A renewable flocculant from a poultry slaughterhouse waste and preliminary estimate of production costs

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1. Introduction

Nine billion chickens are processed in the U.S. per year (U.S. Department of Agriculture, 2011). About 6% of a chicken's body weight is blood (CKB), of which 70% is drainable (Carawan et al., 1979; Mountney and Parkhurst, 1995). Thus, about one billion pounds of useable CKB is produced in the U.S. per year. In some processing plants CKB is not recovered. The CKB, comingle with slaughterhouse waste water, constitutes the effluent stream which must be treated at significant cost (Del Nery et al., 2007; Mountney and Parkhurst, 1995). In many processing plants a portion of the CKB is recovered. The recovered CKB may be sold to a local rendering plant, and the profit used to offset pollution control costs. In some cases it may be necessary to give the CKB away in exchange for its removal from the plant or even pay for its removal (Carawan et al., 1979). An additional income stream for chicken processors would arise from development of new uses for CKB.

A flocculant is a substance that causes particles suspended in a fluid to aggregate and form discrete flocs (Krishnan and Attia, 1988). Aggregation of the fine particles usually results in accelerated sedimentation to give a clarified solution. Many flocculants are polymeric, and they are used in a wide variety of processes such as wastewater clarification (Maximova and Dahl, 2006), paper manufacture, concentration during chemical operations, and dewatering and thickening in mineral operations (Svarovsky, 2000). They are also used as filtration and centrifugation aids (Lewellyn and Avotins, 1988).

The most widely used polymeric flocculant is anionic polyacrylamide (PAM) because it has low toxicity to aquatic life (Nasser and James, 2007). PAM is also applied directly to soil to prevent erosion in agricultural and construction areas (Sojka et al., 2007). PAM is manufactured from chemicals that are made from natural gas, so it is expected that the price of PAM will rise over time as supplies of natural gas are depleted. Thus, renewable, biodegradable replacements are being sought. Toward this goal, derivatives of amylopectin, carboxymethylcellulose, guar gum, starch, and glycogen have been examined as coagulation/flocculation aids in waste water treatment (Renault et al., 2009). Extracellular biopolymeric materials from microorganism fermentation have recently been investigated as a new source of renewable flocculants.
(Salehzadeh and Shojaosadati, 2001). Additionally, suspensions of chitosan, starch xanthate, cellulose xanthate, and acid-hydrolyzed cellulose microfibrils have been tested for control of soil sediment runoff (Orts et al., 2000). Such renewable flocculants and erosion control agents are usually effective at significantly higher concentrations than PAM.

We have previously demonstrated that common agriculturally derived proteins can be effective flocculants of clay (Piazza and Garcia, 2010a,b). Flocculation activity of proteins is usually observed at pH values lower than the protein isoelectric point, indicating a need for the protein to have a net positive charge. Bovine and porcine blood show flocculant activity when low pH buffer is added, and purified bovine hemoglobin was found to be a good flocculant. Here we describe results of tests with CKB fractions as flocculants, and show that the flocculation performance of the best CKB fractions is similar to that obtained with PAM at 5 h or longer and better than PAM at 1 h. However, economic viability of a CKB-derived flocculant is dependent upon the ability to dehydrate the blood with retention of flocculant activity. Since the flocculant activity is only evident under slightly acidic conditions, an inexpensive acidification step is also required. We have investigated these aspects of flocculant production and have completed an economic analysis of production costs.

2. Methods

2.1. Materials

A fine kaolin (clay) with the trade name “Polygloss 90” from Huber Engineered Materials was a gift from the M. F. Cachat Company (Lakewood, OH). Polygloss 90 had a surface area of 22.0 m²/g. Zwitterionic buffers, MES [2-[morpholino]ethanesulfonic acid], HEPES [N-(2-hydroxyethyl)piperazine-N’-(ethanesulfonic acid)], and CAPS [3-(cyclohexylamino)-1-propanesulfonic acid] were obtained from Sigma–Aldrich (St. Louis, MO). Anionic PAM from Cytec with trade name “Superfloc A–110 Flocculant” was a gift from Kemira (New Milford, CT). Water was purified to a resistance of 18 megohm-cm using a Barnstead E-pure system. CKB was collected directly from decapitated birds at Tyson Foods in New Holland, PA.

