Available online at www.sciencedirect.com
SCIENCE DIRECT®

Resources, Conservation and Recycling 39 (2003) 341–367

Resources Conservation & Recycling

www.elsevier.com/locate/resconrec

Economic simulation modeling of reprocessing alternatives for corn masa byproducts

K.A. Rosentrater [a,b], T.L. Richard [b,*], C.J. Bern [b], R.A. Flores [c]

[a] Engineering and Industrial Technology Department, Northern Illinois University, DeKalb, IL, USA
[b] Agricultural and Biosystems Engineering Department, 3222 NSRIC, Iowa State University, Ames, IA 50011, USA
[c] Eastern Regional Research Center, ARS, USDA[1], Wyndmoor, PA, USA

Received 14 February 2002; received in revised form 27 October 2002; accepted 18 November 2002

Abstract

Increasing production of corn masa for tortillas, chips, and related snack foods is resulting in large quantities of organic residuals requiring environmentally sound management. These byproduct streams appear suitable for use as livestock feed material, thus eliminating landfilling costs. Possibilities for developing livestock feed include direct shipping to livestock feeding facilities, blending prior to shipping, extrusion processing, pellet mill processing, and dehydration. To assess the viability of these options for reprocessing masa byproducts as livestock feed materials, an economic model was developed and applied to each of these alternatives. Through a series of simulation runs with this model, it was determined that direct shipping was by far the most inexpensive means of recycling masa processing residuals (10–57 \$/Mg). Other alternatives examined in increasing order of costs included blending prior to shipping, extrusion, pellet mill processing (3–15, 5–18, and 4–18 times greater than direct shipping, respectively), while dehydration was clearly cost-prohibitive (33–81 times greater). Bagged feed was slightly more expensive to produce than bulk feed (1.1 times greater), and reprocessing costs increased as delivery distance increased, due to increased labor, equipment, and fuel costs, but decreased as byproduct generation rate increased, due to the development of the economies of scale. Alternately, based on a tipping fee of 50 \$/Mg, the total estimated cost to landfill ranged from 65 to 112 \$/Mg. Based on this cost analysis, direct shipping and

* Corresponding author. Tel.: +1-515-294-0465; fax: +1-515-294-9573.
E-mail address: tlr@iastate.edu (T.L. Richard).

[1] Mention of a brand name or firm does not constitute an endorsement by the US. Department of Agriculture or Iowa State University over others of a similar nature not mentioned.

0921-3449/03/\$ - see front matter.
doi:10.1016/S0921-3449(02)00175-1

feeding to livestock is the recycling option of choice for masa processing byproducts. Although specific details of process configurations and associated costs will vary, similar results are likely for other high moisture food processing residuals destined for utilization as livestock feed or components thereof.

Keywords: Systems analysis; Simulation modeling; Byproduct utilization; Food processing waste; Costs

1. Introduction

The flow of materials and energy in industrial systems has important implications for both pollution control and economic efficiency (Ayers and Ayers, 1996; Vellinga et al., 1998). One of the larger categories of material flows is renewable organic matter, including agricultural and forest products such as food, clothing, paper, and building materials (Graedel and Allenby, 1995). These sectors generate large volumes of pre- and post-consumer organic residuals (Kashmanian et al., 2000), which have potential value as energy, nutrients, fiber, and industrial chemicals (NRC, 2000). Several recent studies have applied life cycle analyses, simulation modeling, and other analytical industrial ecology tools to recycling opportunities for post-consumer organic residuals, such as waste paper and packaging (Finnveden and Ekval, 1998; Byström and Lönnstedt, 2000) and other organic materials (Sonesson et al., 1997; Sonesson, 1998; Sonesson et al., 2000). Studies of pre-consumer residuals are typically less comprehensive since system boundaries are smaller, but these analyses can provide important information about tradeoffs among alternative processing and utilization strategies (Allen and Behamanesh, 1994; CAST, 1995). This study examines reprocessing options for a pre-consumer organic residual generated in the food processing sector. It may, in fact, serve as a model for similar organic residuals from other bio-based industrial processes.

Alternative recycling and utilization strategies for agricultural and food processing residues include reprocessing and recycling within the manufacturing plant itself, resale for other end uses, incineration, biomass energy production, and use as a nutrient source for fermentation (Derr and Dhillon, 1997; Ferris et al., 1995; Glatz et al., 1985; Godfrey, 1983; Smith et al., 1974; Wang et al., 1997). Composting, yet another byproduct recycling option, converts organic waste streams into soil conditioning and fertilizing amendments, and has gained popularity in recent years as an effective disposal method for organic and food residuals (Kashmanian et al., 2000). Composting has been successfully used for a variety of food wastes, including gelatin extraction residues (Hyde and Consolazio, 1982), cranberry mash residuals (Steuteville, 1992), tomato processing byproducts (Vallini et al., 1984), brewery sludges (Beers and Getz, 1992), grape pomace from wineries (Logsdon, 1992), and food service organics (Goldstein, 1992; Shambaugh and Mascaro, 1997).

