

# Recovery and Utilization of Useful By-Products from Egg Processing Wastewater by Electrocoagulation<sup>1</sup>

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**ABSTRACT** The efficacy of a laboratory electrocoagulation (EC) system for treating egg processing plant wastewater (WW) is reported. For simulated and industrial egg processing WW, chemical oxygen demand, turbidity, and total suspended solids (TSS) were reduced 92 to 97%, 97%, and 99%, respectively, after treatment with EC. The final TSS concentration and turbidity values were 30 mg/L and 5 formazin turbidity units (FTU), respectively, similar to that of potable water standards. The recovered by-product solids had a similar pattern of essential amino acids compared to that of liquid whole egg and were comparable to the Food Agriculture Organization's essen-

tial amino acid profile for an ideal protein. The relative protein digestibilities of the recovered solids and a commercial corn meal averaged 130 and 56%, respectively, compared to liquid whole egg (set at 100%). An economic analysis of EC indicated that this treatment is economically feasible in that a savings of approximately \$425,000 per year is possible in addition to recovering the capital equipment costs after about 14 mo of operation. These findings demonstrate that EC can be successfully applied to treat egg processing plant WW, yielding a high quality water suitable for recycling and valuable by-products having a highly digestible protein and fat value.

(*Key words:* egg processing plant wastewater, by-product recovery, digestibility, electrocoagulation, nutritional analysis)

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## INTRODUCTION

Annually, the egg processing industry generates about 2.5 billion gallons of wastewater (WW), which contains very high organic loads associated with egg losses (Carawan et al., 1979). In some municipalities, untreated egg processing WW is discharged directly into municipal sewers or applied to cropland because land and sewer charges have traditionally been low (Walsh, 1994). As a result of rapidly rising water, land, and sewer use costs and the associated pollution problems, regulations limiting these practices have become more stringent. Thus, these practices are no longer acceptable for food companies (R. E. Carawan, 2001, Department of Food Science, North Carolina State University, Raleigh, NC, personal communication). Egg Processors must begin to identify methods to reduce waste loads as well as to reuse or recycle their WW and reclaim potentially valuable by-products. The possibility of recovering useful by-pro-

ducts from WW as a means of alleviating waste disposal problems has attracted increased interest in recent years (Beszedits, 1982; Crickenberger and Carawan, 1991; Evans, 1992). Several practical recovery technologies have been developed including ultrafiltration, precipitation/coagulation, and electrocoagulation (EC) (Beszedits, 1982). Although previous research has indicated that precipitation/coagulation and ultrafiltration processes were good methods to treat WW from egg processing, there are still some limitations associated with these two technologies (Beck et al., 1974; Beszedits, 1982).

Electrocoagulation was developed in 1974 and has attracted increased interest in recent years (Bersier et al., 1994). Electrocoagulation is a recovery treatment process that uses an electrical current for the destabilization of colloidal and emulsified particles. It may be used with or without addition of coagulants. Compared with other treatment processes such as precipitation/coagulation, ultrafiltration, and evaporation/drying, this process has many advantages (Beck et al., 1974; Beszedits, 1982; Scott,

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**Abbreviation Key:** AQC = 6-aminoquinolyl-N-hydroxysuccinimide carbamate; BEN = bentonite; BOD = biological oxygen demand; CMC = carboxymethylcellulose; COD = chemical oxygen demand; EC = electrocoagulation; FTU = formazin turbidity units; PCA = precipitation/coagulation agents; TSS = total suspended solids; WW = wastewater.

1995): (1) competitive capital and operational cost [costs average less than \$0.005 per 3,780 L (1,000 gal)]; (2) high removal efficiencies for chemical oxygen demand (COD), biological oxygen demand (BOD), total solids; and fat, oil, and grease; (3) no need for additional separation equipment (flocs rising to the surface are easily skimmed off and contain solids contents of about 9 to 12% as compared to 3 to 5% for dissolved air flotation treatment); (4) ability to handle variable flows; (5) small detention or treatment times of less than 15 min as compared to precipitation/coagulation methods that require at least 30 min; (6) reduced space requirements; (7) the use of a safe direct current voltage of only 10 to 30 V; and (8) the treated WW can be subsequently chlorinated to assure microbiological acceptability.