2.2. Preparation of CKB fractions

Three CKB fractions were prepared. The first fraction which is termed “blood fraction A” is whole CKB, excluding the portion that had coagulated during storage. The second fraction which is termed “blood fraction B” is the supernatant fraction from centrifugation of fraction A (whole blood) at 5200 × g (2 × 10 min). The third fraction termed “blood fraction C” is the supernatant from centrifugation of heated blood fraction A. Blood fraction A was heated on a hot plate with stirring at about 1 °C per minute. When the temperature of the blood reached 75 °C coagulation took place, and the blood was immediately removed from the hot plate. The blood was centrifuged at 5200 × g (2 × 30 min). Triplicate samples (1 mL) of all of the treatments were placed in glass vials which were subsequently taken to dryness under a stream of nitrogen and then dried to constant weight in a vacuum oven at 45 °C to obtain sample dry weight values. CKB fractions A, B, and C were stored at −20 °C until dehydration or flocculation testing.

2.3. Freeze dried CKB fractions

CKB fractions A, B, and C were dehydrated by freeze drying. Blood fractions were divided into 120 mL aliquots, placed into 600 mL round bottom flasks, and frozen in dry ice/acetone. The frozen fractions were placed onto a vacuum line (150 mTorr) equipped with a dry ice/acetone trap until all water was removed, approximately 18 h. The freeze dried CKB fractions are termed A-f, B-f, and C-f. These freeze dried fractions were stored at −20 °C until diluted with water for flocculation testing.

2.4. Spray dried CKB fractions

CKB fractions A, B, and C were dehydrated using a Büchi (Flawil, Switzerland) B-191 Mini Spray Drier. Chilled water (<5 °C) was circulated through the annular cavity in the spray nozzle to prevent premature coagulation. Operating conditions were adjusted to maintain the air exiting the drying chamber at 95–105 °C. The spray dried CKB fractions are termed A-s, B-s, and C-s. These were stored at 22 °C in a desiccator term Drierite.

2.5. Flocculation testing

The flocculation effectiveness of the CKB fractions was determined by observing their ability to accelerate the sedimentation of finely divided clay (kaolin). All assays were performed in 15 mL conical, glass centrifuge tubes with plastic snap caps. In a typical experiment 47.3 mg Polygloss kaolin was added to a tube containing the indicated concentration of the previously frozen CKB fractions or aqueous solutions of the freeze dried or spray dried fractions (20–800 mg/L) in a total volume of 10 mL. All experiments were replicated with and without the addition of 0.2 mM calcium chloride. The contents of the capped tubes were mixed by inverting the tubes several times. Thereafter the tubes were placed in a tube rack, and the tubes were left undisturbed while the contents settled at 22 °C. At the indicated time, a 0.1 or 0.2 mL aliquot was removed after placing the tip of a P200 Gilson Pipette 22 mm below the surface (50 µL mark on the pipette tip). The aliquot was diluted to 1.0 mL, and the absorption of this kaolin suspension at 600 nm was measured. If the absorption was greater than 1.5 absorption units, the sample was further diluted with deionized water. All absorption measurements were corrected for dilution and for absorption by the blood fraction containing no kaolin. Absorption was converted to kaolin in suspension (g/L) with the aid of calibration curves prepared with a range of kaolin suspensions. These calibration curves showed that there was a linear relationship between absorption at 600 nm and the mass fraction of suspended kaolin. In all cases, the blood flocculant concentration was expressed in units of g/L, and the mass of the dried fraction was used.