While composting and other innovative approaches have clearly demonstrated applicability, one traditional approach that should not be overlooked is the use of food processing residues as livestock feed. The economic value of organic residuals is higher in feeding applications, where both the energy and nutrients are used, than in conversion to fuels or fertilizers, which typically utilizes only one of these categories at a time (Fontenot, 1998). Many research efforts have focused on incorporating food manufacturing byproduct streams into livestock diets. One aspect of this work has included the direct feeding of food service and food processing wastes (Glenn, 1997; Polanski, 1995; Price et al., 1985). Another area has included the development of feed ingredients from slaughterhouse byproducts (Luzier and Summerfelt, 1995; Martins and Guzman, 1994; Wang et al., 1997). Additionally, many livestock feed materials have been developed in the grain processing industry, especially within corn dry milling, corn wet milling, and corn alcohol distillation (Trenkle and Ribeiro, 1999; Trenkle, 2002).

Corn masa processing, however, is one area of the grain industry that generates large quantities of waste materials, but that to date, has received little attention vis-à-vis byproduct disposal alternatives. Corn masa is used to produce corn tortillas and corn tortilla chips. Tortillas have been a staple in the diets of Mexican and Central American peoples for centuries. Common foods made with tortillas include tacos, tamales, quesadillas, and enchiladas (Krause et al., 1992; Ortiz, 1985; Serna-Saldivar et al., 1990). Currently, Mexican-style foods and corn-based snacks are booming in popularity. Tortilla sales in the United States alone were estimated at $4 billion in 2000 (Solganik, 1997), and are expected to reach $5.5 billion by 2003 (TIA, 2001).

Corn masa is produced by simulating, on an industrial-scale, the ancient Aztec art of lime-cooking corn. Whole corn is cooked with 120–300% water (original corn weight basis) and 0.1–2.0% lime (original corn weight basis) for 0.5–3.0 h at 80–100 °C, and is then steeped for up to 24 h. This process, called ‘nixtamalization’, can be either a batch process or a continuous process, depending on production equipment. The cooked grain (known as ‘nixtamal’) is then separated from the steep liquor (called ‘nejayote’), which is rich in lime and corn pericarp tissues which were loosened during cooking and steeping. The nixtamal is washed to remove any excess lime and pericarp, and is then stone ground to produce a dough called ‘masa’. The masa is molded, cut, or extruded, and is then baked or fried to make tortillas, tortilla chips, or corn chips. The masa can also be dried and milled into masa flour, which is later reconstituted and made into fresh tortillas at food service establishments (Serna-Saldivar et al., 1990; Gomez et al., 1987; Parades-Lopez and Saharopulos-Parades, 1983; Ramirez-Wong et al., 1994; Rooney and Serna-Saldivar, 1987).

Nejayote, the steeping liquid byproduct, contains approximately 2% total (dissolved and suspended) solids. Typically the suspended solids (50–60% of the total solids) are removed by screening, centrifugation, or decanting, and are then disposed of in landfills. The remaining water and dissolved solids are generally sent to municipal water facilities for treatment. These solids in the waste stream, which consist primarily of fiber-rich corn pericarp tissues, represent corn dry matter losses that occur during processing. Estimates of this dry matter loss have ranged from 5.0 to 17.0% of the original corn mass (Serna-Saldivar, et al., 1990; Rooney and Serna-Saldivar, 1987; Bressani et al., 1958; Gonzalez de Palacios, 1980; Katz et al., 1974; Khan et al., 1982; Pflugfelder, et al., 1988). The corn mass loss during nixtamalization is affected by many processing parameters, including corn hybrid, kernel hardness, lime concentration, cooking and steeping times and temperatures, friction and damage during washing and transport, and production equipment used. These processing losses can be economically significant due to lost masa yield, waste processing and disposal costs, potential environmental pollution, and subsequent legal penalties (Serna-Saldivar, et al., 1990; Rooney and Serna-Saldivar, 1987; Khan et al., 1982).

Although limited in number, a few studies have been conducted into alternative disposal options for masa byproduct streams. Four biological treatment options for nejayote were investigated on a laboratory-scale (Gonzalez-Martinez, 1984), including activated sludge processing, anaerobic contact processing, submerged aerobic fixed-film cascade processing, and anaerobic packed-bed processing. This study found that the activated sludge and anaerobic packed-bed reactors were effective treatment options for these waste waters. (Pflugfelder et al., 1988) studied the composition of masa processing dry matter losses, and included these losses in a mass balance of the masa manufacturing system. Rosentrater et al. (1999) conducted an extensive physical and nutritional characterization of typical masa byproduct solids (i.e. suspended solids removed from the nejayote stream), and results indicated that such byproducts are amenable to incorporation into livestock rations. Velasco-Martinez et al. (1997) investigated the suitability of implementing nejayote solids into poultry broiler diets, and found no differences in performance between control diets and diets utilizing nejayote solids. Rosentrater (2001) developed and characterized livestock feed ingredients by mixing nejayote solids with soybean meal at various blend ratios, and then extruding the blends at different processing conditions, both on a laboratory-scale and on a pilot-scale.