Although there is little information about the use of this technology for egg processing plant WW, successful treatment applications of WW from other food processing plant discharges such as meat, poultry, dairy, and the oils industries have been reported in a number of publications and patents (Beck et al., 1974; Miller, 1975; Beszedits, 1982; Scott, 1995).

The most successful commercial WW treatment technology incorporating EC was the Lectro Clear system that was developed by the Swift Environmental System Co. to recover fat, protein, and oils from meat and oil processing plant WW and then later was modified by Dravo Corp. (Smith, 1980). This EC system used a 12.5-V cell combined with coagulant addition. Recoveries of total solids and fat, oil, and grease were greater than 98%. No information was provided on the composition of the by-products or their potential for use in animal feeds. However, this system may be used as noted in the following studies to recover significant amounts of by-products for use in animal feeds (Otake et al., 1977; Ramirez and Clemens, 1978).

In the present study, a laboratory-scale EC system was assembled and tested to evaluate its efficacy in treating egg processing plant WW. Furthermore, by-products recovered by EC were evaluated for proximate composition, amino acid profiles, and protein digestibility to determine their suitability for use in animal feeds. Finally, the total operating costs of a commercial EC system was estimated and compared to current municipal treatment surcharges.

## MATERIALS AND METHODS

### Materials

Pepsin, bentonite (BEN), and carboxymethylcellulose (CMC) were obtained from Sigma Chemical Co.<sup>3</sup> Ortho-

phthaldehyde was from Pierce,<sup>4</sup> and SDS, sodium tetraborate, and electrophoresis-grade 2-mercaptoethanol were from Bio-Rad Laboratories.<sup>5</sup> Corn meal, which contained 16.5% protein and 3.0% fat, was donated from a midwestern chicken farm. All other chemicals were reagent grade and were purchased from Sigma Chemical Co.

The derivatization reagent kit, 6-aminoquinolyl-N-hydroxysuccinimidyl carbamate (AQC), 0.2 M borate buffer, and DNA-grade acetonitrile were obtained from Waters Corp.<sup>6</sup> The internal standard  $\alpha$ -aminobutyric acid was purchased from Seelze Chemical Company.<sup>7</sup> All other chemicals for HPLC analysis were analytical reagent grade and were purchased from Sigma Chemical Co.

### WW Samples

Wastewater samples were collected from a commercial egg processing plant. In addition, simulated egg WW samples were also prepared (0.4% wt/vol, liquid whole egg blended in tap water).

### Experimental Apparatus

The electrodes used in the EC system were made of aluminum, iron, or stainless steel and had surface areas of 30 cm<sup>2</sup> [1.0 cm (width)  $\times$  13.5 (height)  $\times$  2 cm (depth)], 54 cm<sup>2</sup> (2.0  $\times$  13.5  $\times$  2 cm), and 108 cm<sup>2</sup> (4.0  $\times$  13.5  $\times$  2 cm). Two electrodes oriented vertically and placed 7 cm apart were lowered into a 2.02-L rectangular glass tank [35.6 cm (width)  $\times$  30.5 cm (height)  $\times$  30.5 cm (depth)] containing 1 L of WW. Electrodes were attached to a variable Tri-Power Supply<sup>8</sup> to provide direct current and to control voltage.

### EC Procedures (Preliminary Screening Studies)

Several preliminary screening trials were initially conducted to establish effective operating parameters for the EC system. The specific EC operational parameters that were evaluated included electrode composition and surface area, mixing rate, ionic strength (NaCl concentration), precipitation/coagulant agent (PCA), and WW pH. For each of these initial screening trials, one trial per EC parameter was completed. Based on the literature describing various types of electrodes and PCA, three types of electrodes (iron, aluminum, stainless steel) and two PCA (CMC and BEN) were chosen to evaluate in the preliminary studies. EC-treated WW supernatant quality, as determined by COD removal and turbidity reduction, was used to identify the most effective treatment parameters. Based on these trials, the following operational procedures were established. Two electrodes (each having a 30 cm<sup>2</sup> surface area) were lowered in 1,000 mL of WW (22 to 25 C) contained in the 2.02-L glass tank, and a 10- to 20-V direct current potential was applied. The current varied from 2.0 to 5.0 A.

The procedure began with pH adjustment of the WW to 4.5, using 1 N hydrochloric acid, for samples evaluated

<sup>3</sup>Sigma Chemical Company, St. Louis, MO.

<sup>4</sup>Pierce Chemical Company, Rockford, IL.