Some experiments contained pH buffers. Buffer solutions were prepared using the zwitterionic buffers MES, HEPES, CAPS and, and the pH values of these solutions were adjusted to pH 5.5, 7.0, 10.0, respectively, with sodium hydroxide. Sedimentation experiments were prepared as described in the paragraph above except the concentration of the buffer was 30 mM in each assay tube.

3. Results and discussion

3.1. Flocculation testing of CKB and CKB fractions

Fresh CKB was collected from a local processing plant. Whole CKB, freed of coagulated blood, centrifuged blood and heated blood, were prepared as described in Section 2. These are termed blood fractions A, B, and C, respectively. The CKB fractions were stored frozen until flocculation testing was conducted.

Flocculation ability was determined by observing the influence of CKB and fractions upon the rate of settling of finely divided clay (kaolin) particles. These clay particles consist of the silicate mineral kaolinites, and therefore their surfaces are predominately negatively charged. The efficacy of the flocculation testing procedure was demonstrated previously by using a commercial
polymeric flocculant, anionic polyacrylamide (PAM) (Piazza and Garcia, 2010a,b). Varying concentrations up to 3 g/L of CKB fractions A, B, and C were tested for their flocculation activity, alone and with 0.2 mM calcium chloride. Calcium chloride was tested because a source of calcium ion is an absolute requirement for flocculation by anionic PAM. Calcium ions act as a bridge between the negative charges on PAM and the negative charges on the clay particles. The amount of kaolin particles remaining in suspension was determined at 1, 5, and 24 h. At 1 h and 5 h, no decrease in kaolin particles compared to the control values was observed for any fraction with or without the addition of calcium chloride. At 24 h, there was a significant reduction of kaolin particles compared to the control values at concentrations 2 g/L or greater, and calcium chloride had only a small effect on the test results. At a concentration of 3 g/L, fraction A was the most effective fraction, reducing the kaolin concentration in suspension to less than 1% of control values. Fraction B was the next most effective, removing 18% and 7% of the suspended kaolin without and with the addition of calcium chloride, respectively. Fraction C was the least effective fraction, removing 51% and 56% of the suspended kaolin without and with the addition of calcium chloride. Experiments with freeze dried fractions and spray dried fractions were also performed at concentrations up to 45 g/L. These fractions showed the ability to reduce the kaolin concentration compared to control values only at 24 h, and high concentrations of the fractions were required for action.

3.2. Influence of buffer addition on flocculation by CKB fractions A, B, and C

The pH of CKB fractions A, B, and C had values between 7.8 and 8.5. In prior research, it was noted that pH had a strong influence on the flocculation tests. The buffers used were MES, HEPES, CAPS and, and their pH values were adjusted to pH 5.5, 7.0, 10.0, respectively. The three buffers were mixed with different amounts of blood fractions A, B, and C, and flocculation testing was performed. The data for CKB fraction A is shown in Fig. 1, which contains six graphs. The upper two graphs (graphs A and B) show experimental results from trials using pH 5.5 buffer. The middle set of graphs (C and D) show results from trials using pH 7.0 buffer, and the lower set of graphs (graphs E and F) show results from trials using pH 10.0 buffer. The graphs on the right (graphs B, D, and F) show the results of trials that contained 0.2 mM calcium chloride; the graphs on the left (graphs A, C, and E) show those that contained no calcium chloride. Although the results displayed in each graph are different, the overall trend is that the trials performed with pH 5.5 buffer showed strong flocculating behavior at relatively low levels of CKB fraction A (≥0.12 g/L), whereas the trials performed at pH 7.0 and 10.0 gave either no flocculation or flocculated at concentrations greater than
1.0 g/L. CKB fractions B and C showed similar results (graphs not shown) in that strong flocculating activity at low concentration was noted only in the presence of pH 5.5 buffer.