Before any recycling or reuse alternative is adopted for a given byproduct stream on an industrial-scale, each technically-viable option should be examined for feasibility, with special consideration given to the economics of each choice. This type of assessment is necessary for managers' decision-making processes, so that the most cost-effective disposal method can be chosen for a given facility (Clarke, 2000; Huang, 1979; Kuchenrither, et al., 1984; McCartney, 1998; Schulte and Kroeker, 1976; Stapleton, et al., 1984). One means of accomplishing this is to develop a computer model of the production system. Many models have been developed for the food and grain processing industries to assess or simulate production (Bandoni et al., 1988; Flores, et al. 1991). Some models have also been developed to model and assess the economics associated with various processing systems (Flores et al., 1993; Liu et al., 1992).

Because masa processing byproducts show potential for incorporation into livestock rations, the objective of this investigation was to develop a computer model to simulate and assess the economics involved with the production of livestock feed ingredients from these residual streams. Specifically, direct shipping, blending prior to shipping, extrusion processing, pellet mill processing, and dehydration were compared to landfilling, the traditional method of masa residue disposal, and were subsequently examined for economic feasibility.

2. Model development

Before delving into the details of the model's framework, it is important to qualitatively describe each of the proposed reprocessing options. Each operation, described below, is based upon the authors' experience and upon information found in literature (AFIA, 1985; Barbosa-Canovas and Vega-Mercado, 1996; Mercier et al., 1989). A process flow diagram is provided for each option (Figs. 1–5), and a complete equipment listing, based on the appropriate flow diagram, is also provided (Table 1). It should be noted that each operation has been designed to minimize the equipment and processing steps necessary to collect dewatered masa residues, process the residues into value-added byproduct feed materials, and deliver the resulting products to livestock feeding operations (i.e. a 'minimal processing' philosophy was used (Gunjal et al., 1999)).

2.1. Reprocessing options

2.1.1. Landfilling

This traditional approach has been included in the model to provide baseline results with which all other recycling options can be compared. The equipment used for this disposal method is identical to that used for direct shipping, and will be discussed in that section.

2.1.2. Direct shipping

Landfilling and direct shipping (Fig. 1) are the simplest disposal methods for masa residuals vis-à-vis processing steps and equipment required. For the purposes of this model, the same equipment can be used for each of these options; only the final destination of the byproduct differs (livestock facility or landfill). With this method,

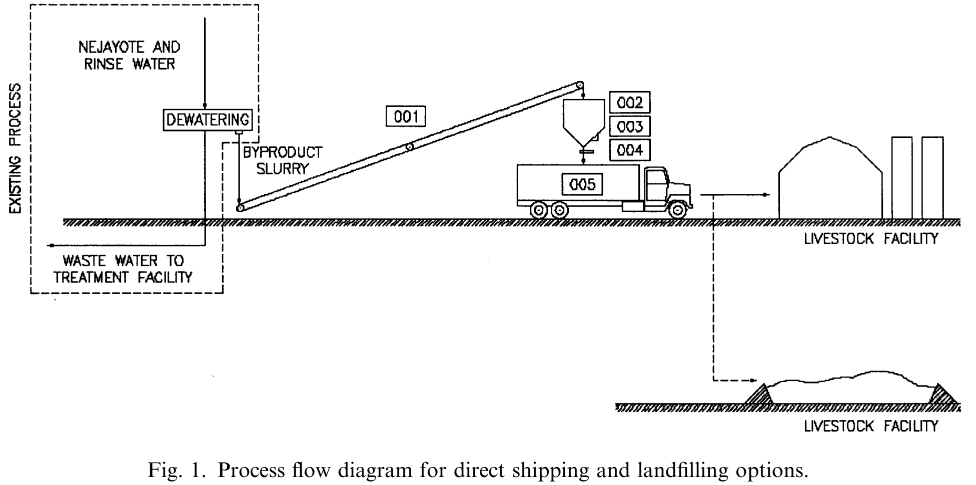

Fig. 1. Process flow diagram for direct shipping and landfilling options.