<sup>5</sup>Bio-Rad Laboratories Inc., Hercules, CA.

<sup>6</sup>Waters Corporation, Milford, MA.

<sup>7</sup>Seelze Chemical Company, Seelze, Germany.

<sup>8</sup>Health Company, Benton Harbor, MI.

without PCA treatment and to a pH range of 2.5 to 9 for WW samples containing PCA. pH adjustment was followed by addition of a single coagulation agent at 1 of 10 different concentrations (50 to 1,000 mg/L) followed by mixing for 2 min at 40 rpm. For simulated WW samples, 1.5 g sodium chloride was added to increase electrical conductivity. During the process, a floc formed on the cathode electrode with gases being released from both electrodes. The floc had a tendency to adhere to the electrode, resulting in decreased current. To alleviate buildup, the electrodes were gently tapped periodically to release any adhering floc that floated to the surface and formed a whitish froth. Water samples were taken from the approximate geometric center of the tank at 2-min intervals and were analyzed for turbidity. Floc forming time (treatment time) was defined as the length of time from initiation of the current until the turbidity was reduced to less than 5 formazin turbidity units (FTU). Floc forming time ranged from 10 to 40 min, depending on the characteristics of WW, electrode materials, and treatment. Duplicate WW samples were taken before and after treatment and were analyzed for COD, total suspended solids (TSS), protein, and fat according to standard methods (APHA, 1994). Recovered solids were dried in a drying oven at 70 C and were analyzed for protein, fat, and ash contents (APHA, 1994).

### EC Validation Studies

After the initial screening studies, EC validation studies were conducted in duplicate trials with egg processing plant WW [with and without CMC (50 mg/L, pH 3.0) or BEN (200 mg/L, pH 4.5)], simulated egg processing WW (1.5 g NaCl added, pH 4.5), and the most effective EC parameters that were previously identified (108 cm<sup>2</sup> stainless steel electrodes, 15 V, 60 rpm mixing rate). Duplicate WW samples were taken before and after EC and were analyzed for COD, TSS, and turbidity as described above. Egg solids recovered by EC were analyzed for protein, fat, amino acid profiles, and protein digestibility.

### Protein Digestibility

The digestibility of each recovered EC solid, a commercial corn meal, and liquid whole egg was determined following the procedures of Porter et al. (1984) and Church et al. (1985).

### Sample Digestion

A pepsin solution was prepared by dissolving 100 mg pepsin in hydrochloric acid (pH 2) and incubated for 5 min in a 37 C water bath (Porter et al., 1984). Substrate solutions [including recovered by-products from CMC and BEN coagulation, corn meal, and liquid whole egg (25 mL)] were made by dissolving each substrate in hy-

drochloric acid (pH 2) to give a final protein concentration of 2 mg/L and then were heated for 5 min in a 37 C water bath. All protein solutions were filtered through 0.45 μm Whatman filter paper. The above two solutions were mixed in sealed digestion tubes and held at 37 C in a water bath. All samples were standardized to the same protein concentration. Samples (40 μL) were taken from the top of the digestion tubes at 40, 60, and 90 min and after 20 h and were analyzed by the orthophthaldehyde assay method.

### Digestibility Assay

Orthophthaldehyde reagent was made as described by Church et al. (1984). Portions (usually 20 to 50 μL) of the solution to be assayed were withdrawn from digesting tubes and added directly to 1.0 mL of the orthophthaldehyde reagent. The solution was mixed and incubated for 2 min at ambient temperature. Absorbency was measured at 340 nm in a Kontron 810/820 recording spectrophotometer.<sup>9</sup> Quantitation of the number of amino acid groups released or protein digestibility was calculated from the following equation:

$$\text{digestibility} = \frac{w_p}{d\varepsilon} \frac{\Delta A_{340}}{[P]}$$

where  $w_p$  = average amino acid residue weight (115),  $d$  = dilution factor,  $\Delta A_{340}$  = increase in absorbency at 340 nm,  $[P]$  = initial protein concentration (in mg/L) estimated from a total Kjeldahl nitrogen assay, and  $\varepsilon$ , the extinction coefficient, = 5,850 M<sup>-1</sup>cm<sup>-1</sup> (Porter et al., 1984). The relative digestibility of pure liquid whole egg was calculated as  $\Delta A_{340 i} / \Delta A_{340 e}$ , where  $\Delta A_{340 i}$  = increase in absorbency at 340 nm from each recovered by-product, and  $\Delta A_{340 e}$  = increase in absorbency at 340 nm from liquid whole egg.