The concentration of flocculant required to reduce the kaolin level at or below 1 g/L in 1 h and 5 h was noted from concentration graphs of CKB fractions A, B, and C. Only the results obtained in the presence of pH 5.5 buffer are shown in Table 1. Without the addition of calcium chloride, a reduction of kaolin at or below 1 g/L in 1 h required 84 mg/L of blood fractions A or B. No tested level of blood fraction C could reduce the kaolin level below 1 g/L in 1 h. At 5 h, 84, 84, and 79 mg/L of CKB fractions A, B, and C, respectively, were needed to reduce kaolin at or below 1 g/L. With the addition of calcium chloride, the reduction of kaolin at or below 1 g/L in 1 h required 28, 84, and 79 mg/L of blood fractions A, B, and C, respectively. In 5 h, 28, 27, and 26 mg/L of CKB fractions A, B, and C, respectively, were needed to reduce kaolin at or below 1 g/L.

Table 1 shows the published results obtained with PAM, porcine gelatin (Piazza and Garcia, 2010a,b), and bovine hemoglobin. It can be seen that the results obtained with CKB fractions A, B, and C are similar to that given by gelatin. Bovine hemoglobin and anionic PAM at generally required a lower concentration to give the same flocculant activity CKB fractions, but this was not always the case. See, for example, fraction CKB A with calcium chloride at 1 h and 5 h, and fraction CKB B at 5 h. The action of the CKB fractions is very different than that of anionic PAM because calcium chloride is an absolute requirement for PAM activity. Based on the results presented here and prior results with purified proteins, the addition of the low pH buffer causes the proteins in CKB to have a net positive charge. This causes the CKB proteins to be attracted to the surface of the clay particles, which contain negatively charge silica groups. Thus calcium ion is not needed as a bridging ligand with the CKB fractions. However, the addition of calcium chloride to the CKB fractions generally caused them to be slightly more effective flocculants, and the small stimulation by calcium ion may indicate a role for the carboxylic acid groups in flocculation by the CKB fractions. Also note that the flocculant action of the CKB fractions is evident at 1 h, but PAM flocculant action was not evident until 5 h. The slower flocculation activity of PAM is probably related to the high viscosity of its solutions, which slows sedimentation of the clay flocs.

3.3. Freeze dried CKB fractions A-f, B-f, and C-f with pH 5.5 buffer

A property of commercially successful flocculants is that they are dehydrated for storage and shipment to the site of use. Thus, the ability to dehydrate the blood-based flocculants with retention of activity is of critical importance. Testing began using freeze dried samples because freeze drying is a mild drying procedure which is known to be effective in retaining the activity and conformation of proteins. Freeze dried CKB fractions A, B, and C are termed A-f, B-f, and C-f, respectively. Tests were conducted only with the addition of pH 5.5 buffer. The freeze dried samples were dissolved in water before testing them as flocculants. The results of trials with these fractions are summarized in Table 1. To reduce the kaolin level at or below 1 g/L in 1 h and 5 h required at minimum the following concentrations of CKB fractions. A-f and B-f, respectively: 1 h, no calcium chloride, 170 and 340 mg/L; 1 h, with calcium chloride, 85 and 170 mg/L; 5 h, calcium chloride, 85 and 170 mg/L; 5 h, with calcium chloride, 55 and 85 mg/L. No tested concentration of CKB fraction C-f was able to reduce the level of kaolin to or below 1 g/L in 1 h or 5 h.

Overall the spray dried samples, A-s, B-s, and C-s, performed the worst, compared to the frozen and freeze dried samples. Nevertheless, at 5 h, without added calcium chloride, only a slightly higher concentration of spray dried A-s was required compared to that for frozen blood sample A. When calcium chloride was added, less than twice the amount of A-s was required compared to that for sample A. CKB fraction B-s performed worse than A-s, and the EP of fraction C-s was extremely poor. Fraction C-s had been heated twice, once during the preparation of the fraction, and once again during the spray drying process. Therefore the relatively poor result obtained with fraction C-s compared to C-f demonstrates that additional heat damage of the blood protein occurred during the spray drying process.