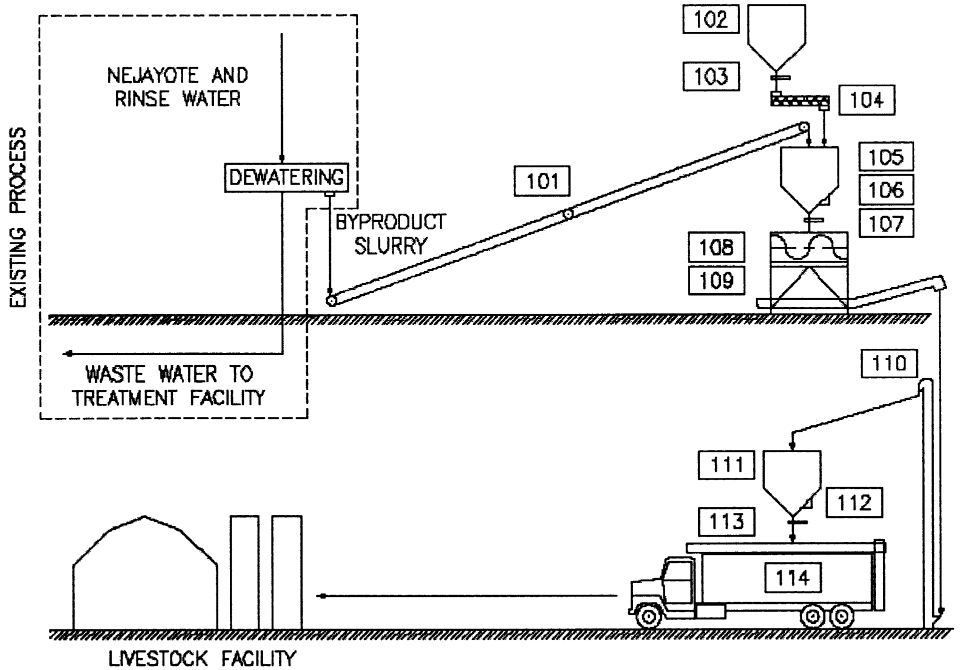

Fig. 2. Process flow diagram for blending option.

dewatered masa byproduct slurry is transported via a belt conveyor into a surge (holding) bin for loading onto a delivery truck at a later point in time. The major constraint with this recycling alternative is that masa byproduct steams have a very high moisture content ($\approx$90% (w.b.) (Rosentrater et al., 1999). This limits holding time prior to delivery due to a higher risk of microbial spoilage (Barbosa-Canovas and Vega-Mercado, 1996); high moisture byproducts should be delivered within 24 h to avoid this degradation (Price et al., 1985).

2.1.3. Blending

Blending (Fig. 2) masa byproducts with a dry carrier material, such as a high-protein source (e.g. soybean meal) or possibly another, less expensive byproduct (e.g. grain dust), prior to shipping can both enhance the nutritional properties of the masa byproduct and increase the shelf-life of the final feed product due to a decreased mixture moisture content. Essentially, the process of blending prior to shipping entails transporting the dewatered slurry with a belt conveyor to a surge bin, which serves as an inlet scale for a mixer. After a batch of the masa byproduct have been mixed with the carrier material, a conveyor transports the feed mixture to a bucket elevator, which conveys the feed into another holding (surge) bin, which is then used to fill a bulk feed delivery truck.