### Amino Acid Analyses (Sample Hydrolysis)

EC and liquid whole egg samples and a Food and Agricultural Organization (FAO) reference protein sample (100 mg) were hydrolyzed as described previously (Gehrke et al., 1985; Liu et al., 1995). After hydrolysis, 1- to 2-mL samples were dried in a vacuum oven (10 mm Hg) set at 30 C followed by addition of a 2.5 μmol α-aminobutyric acid internal standard solution (250 nmol/mL for all samples) and ultrapure water to yield a final total amino acid concentration of less than 13 μmol/mL. After being mixed, 10 μL samples were pipetted into the bottom of derivation tubes. Seventy microliters of a 0.2 M borate buffer (pH 8) was added to each tube and mixed for 10 s on a vortex mixer. A 20-μL aliquot of the AQC solution (3 mg/mL in acetonitrile) was added to the tubes, and the solutions were immediately mixed on a vortex mixer, sealed, and heated in a reaction block for 10 min at 50 C.

<sup>9</sup>Optical Technology Device Inc., Elmsford, NY.

## HPLC Analysis of Amino Acids

The LC system comprised two pumps (Model M510),<sup>10</sup> a high-pressure injection syringe with a 10- $\mu$ L needle, and a Schoeffel FS UV detector set at 248 nm. A Millennium 2010 chromatography manager<sup>10</sup> was used to control the system and collect data. Mobile phase A was 140 mM sodium acetate and 17 mM triethylamine titrated to pH 4.95 with phosphoric acid. Mobile phase B was 60% acetonitrile in water (vol/vol) containing 0.01% acetone. Four-microliter injections of the derivatives were separated on a 4- $\mu$ m RP-C<sub>18</sub> column (150  $\times$  3.0 mm).<sup>10</sup> The flow rate was set at 1.0 mL/min at 70 C. Gradient conditions were as described by Church et al. (1984).

## RESULTS AND DISCUSSION

### Preliminary Screening Studies (Factors Affecting EC Current)

In addition to neutralizing the charge on pollutant particles, EC produces electrolytic microbubbles (hydrogen, oxygen, and chlorine if chlorides exist) that become entrained and occluded in the flocs formed, causing them to rise to the surface. Therefore, increasing the number of microbubbles will increase removal efficiency and reduce floc forming time (Bard and Faulkner, 1980). The concentration of microbubbles is proportional to the current (*i*). Current (*i*) is determined by the distance between electrodes, electrode surface area, mixing rate, solute concentration, diffusion coefficient, and solution viscosity (Bard and Faulkner, 1980). Besides placement of the electrodes, other important factors in designing EC treatment systems include choice of electrode material and avoidance of electrode fouling (Beck et al., 1974).

According to Bard's research on bulk electrolysis, the current can be expressed by the following equation:

$$i = nFAm_0C_0$$

where *n* = electrons per molecule oxidized or reduced; *F* = the faraday constant; charge on 1 mol of electrons (C); *A* = electrode surface area (cm<sup>2</sup>); *m*<sub>0</sub> = mass transfer coefficient (cm/s); *C*<sub>0</sub> = molar solute concentration, which usually indicates the concentration of electrolytes in solution such as sodium chloride; and *i* = current.

In these studies, the operating current was primarily dependent on the electrode surface area, mixing rate, and solute concentration. Our findings confirmed (Table 1) that as electrode surface area, mixing rate, and solute concentration increased, there was an associated increase in operating current (data not shown) and reduction in floc forming time. Furthermore, turbidities were decreased to  $\leq 4$  FTU in all treatments. In the case of electrode surface area, forming times were reduced 32.4% from 17

min to 11.5 min as surface area increased from 27 to 108 cm<sup>2</sup>. As the rate of mixing increased from 30 to 60 rpm, there was an associated decrease of 25% in forming times from 20 to 15 min. Increases in the WW ionic strength from 0.5 to 2.0 g/L of salt resulted in a 36.7% reduction in forming time from 30 to 19 min.