3.5. Enhancement of flocculation with acid

As shown in prior sections, flocculation activity by the CKB fractions required the addition of buffer to lower the pH to 5.5. Buffer is a relatively expensive component, and experiments were conducted to determine if flocculation could occur with the addition of relatively inexpensive acid. Three acids were tested: citric, phosphoric, and sulfuric acids. Varying amounts of dilute acids were added with a constant amount of CKB fraction A. The pH of the flocculating medium was determined by placing the glass probe of a pH meter into the flocculating medium after the 24 h measurement.

The data shown in Figs. 2–4 show the results of experiments with citric, phosphoric and sulfuric acids, respectively. When CKB fraction A is added (open squares), complete sedimentation of Polygloss kaolin is observed in 5 h at pH 5.2 with citric acid and at pH 5.5 with phosphoric and sulfuric acids. With no addition of CKB fraction A (closed circles), more acid must be added to completely neutralize the negative charges on the surface of the kaolin particles to induce their flocculation and subsequent sedimentation. A decrease in the pH to 3.2 was necessary with citric acid and to pH 4.1 with phosphoric and sulfuric acids to give complete sedimentation in 5 h. Although the changes in pH required for complete sedimentation with and without the addition of CKB fraction A seem relatively small, it is important to remember that pH is a logarithmic measurement; pH is equal to $-\log [H^+]$ where $[H^+]$ is the hydrogen ion concentration. Therefore, it is possible to calculate the hydrogen ion concentration which is needed for complete sedimentation in 5 h with and without the addition of CKB fraction A. These calcula-
### Table 1
Comparison of flocculant effectiveness.

<table>
<thead>
<tr>
<th>CKB fraction or sample</th>
<th>Time</th>
<th>+Ca</th>
<th>+Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 h</td>
<td>5 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+Ca</td>
<td></td>
</tr>
<tr>
<td>Required concentration of flocculant (mg/L)b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No buffer added</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>B</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>C</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>PAMc</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>+30 mM, pH 5.5 MES buffer</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>84</td>
<td>28</td>
<td>84</td>
</tr>
<tr>
<td>B</td>
<td>84</td>
<td>84</td>
<td>84</td>
</tr>
<tr>
<td>C</td>
<td>79</td>
<td>55</td>
<td>79</td>
</tr>
<tr>
<td>A-f</td>
<td>170</td>
<td>55</td>
<td>170</td>
</tr>
<tr>
<td>B-f</td>
<td>85</td>
<td>55</td>
<td>85</td>
</tr>
<tr>
<td>C-f</td>
<td>NS</td>
<td>340</td>
<td>340</td>
</tr>
<tr>
<td>A-s</td>
<td>170</td>
<td>85</td>
<td>170</td>
</tr>
<tr>
<td>B-s</td>
<td>340</td>
<td>170</td>
<td>340</td>
</tr>
<tr>
<td>C-s</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Porcine gelatinc</td>
<td>75</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td>Bovine hemoglobinc</td>
<td>30</td>
<td>Not determined</td>
<td>Not determined</td>
</tr>
</tbody>
</table>

a +Ca: binding assay contained 0.2 mM calcium chloride.

b Required concentration of flocculants to give suspended Polygloss kaolin at or below 1 g/L in 1 h and 5 h.

c Results from Piazza and Garcia (2010a,b).

d NS: no satisfaction of sedimentation criteria at any tested concentration.

e Assay contained 17.8 mM, pH 5.5 MES buffer.

3.6. Preliminary estimate of production costs and resource and environmental impacts

A preliminary analysis of the cost of flocculant production from CKB blood was prepared (Tables 2–4). The cost inputs include production costs which are shown in Table 2 and the avoided cost as in Table 4. The cost analysis was based upon the production of a spray dried flocculant (CKB fraction A-s) from CKB fraction A, which is CKB without any processing, other than removal of
Table 2
Cost inputs for flocculant facility.