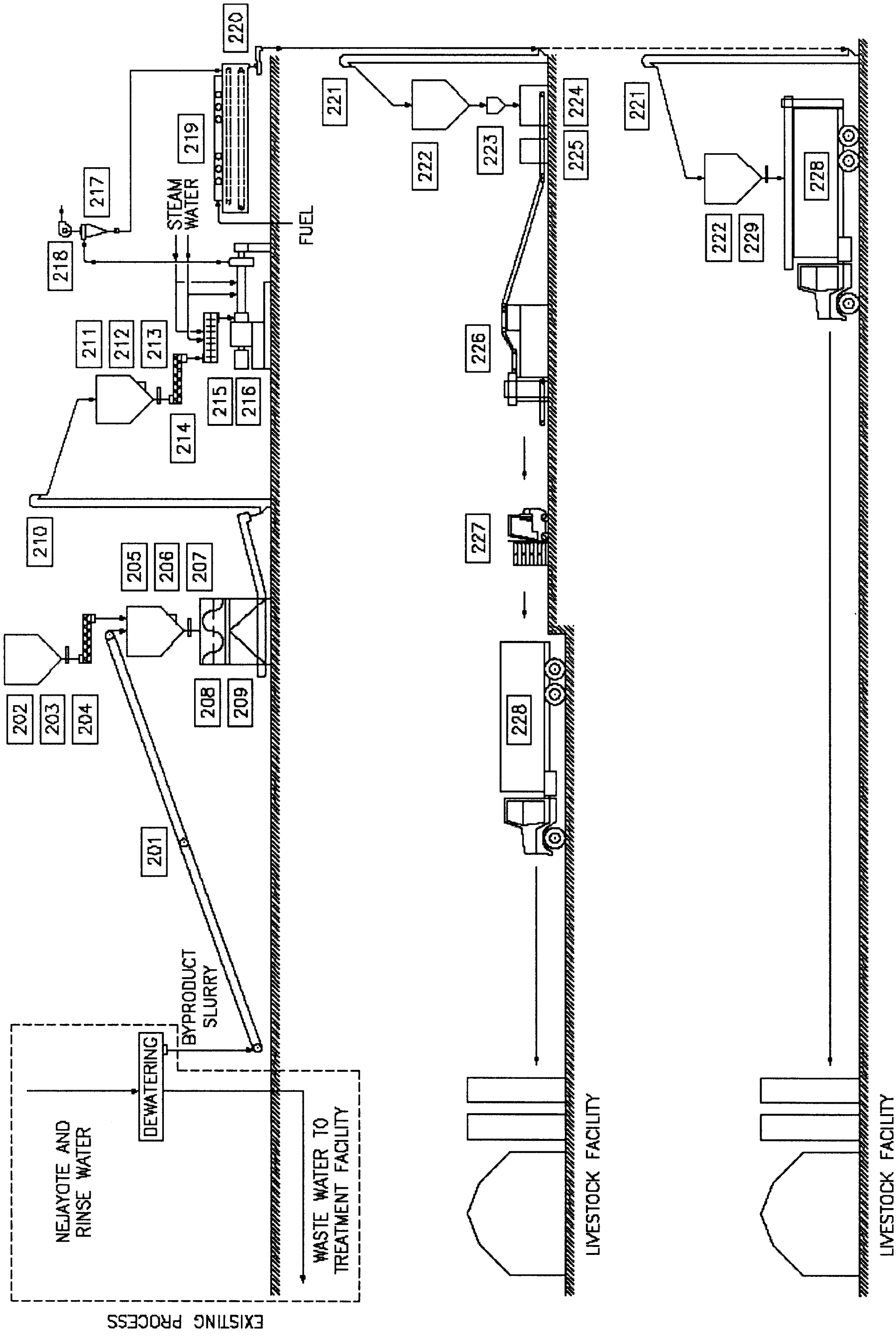

Fig. 3. Process flow diagram for extrusion options.