### pH Effects

Because the charge on protein particles is dependent on the pH of the solution, the WW pH must be controlled for optimum removal efficiencies using EC. The effect of pH on WW forming times is summarized in Table 2. Forming time was shortest when initial pH of the solution was between 4.5 and 5. At this pH, COD removal averaged 93%. Previous studies have indicated that the total charge on protein surfaces approaches zero at pH 4 to 5 (Mauron, 1973). At this pH, particulates coalesce, and the electrolytic microbubbles interact with the particulates to form a stable solid-gas composite. Consequently, it takes less time to remove proteins and fats from solution.

### Effect of Electrode Composition and Coagulant Types

The choice of electrode composition is a very important consideration in designing EC treatment systems. EC forming times were 33% less (16 min versus 24 min) for aluminum and iron electrodes than for stainless steel electrodes (Table 3). Similar COD reductions (92 to 95%) and final turbidities ( $\sim 3$  FTU) were achieved, irrespective of electrode composition. The floc formed faster, required less power, and appeared more stable when the aluminum and iron electrodes were used, indicating an interaction of the aluminum and ferric ions with the floc. These two types of electrodes have higher dissolution rates, which resulted in elevated concentrations of aluminum and ferric ions in the recovered sludge and treated WW (data not shown). Although higher COD and TSS reductions and shorter forming times would be achieved using the aluminum and iron electrodes, they are not good choices for designing EC systems, especially aluminum, because of the potential toxicity of aluminum and iron and electrode dissolution characteristics (Guthrie, 1979). Stainless steel was found to be a suitable electrode material because it did not foul and it yielded comparable removal efficiencies as aluminum and iron.

Other studies have indicated that carbon or other special alloy electrodes and combination electrodes may be suitable alternatives (Beck et al., 1974; Scott, 1995), depending on their removal efficiencies. Those studies also showed that forming time could be decreased and organic removal efficiencies improved by adding PCA. Our results supported their findings in that forming times were reduced by 5 min or 33% when CMC and BEN were added as coagulants (Table 4). COD and final turbidities, however, were not influenced by the presence or absence of coagulants.

<sup>10</sup>Waters Corp., Milford, MA.

**TABLE 1. Effects of electrode surface area, mixing rate, and salt concentration on the efficacy of electrocoagulation (EC) in treating simulated egg processing wastewater<sup>1,2</sup>**

EC factors	Forming time <sup>3</sup> (min)	COD reduction (%)	Final turbidity (FTU)	
Electrode surface area <sup>4</sup> (cm <sup>2</sup> )	27	17	ND	2
	54	13.5	ND	2
	108	11.5	ND	2
Mixing rate <sup>5</sup> (rpm)	30	20	ND	3
	50	17	ND	2
	60	15	ND	3
Salt concentration <sup>6</sup> (g)	0.5	30	91	4
	1.0	24	95	1
	2.0	19	92	3

<sup>1</sup>n = 1.<sup>2</sup>FTU = formazin turbidity units; COD = chemical oxygen demand; ND = not determined.<sup>3</sup>Forming time = length of EC (min) to reduce turbidity to less than 5 FTU.<sup>4</sup>Simulated egg processing wastewater: initial COD = 1,680 mg/L, initial pH = 7.01, 1.5 g NaCl added, operation voltage = 20 V, aluminum electrodes.<sup>5</sup>Simulated egg processing wastewater: initial COD = 1,395 mg/L, initial pH = 4.5 using hydrochloric acid, 1.5 g NaCl added, operation voltage = 15 V, aluminum electrodes.<sup>6</sup>Simulated egg processing wastewater: initial COD = 1,395 mg/L, initial pH = 4.5 using hydrochloric acid, operation voltage = 15 V, aluminum electrodes.

### Other EC Factors

The results of this study agreed with the findings of other researchers in that flocs of high solids concentration were achieved with EC. For example, Beck and co-workers (1974) and Smith (1980) found EC skimmings having 9 to 12% solids compared to 3 to 5% by air flotation and 1 to 2% by precipitation/coagulation.

