conductivity (see Table 1), the RF electrical field results in a small fractional component of dielectric heating with a large fractional component of resistive heating. This combination of interaction mechanisms is the key characteristic that promotes high energy efficiency under the conditions described in this study. This fact distinguishes our approach from the use of conventional RF-based systems, which are solely based on operating with FCC-assigned frequencies.

In addition, it appears that RF thermal processing is superior to conventional heat processing, because it effectively controls MAP, a pathogen that exhibits clumping ability that seems to make it resistant to conventional surface heat processes (Chiodini and Hermon-Taylor, 1993; Sung and Collins, 1998; Miller et al., 1996). In California's dairy industry alone, current estimates of MAP-infected cows range from 5 to 29% of the more than 2 million animals in milk production. Therefore, currently pasteurized liquid milk and some other dairy products may contain MAP as well. It is estimated that MAP is responsible for \$2 billion per year losses. Losses are due to animal diseases, deaths, reduced productivity, and cross-infectivity, particularly in cows, but also in other animals such as sheep. As a result, new regulations may force the industry to introduce effective disinfection technologies. Thermal processing with RF could then address many of the current challenges for disinfection including a new, more effective processing alternative for liquid milk.

The technologies used in municipal wastewater processing (i.e., chlorination, ozonation, ultraviolet radiation) have been appropriate because of their large-scale applications. It is not yet clear whether these technologies would be effective and competitive at a much smaller scale characteristic of concentrated animal feeding operations. Implementation of any of these technologies is expected to be questionable because of installation and operational costs in the farm environment, and the needs for on-line technical support and space in particular for equipment needed for UV radiation treatment. All the municipal-use technologies leave chemical residues, which raises concerns regarding human and environmental risks and prompts questions about expanded uses under a stricter regulatory environment. Chlorination techniques are known to cause the formation of toxic chemical residues that would affect the use of wastewater in irrigation; ozonation efficacy is not considered likely because of the chemical composition of animal farm wastewater; and ultraviolet radiation is severely limited in penetration due to the high UV-absorbent chemicals present. In contrast, RF pro-

cessing is perceived as a friendlier (nonchemical) approach, potentially efficient, and flexible enough to accommodate the needs of a range of small and large animal-feeding operations. All of the above suggest that RF thermal processing could be considered an alternative technology capable of providing the expected safety assurances when recycling manure and reusing water resources in the livestock and poultry industries.

Because RF systems can be built at power levels from hundreds of kilowatts up to a few megawatts, only installation and operational costs are critical in designing appropriate systems for commercial-scale use. Newly designed systems have been tested using nonconventional (i.e., non-FCC-approved) frequencies. These operate with high overall energy-use efficiency (>80%) and can be manufactured with significant cost reductions compared with commercially available conventional RF systems (Lagunas-Solar and Essert, 2003).

Preliminary economic estimates for the cost of installation and operation of an RF thermal processing system based upon the results and concepts advanced in this work are given in Table 3. Several sizes of dairy facilities were used as models for estimating the specifications and cost of installation and operation of an RF thermal processing system capable of processing their estimated daily output of wastewater. It was assumed that each cow produces a daily average of 113.6 L (30 gallons) of wastewater. As shown in Table 3, RF systems can be built at different power levels that would allow the tailoring of processing times to the farm's needs while minimizing installation costs. Processing (operating) costs for treating wastewater are expected to be constant at an estimated \$0.0034/L (\$0.013/gallon), as the process depends solely on energy-use efficiency, cost of electrical power, and temperature gradients to reach disinfection levels. Other cost factors included for needed accessories and monitoring the process are independent of the size of operation or chosen processing times. The selected models can easily be applied to other size facilities, as specifying RF system power levels (and costs) would be directly proportional to the daily wastewater throughput or to the number of animals.

Finally, presence of harmful bacteria and parasites excreted by livestock and poultry and their potential transmission to humans through water (Atwill, 1997), as well as adverse environmental impacts of other contaminants in wastewater, support the notion that mandatory treatment of wastewater will be forthcoming, posing major technical and economic challenges to the livestock and poultry industries. Under this scenario, RF thermal processing appears to be an energy-efficient and environmentally safe choice, and compares well with the existing alternatives servicing the treatment

needs of municipal wastewater. The results of this work also suggest that RF may provide cost-effective solutions, if the new design and engineering approaches indicated here are fully developed.

CONCLUSIONS

Given the positive results of disinfection, system logistics, and economics for RF thermal processing of animal manure presented here, the known limitations of other existing technologies for processing municipal wastewater, and the anticipated need for wastewater treatment in the livestock and poultry operations, RF thermal processing of wastewater may be an alternative for the livestock and poultry industries. With RF thermal processing, high disinfection levels can be achieved while preserving chemical and nutritional composition. Therefore, RF would allow recycling of solids and liquids from wastewater into feed supplements and soil fertilizers safely and effectively without quality deterioration. Because wastewater can be processed as a whole (before separating its phases), the treated solids and sanitized liquids would provide needed resources free of infective agents for management and recycling manure in a manner that would allow safe recycling practices in the farm environment. However, to reach its potential, design and engineering work of new RF sources should be continued to allow for field demonstrations of its capabilities.

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