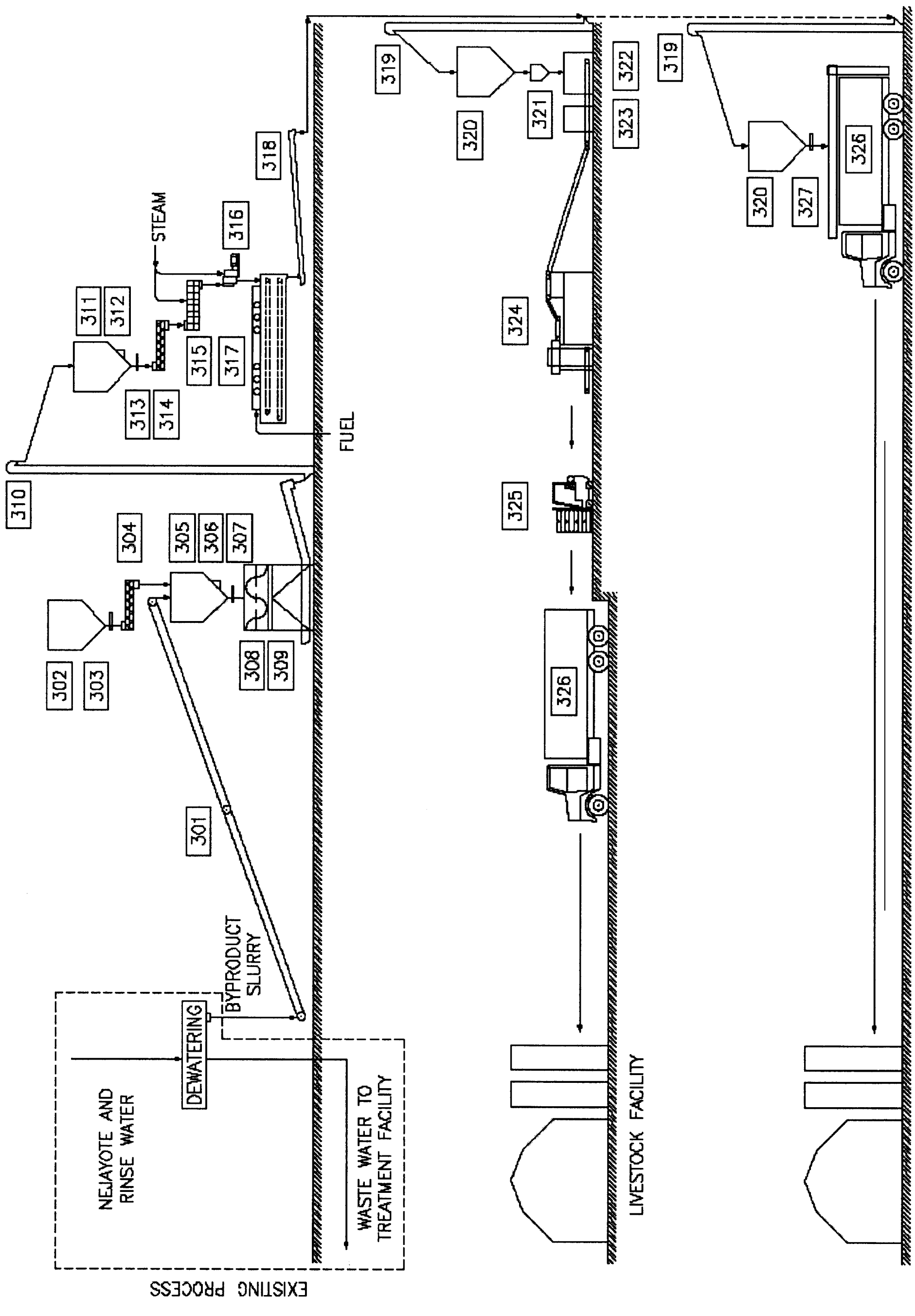

Fig. 4. Process flow diagram for pelleting options.

Table 1
Equipment list for reprocessing options

Process	Direct	Blending	Extrusion equipment tag	Pelleting	Drying
Item					
Belt conveyor	001	101	201	301	401
Soy storage bin	–	102	202	302	–
Gate	–	103	203	303	–
Screw conveyor	–	104	204	304	–
Scale/surge bin	002	105	205	305	402
Vibrator	003	106	206	306	403
Gate	004	107	207	307	404
Mixer	–	108	208	308	–
Drag conveyor	–	109	209	309	–
Bucket elevator	–	110	210	310	–
Scale/surge bin	–	111	211	311	–
Vibrator	–	112	212	312	–
Gate	–	113	213	313	–
Screw conveyor	–	–	214	314	–
Conditioner	–	–	215	315	–
Extruder	–	–	216	–	–
Pellet mill	–	–	–	316	–
Cyclone	–	–	217	–	–
Fan	–	–	218	–	–
Dryer/cooler	–	–	219	317	405
Screw conveyor	–	–	–	–	406
Drag conveyor	–	–	220	318	–
Bucket elevator	–	–	221	319	407
Scale/surge bin	–	–	222	320	408
Bagging scale	–	–	223	321	409
Bagger	–	–	224	322	410
Sewer	–	–	225	323	411
Palletizer	–	–	226	324	412
Fork lift truck	–	–	227	325	413
Delivery truck	005	114	228	326	414
Gate	–	–	229	327	415

2.1.4. Extrusion

Extrusion processing (Fig. 3) of masa byproducts is very process intensive. A major constraint with this type of processing, however, is the moisture content range which is amenable to extrusion (i.e. the raw masa byproduct stream must be mixed with a dry carrier material to reduce the moisture content to approximately 25% (w.b.) for the extruder to process this material). Similar to blending prior to shipping, the masa residues are transported via a belt conveyor to a scale/surge bin above a mixer. After a batch of the masa byproducts have been mixed with a dry blending agent, the feed mixture is transported to a bucket elevator, and then placed in another holding/surge bin. The material is then metered out of the bin, using a screw conveyor, to a preconditioner, where steam and water are added so that the material is properly prepared for extrusion. After exiting the extruder, the feed