If electrolytes are absent in the WW with the exception of protein and fat (i.e., simulated WW sample), the EC current was very small and produced only minimal amounts of hydrogen and oxygen. Under these circumstances, sodium chloride or other ions can be added to increase conductivity. In most industrial WW, there are generally many foreign solutes present. Egg processing WW generally contains high concentrations of sodium, chloride, and calcium. According to electrochemical theory (Bard and Faulkner, 1980), any solute that can be oxidized at the operating voltage will be collected at the anode. For example, if sulfides and chlorides are present in the WW, sulfur and chlorine will be formed, respec-

tively. In the present study, hydrochloric acid was used to adjust the pH of WW because of its ability to neutralize OH<sup>-</sup> ions that accumulate around the anode. Other reasons for using hydrochloric acid would be to generate chlorine in the WW, a common disinfectant used for treating drinking water and food processing applications. The pH of egg processing WW increased from around 4 to 5 before EC treatment to 7 after treatment, a pH compatible with the discharge limits (pH 5.5 to 11.0) established by most municipalities.

### EC Validation Studies

The efficacy of a defined EC treatment, with or without coagulant addition, on treating egg processing plant effluents and a simulated egg processing WW is summarized in Table 5. COD reductions after EC averaged over 90% for all WW samples. In terms of COD removal, this treatment performed within the range of removal efficiencies previously reported by Beszedits (1982) for treating meat and poultry processing WW. Compared to EC

**TABLE 2. Influence of wastewater pH adjustment on the efficacy of electrocoagulation (EC) in treating a simulated egg processing wastewater<sup>1,2</sup>**

pH	Forming time <sup>3</sup> (min)	COD reduction (%)	Final turbidity (FTU)
2.5	25	50	103
3.5	15	87	1
4.5	13	93	1
5	13	93	2
6	14	94	1
7	15	94	2
8.5	15	94	2
9.5	15	94	2

<sup>1</sup>Simulated egg processing wastewater (0.4% liquid whole egg in water, wt/vol): 1.5 g NaCl added, operation voltage = 20 V, stainless steel electrodes; n = 1.<sup>2</sup>FTU = formazin turbidity units.<sup>3</sup>Forming time = length of EC (min) to reduce turbidity to less than 5 FTU.

**TABLE 3. Effect of electrode composition on the efficacy of electrocoagulation (EC) in treating a simulated egg processing wastewater<sup>1,2</sup>**

Electrode composition	Forming time <sup>3</sup> (min)	COD reduction (%)	Final turbidity (FTU)
Iron	16	95	3
Aluminum	16	95	3
Stainless steel	24	92	4

<sup>1</sup>FTU = formazin turbidity units; COD = chemical oxygen demand.

<sup>2</sup>Simulated egg processing wastewater (0.4%, liquid whole egg in water, wt/vol); initial COD = 2,410 mg/L, initial turbidity = 520 FTU, operation voltage = 15 V, initial pH = 4.5 using hydrochloric acid, 1.5 g NaCl added; n = 1.

<sup>3</sup>Forming time = length of EC time (min) to reduce turbidity to less than 5 FTU.

without coagulants, the CMC and BEN added to WW before EC treatment did not greatly improve COD removal (92% versus 94 to 95%) but did shorten the forming times from 35 to 26 min (26 versus 35 min).

TSS and turbidity reductions were independent of coagulant use and type and WW source and averaged 97 and 99%, respectively. Final TSS concentrations and turbidities were less than 30 mg/L and 5 FTU, respectively, similar to those of drinking water (Environmental Protection Agency, 1977). Thus, it is possible that these recovered supernatants could be recycled, after disinfection, for further use in washing of processing equipment and floors.

Precipitates were collected after EC and dried at 70 °C; the resulting egg solids were analyzed for protein and fat contents. Protein and fat recovery efficiencies were similar to those of COD recoveries and depended on the WW source, coagulant type, and initial concentrations of protein and fat. The recovered sludges contained high concentrations of protein (36 to 50%) and fat (32 to 42%) (data not shown).

### Protein Digestibility

Because egg protein has the highest biological value and protein efficiency ratio among other proteins derived from such food sources as meat, milk, corn, rice, and flour, the relative protein digestibility of each recovered EC solid (without coagulant treatment) and a commercial corn meal was determined by assuming a protein digestibility value of 100% for liquid whole egg protein

(Guthrie, 1979). The relative protein digestibilities of the recovered EC solids and commercial corn meal averaged 130 and 56%, respectively (data not shown). Thus, the digestibilities of the recovered proteins after EC treatment were considerably higher than liquid whole egg protein and significantly higher than the commercial corn meal. As suggested by H. E. Swaisgood (1996, Department of Food Science, North Carolina State University, Raleigh, NC, personal communication), this increase in digestibility of the EC-treated proteins may be explained by an EC-mediated denaturation of proteins, making them more susceptible to enzymatic (pepsin) digestion. These findings confirmed that the digestibility of the corn meal proteins were inferior to animal proteins (Guthrie, 1979). Because of the high nutritional value and digestibility, egg solids recovered by EC might serve as an excellent livestock feed ingredient or for other applications.