<table>
<thead>
<tr>
<th>Blood/h processed</th>
<th>Processing facility size</th>
<th>150,000 chickens/day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Blood/day (8 h)</td>
<td>18,415 lbs</td>
</tr>
<tr>
<td>Flocculant/day</td>
<td>Mass flocculant/blood = 0.13</td>
<td>2394 lbs</td>
</tr>
<tr>
<td>Flocculant/h</td>
<td>299.25 lbs</td>
<td></td>
</tr>
<tr>
<td>Energy cost</td>
<td>Natural gas</td>
<td>4,005,250 BTU/h</td>
</tr>
<tr>
<td>Equipment cost</td>
<td>Spray dryer</td>
<td>$1,000,000</td>
</tr>
<tr>
<td></td>
<td>Blood collection trough</td>
<td>$10,000</td>
</tr>
<tr>
<td></td>
<td>Surge tank</td>
<td>$25,000</td>
</tr>
<tr>
<td></td>
<td>Pump to spray dryer</td>
<td>$5000</td>
</tr>
<tr>
<td></td>
<td>Conveyors to product bagging</td>
<td>$5000</td>
</tr>
<tr>
<td></td>
<td>Product bagging</td>
<td>$25,000</td>
</tr>
<tr>
<td></td>
<td>Product load and storage</td>
<td>$5000</td>
</tr>
<tr>
<td></td>
<td>Misc</td>
<td>$5000</td>
</tr>
<tr>
<td>Total equipment cost</td>
<td></td>
<td>$1,100,000</td>
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<tr>
<td>Capital cost</td>
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<td>$2,200,000</td>
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</table>

Table 3
Production costs for flocculant facility.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit measure</th>
<th>Unit cost</th>
<th>Hourly cost</th>
<th>Production cost per lb flocculant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw materials</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Chicken blood</td>
<td>2302 lbs/h</td>
<td>lbs/h</td>
<td>$0.0000</td>
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<tr>
<td>Sulfuric acid</td>
<td>0.1702 lb/lb</td>
<td>lb/lb product</td>
<td>0.075</td>
<td>$0.0128</td>
</tr>
<tr>
<td>Labor</td>
<td></td>
<td>Hour</td>
<td>40</td>
<td>$0.1337</td>
</tr>
<tr>
<td>Utilities</td>
<td></td>
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</tr>
<tr>
<td>Electricity</td>
<td>75.0788 kWh/h</td>
<td>MMVTU/h</td>
<td>0.08</td>
<td>$0.0201</td>
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<tr>
<td>Facility charges</td>
<td></td>
<td></td>
<td>6.01</td>
<td>$0.0509</td>
</tr>
<tr>
<td>Capital cost</td>
<td>2,200,000</td>
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<td>$0.3676</td>
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<tr>
<td>Economic life</td>
<td>10 years</td>
<td></td>
<td></td>
<td>$0.1103</td>
</tr>
<tr>
<td>Units product/year (250 days/year)</td>
<td>598,500 lb</td>
<td>$0.0735</td>
<td>$0.7689</td>
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</tr>
<tr>
<td>Depreciation</td>
<td></td>
<td></td>
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<tr>
<td>Maintenance/year</td>
<td>3% capital cost</td>
<td></td>
<td>$0.1103</td>
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<tr>
<td>Other facility related costs</td>
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<tr>
<td>Administration and supplies</td>
<td>2% capital cost</td>
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<td>$0.0735</td>
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<tr>
<td>Production cost per lb</td>
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<td></td>
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<td>$0.33</td>
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Table 4
Avoided cost for flocculant facility.

<table>
<thead>
<tr>
<th>Biochemical oxygen demand cost reduction</th>
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<tbody>
<tr>
<td>Annual production flocculant – pounds/year</td>
<td>598,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biological oxygen demand (BOD) per 1000 chickens processed</td>
<td>45 lbs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percentage BOD reduction</td>
<td>50%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of birds processed/day</td>
<td>150,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of processing days/year</td>
<td>250</td>
<td></td>
<td></td>
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<tr>
<td>BOD reduction/year</td>
<td>843,750 lbs/year</td>
<td></td>
<td></td>
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<tr>
<td>BOD surcharge/lb BOD (Philadelphia, PA)</td>
<td>$0.314</td>
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<tr>
<td>Annual BOD reduction cost</td>
<td>$246,938</td>
<td></td>
<td></td>
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<tr>
<td>Avoided cost/pound of flocculant produced</td>
<td>$0.4427</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net processing cost of CKB flocculant (production cost – avoided cost)</td>
<td>$0.33</td>
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</tbody>
</table>