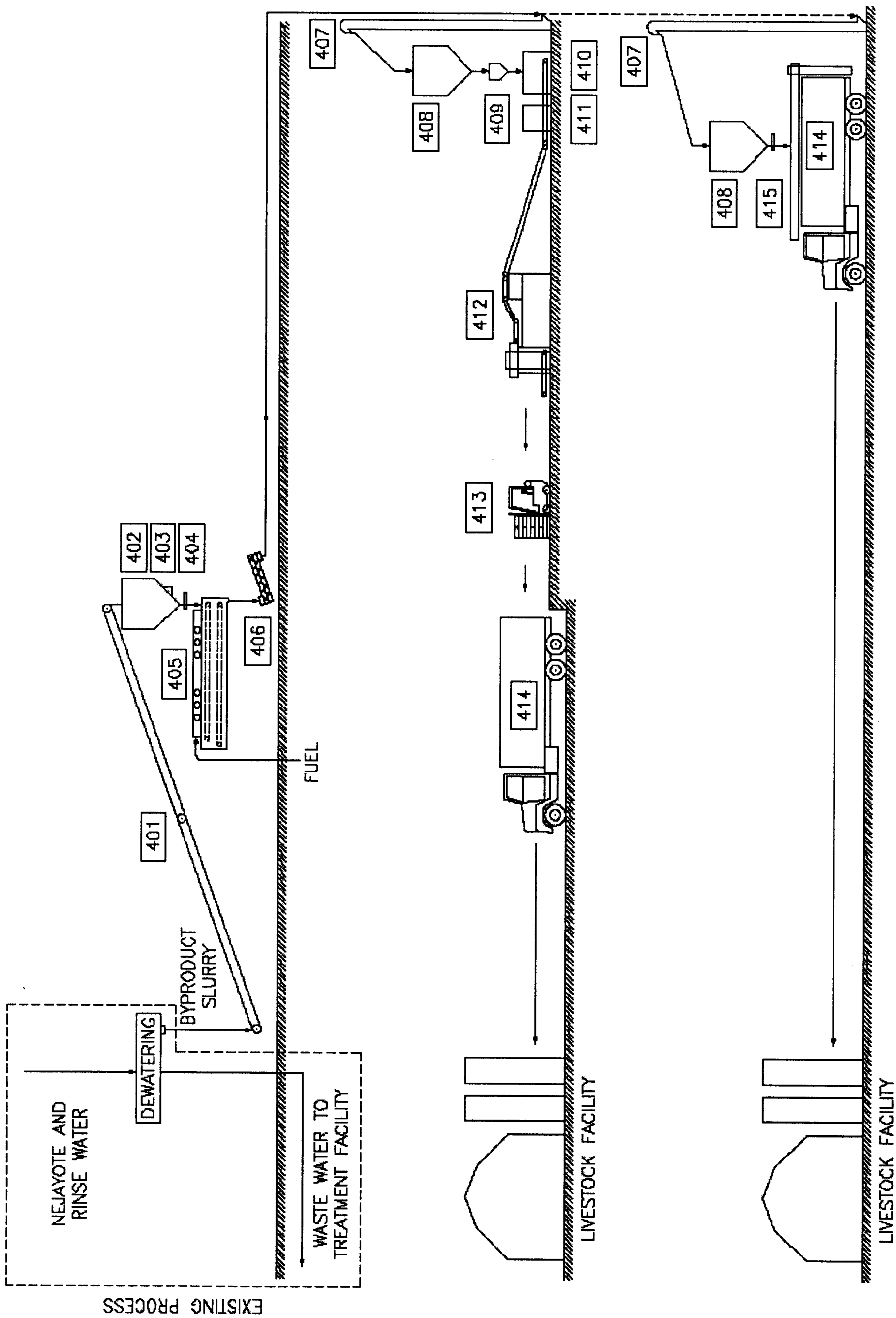

Fig. 5. Process flow diagram for dehydration options.

material is pneumatically conveyed to a dryer/cooler, where water is removed until the feed product is at an appropriate moisture content level. The feed is then cooled. It is generally recommended that feed materials have a final moisture content below 15% (w.b.), because this moisture level is microbiologically stable (Beauchat, 1981; McEllhiney, 1985). A bucket elevator then transports the dried and pelleted feed material into a surge bin for temporary storage.

At this point, there are two possible alternatives that could be implemented: the processed feed can either be delivered in bag form or in bulk form to the farm. If a bagged form is chosen, the feed will then exit the surge bin into a bagging scale, and then will enter an automatic bagging and palletizing system. Then, a forklift will place the bagged and palletted feed onto a delivery truck. If, however, a bulk feed is desired, the surge bin will empty directly into a bulk feed delivery truck.

2.1.5. Pelleting

Producing feed materials from a pellet mill processing line (Fig. 4) is very similar to extrusion processing vis-à-vis equipment required. As with extrusion, pellet mill processing of feedstocks is confined to a limited moisture content range and, thus, the masa byproduct slurry must be blended with a dry material, to achieve 25% m.c. (w.b.) prior to processing. The major difference between pellet mill and extrusion processing, other than using a pellet mill instead of an extruder, is that the pelleted feed discharges directly from the pellet mill into the dryer/cooler, and does not require an air lift to transport the material. Once again, the resulting dry feed can either be bagged or left in bulk form.

2.1.6. Dehydration

Dehydration (Fig. 5) of masa byproduct slurries is not as process intensive as either extrusion or pelleting, but it does have substantial fuel costs, because the slurry has such a high moisture content ($\approx$90% (w.b.) (Rosentrater et al., 1999). To achieve a microbiologically-stable feed product, substantial amounts of water must be removed from the byproduct stream. For this model, the final moisture content of the masa byproducts was set at 10% (w.b.), a moisture stable level to prevent spoilage. After dewatering, masa residues are transported via a belt conveyor to a surge bin, and then are fed directly into a dryer. After exiting the dryer, the resulting feed can either be bagged or left in bulk form, which is similar to both the extrusion and pelleting options.

2.2. Economic model heuristics

2.2.1. Scope of model

The overall purpose of this model was to compare the costs of landfilling masa residues with the economics of producing value-added byproduct feed material using five unique reprocessing alternatives. The options incorporated into the model included direct shipping, blending, extrusion, pelleting, and dehydration, as described in the previous section. Recycling options that deserve investigation, but were not examined here, include composting, direct land application, and incineration. Additionally, some potential for fiber separation from the byproduct stream exists (Rosentrater et al., 1999), and this too deserves future attention.

Specifically, the objective of this economic model was to determine byproduct feed sales price ($/Mg) required for each option to reach the breakeven point each year of plant operation, and then to compare these results with the costs of landfilling ($/Mg). The intent in developing this model was to provide a tool to assist masa manufacturers in choosing the most appropriate option for a given production facility.