Measurement of digestibility using a single in vitro enzyme protocol has certain limitations (Porter et al., 1984). In vivo systems use many digestive enzymes, including pepsin, trypsin, chymotrypsin, and intestinal peptidase (Porter et al., 1984; Kennedy et al., 1989). Thus, in vitro single-enzyme digestive assays may not totally reflect the true in vivo digestive process. The greater the number of digestive enzymes used in the in vitro assay, the closer the assay will simulate in vivo systems. In vivo rat digestibility bioassays may be the best way to evaluate protein quality. However, the rat bioassay and other multiple-enzyme digestive assays are expensive and time consuming (Mauron, 1973). Although in vitro digestibility assays do not exactly duplicate the results obtained from

**TABLE 4. Effect of coagulant addition on the efficacy of electrocoagulation (EC) in treating a simulated egg processing wastewater<sup>1,2</sup>**

Coagulant	Concentration (mg/L)	Forming time <sup>3</sup> (min)	COD reduction (%)	Final turbidity (FTU)
Without		15	93	2
CMC <sup>4</sup>	50	10	95	2
BEN <sup>5</sup>	200	10	94	1

<sup>1</sup>COD = chemical oxygen demand; FTU = formazin turbidity units; CMC = carboxymethylcellulose; BEN = bentonite.

<sup>2</sup>Initial COD = 1,410 mg/L, 1.5 g NaCl added, stainless steel electrodes (30 cm<sup>2</sup>); n = 1.

<sup>3</sup>Forming time = length of EC time (min) to reduce turbidity to less than 5 FTU.

<sup>4</sup>Initial pH was adjusted to 3.0 using hydrochloric acid.

<sup>5</sup>Initial pH was adjusted to 4.5 using hydrochloric acid.

**TABLE 5. Efficacy of electrocoagulation (EC) with and without chemical coagulant addition on treating commercial and simulated egg processing plant wastewaters<sup>1</sup>**

Wastewater samples	Initial concentration			Removal efficiency (%)			Forming time (min)
	COD (mg/L)	TSS (mg/L)	turbidity (FTU)	COD (mg/L)	TSS (mg/L)	turbidity (FTU)	
SWS <sup>2</sup>	8,810 ± 173	1,802 ± 151	1,100 ± 167	97 ± 1.71	97 ± 0.98	99 ± 0.76	30 ± 1.1
EPW <sup>3</sup>	4,150 ± 81.8	1,008 ± 77.8	1,700 ± 360	92 ± 1.65	97 ± 0.92	99 ± 0.44	35 ± 1.3
EPW <sup>4</sup> (CMC)	4,150 ± 81.8	1,008 ± 77.8	1,700 ± 360	94 ± 1.15	97 ± 0.74	99 ± 0.84	26 ± 0.89
EPW <sup>5</sup> (BEN)	4,150 ± 81.8	1,008 ± 77.8	1,700 ± 360	95 ± 1.54	97 ± 1.34	99 ± 1.02	26 ± 0.92

<sup>1</sup>COD = chemical oxygen demand, TSS = total suspended solids, FTU = formazin turbidity units, forming time = length of EC (min) to reduce turbidity to less than 5 FTU; n = 2.

<sup>2</sup>SWS = simulated egg processing wastewater, initial pH = 4.5 using hydrochloric acid, 1.5 g NaCl added, voltage = 15 V, stainless steel electrodes.

<sup>3</sup>EPW = egg processing plant wastewater, no NaCl added, voltage = 15 V, stainless steel electrodes.

<sup>4</sup>EPW with carboxymethylcellulose (CMC) added (50 mg/L).

<sup>5</sup>EPW with bentonite (BEN) added (200 mg/L).

bioassay methods, there is strong positive correlation between single enzyme *in vitro* assays and bioassays (Wiseman and Cole, 1989).