coagulated material. It was assumed that the CKB was from a processing plant which treated the CKB as a waste in a wastewater treatment facility. Also the cost of sulfuric acid was included in the analysis, although in areas with acidic water, sulfuric acid addition would not be needed. Sulfuric acid was used because its unit cost ($0.075/lb) is significantly lower than the unit costs of phosphoric acid ($0.59/lb) or citric acid ($0.99/lb). Since the CKB was removed from the processing plant waste stream, there was a tangible benefit in the form of an avoided cost due to decreased biological oxygen demand (BOD). In decreasing magnitude, the major costs of flocculant production were facility charges, labor, maintenance, facility related costs, utilities, and sulfuric acid. The high facility charges were mainly due to the capital costs related to dehydrating the blood. Total cost of flocculant production was $0.77 per pound.

BOD removal costs vary widely among water treatment systems, and the Environmental Protection Agency (EPA) in 1975-6 estimated BOD removal costs for 12 different plants to range from $0.07 to $3.77 per kilogram of BOD removed (EPA 1976 Draft Development Document for Phase II Fruits and Vegetables, US EPA, Washington DC). For this study we have used an avoided cost due to decreased BOD in the plant effluent stream based on rates currently charged by the Philadelphia Water Department of $0.314 per pound of BOD removed (City of Philadelphia Water Department Regulations section 303.4) or an estimated $0.44 per pound of product, giving a net cost of production of $0.33 per pound.

This production cost of $0.33/lb compares favorably to that of anionic PAM. The retail cost of anionic PAM is $2.41 per pound. If it is assumed that half of this cost results from production charges and the other half from marketing and distribution charges, this gives an estimate for the cost of manufacturing anionic PAM as $1.20 per pound. By comparing the flocculation effectiveness of PAM and CKB A-s at 5 h in Table 2, it is concluded that approximately two pounds of CKB are required to replace one pound of PAM. Thus the
value of the CKB flocculant is $0.60 per pound which is above the adjusted CKB flocculant production cost of $0.33 per pound. The calculated value of the CKB flocculant is a conservative estimate because data from 5 h was used in the calculation instead of 1 h data. At 1 h most CKB flocculant fractions performed better than PAM.

Kemira has estimated the annual North American market for synthetic polymeric flocculants to be $1 billion (www.kemira.com). At a retail cost of $2.41 per pound, the quantity of flocculant used per year is estimated to be 415 million pounds. With total annual chicken production in the U.S. at 9 billion, 1.1 billion pounds of CKB is produced each year which is equivalent to 143 million pounds of dried CKB flocculant. Since two pounds of CKB flocculant replaces one pound of synthetic flocculant, the U.S. produced CKB flocculant could replace about 17% of the synthetic flocculant used in North America each year. If all CKB were converted to flocculant, the annual BOD reduction cost would be $59.3 million, although the actual benefit is lower because some processing plants currently collect CKB for rendering.

4. Conclusion

Although it is certainly gratifying to find that CKB may be an important renewable alternative to PAM, the research described herein raises many additional questions: Can improved ways be found to efficiently dehydrate CKB without loss of activity? Can CKB flocculation be used in many applications? Can the flocculation of CKB be ascribed to specific proteins? The last question is of interest because if one or two CKB proteins are responsible for flocculation activity, then the remaining proteins could be separated from the flocculant–active proteins and applied to other uses, thus increasing the value of CKB further. The preliminary estimate of production costs will serve as a reference point to ascertain whether future research findings are contributing to higher economic potential for CKB-based products.

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References