### Amino Acid Analysis

The results of the amino acid analysis of the recovered EC precipitates are reported in Table 6. The recovered EC by-products had similar essential amino acid profiles as found in liquid whole egg. This finding confirmed that the majority of the proteins lost in egg processing WW were recovered by EC. Compared to the United Nations Food and Agricultural Organization (FAO) pattern of essential amino acid profile standards, the coagulated EC by-products contained more than adequate amounts of essential amino acids (Guthrie, 1979; Kennedy et al., 1989). The acid hydrolysis method used in this study destroyed cystine, tryptophan, and a portion of the methionine.

### Economic Analysis

For a WW treatment to be adopted by industry, it must be economical as well as technically feasible. A cost analysis of the EC system was undertaken based on treatment, chemical, and sewer use surcharge costs. The findings are expressed as total costs in dollars per million gallons (3,780,000 L) of WW treated. Total EC costs were com-

pared with WW surcharge costs without treatment to obtain the savings that would be available for annualized capital cost recovery and other annual operation and maintenance costs.

The chemical and power costs were based on US prices in 2001. Sewer use surcharges were based on surcharges in 2001 for a typical metropolitan area with secondary treatment facilities. The sewer use surcharges for excess BOD<sub>5</sub> (5-d BOD assay) and suspended solids were \$0.30 and \$0.25 per pound, respectively (R. E. Carawan, 2001, Department of Food Science, North Carolina State University, Raleigh, NC, personal communication). Table 7 summarizes the results of the economic analysis for a typical commercial egg processor. For each treatment reported, the average BOD (2,918 mg/L) and TSS (2,680 mg/L) concentrations of the untreated commercial WW samples used in our studies were applied to the computations (Xu, 1997). The BOD and TSS recoveries were 90 and 95%, respectively. Total estimated savings across all EC treatments were over \$10,000 per million gallons of treated WW. Large-scale commercial egg processing plants in the US typically generate more than 642,600 L (170,000 gal) of WW per day or 160.6 million L (42.5 million gal) per year (250 d operation). The estimated capital cost of an EC system with a 12-yr life span is approximately \$500,000 (R. E. Carawan, 2001, personal communication). Thus, with a projected cost savings of

**TABLE 6. Amino acid composition of recovered electrocoagulation by-products, liquid whole egg, and a standard reference protein<sup>1</sup>**

Amino acids	Electrocoagulation	Liquid whole egg	FAO <sup>2</sup> standard
	(g amino acid/100 g total protein)		
Threonine	4.11	4.08	2.8
Valine	6.14	6.32	4.2
Cystine <sup>3</sup>			2.0
Methionine <sup>3</sup>			2.2
Isoleucine	5.63	5.56	4.2
Leucine	8.44	8.55	4.8
Phenylalanine	5.17	5.22	2.8
Tryptophan <sup>3</sup>			1.4
Lysine	6.47	6.32	4.2

<sup>1</sup>Average of two pooled samples.

<sup>2</sup>FAO = Food and Agricultural Organization protein standard.

<sup>3</sup>Destroyed by acid hydrolysis assay procedure.

TABLE 7. An economic analysis of electrocoagulation (EC) for treating commercial egg processing plant wastewater

Treatment	EC Power	Coagulant	pH adjustment	Sewer surcharges with EC treatment <sup>2</sup>	Total <sup>3</sup>	Sewer surcharges without EC treatment <sup>4</sup>	Cost savings <sup>5</sup>
				(\$/MG <sup>1</sup> )			
Without coagulant	50	...	53	105	208	11,738	11,530
CMC <sup>6</sup>	50	780	526	105	1,461	11,738	10,277
BEN <sup>7</sup>	50	1,180	53	105	1,388	11,738	10,350

<sup>1</sup>MG = million gallons treated (3.785 million L).

<sup>2</sup>Based on allowable biological oxygen demand (BOD) discharge of 250 mg/L.

<sup>3</sup>Total: summation of power costs, coagulant costs, pH adjustment costs, and sewer surcharge costs.

<sup>4</sup>Based on allowable BOD discharge of 250 mg/L and total suspended solids of 250 mg/L.

<sup>5</sup>Does not include capital costs.

<sup>6</sup>CMC = carboxymethylcellulose at 50 mg/L.

<sup>7</sup>BEN = bentonite at 200 mg/L.

over \$10,000/million gal of treated WW and an annual WW volume of 42.5 million gal/yr, a company might expect to pay off the capital equipment costs in around 14 mo and then save about \$425,000/yr thereafter.

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