2.2.2. Processing capacities

Industrial corn masa production occurs on a variety of scales, and variable characteristics include size of facility, plant location, availability of raw materials, type and composition of raw corn supplies, and ability to ship processed products. Masa production rates can range from less than 12 000 to over 300 000 Mg/year at a single site (Minsa, 2000). Corn matter loss due to the nixtamalization process ranges from 5.0 to 17.0% of the original corn mass. These production ranges are coupled together to produce a large variation in masa byproduct generation rates across the corn masa industry. Thus, the ensuing economic model had to be flexible enough to accommodate a wide spectrum of masa byproduct generation rates.

To cover as broad a range as possible, the model bypassed both potential masa production levels and possible waste production fractions, and instead directly utilized byproduct production rates. Using this approach, not only was the modeling procedure simplified, but the later use of the model by production facility managers was also simplified, because waste generation rate is easily measurable at a given facility. The model incorporated 10 possible byproduct generation rates (Mg/yr): 1000; 2500; 5000; 10 000; 20 000; 30 000; 40 000; 50 000; 60 000; and 70 000. Additionally, a planned benefit is that this model can be applied to similar byproduct utilization scenarios for other food processing residual streams.

The blending, extrusion, and pelleting options require the addition of a dry carrier material. Soybean meal was used in this analysis because of the high protein value and common use in the feed industry. For the purposes of this model, soybean meal addition was based on a 30% masa byproduct/70% soybean meal blend ratio for each of these reprocessing options. This mixture ratio was used because it utilized the greatest byproduct amount, and could still be processed via these operations; Rosentrater, 2001 for more details. If an alternative blending agent is desired, however, this mixture ratio could be easily adjusted when using the model.

2.2.3. Model assumptions and parameters

The premise of this model is that a masa production facility already exists. The intent in constructing this model in this fashion is to provide the facility planner or manager with a tool that can be used to help decide upon optimum waste management options. This model examines the costs associated with installing and operating a reprocessing line in the existing corn masa production plant. This model also examines the costs associated with landfilling the masa byproduct stream to provide baseline results that can be compared to the results of the various

Table 2
General balance sheet implemented by model

Model input variables
Delivery radius (km; mi)[a]
Electricity price ($/kW h)[b]
Gasoline price ($/l; $/gal)[b]
Interest rate (decimal)[b]
Landfill tipping fee ($/Mg; $/ton)[b]
Masa byproduct generation rate (Mg/yr; tons/yr)[a]
Raw ingredient (blending agent) price ($/Mg; $/ton)[b]
Recycling/reprocessing option[b]
Type of feed produced (bulk sludge, dry bulk, dry bagged)[b]
Annual fixed costs ($)[c]
Initial capital investment
Buildings
Equipment
Other (spouting, wiring, engineering, etc.)
Total initial capital investment
Annual equivalent capital investment
Depreciation
Insurance
Interest
Overhead
Taxes
Annual variable costs ($)[d]
Delivery truck insurance
Energy (boiler fuel for steam generation)
Energy (dryer fuel)
Energy (electricity)
Feed bag breakage losses
Feed delivery
Feed storage bags
Fork lift truck operation
Gasoline
Labor
Maintenance and repairs
Miscellaneous supplies
Other variable costs
Pallet repairs and replacement
Raw ingredients (blending agents)
Water
Annual benefits ($)
Byproduct feed sales revenue
Equipment salvage value
Annual equivalent salvage value

[a] Input variables intrinsic to model.
[b] User-specified input variables.
[c] Values are dependent on processing option and production rate.
[d] Values are dependent on processing option, production rate, and delivery distance.

reprocessing options. The assumptions and parameters incorporated into the model are explained in extensive detail elsewhere (Rosentrater, 2001).

The model utilized both intrinsic and extrinsic (e.g. user-specified) variables. Intrinsic variables included the various disposal options (i.e. the five reprocessing options and landfilling), byproduct generation rate (Mg/yr; ton/yr), at the 10 levels discussed previously, and delivery distance (0–100 miles (161 km) by 10-mile (16-km) increments). User-specified variables included interest rate, electricity price ($/kW h), gasoline price ($/l; $/gal), blending agent price ($/Mg; $/ton), and landfill tipping fee ($/Mg; $/ton). Additionally, when using the model, the user can readily specify which disposal option to examine, and for the appropriate options, whether bulk or bagged feed will be produced.

For each waste disposal option, equipment and building facilities were sized to adequately meet processing requirements. Costs to purchase, ship, install, and operate these lines were determined. Using a service life of 15 years ($n = 15$), the model accounted for all annualized costs and benefits for each option. Annualized fixed costs included equipment, buildings, engineering, depreciation, overhead, and taxes, to name but a few. The model also accounted for annualized variable costs, such as electricity, gasoline, dryer fuel, labor, raw ingredients (blending agents), water, maintenance, etc. Annual benefits included only the sale of byproduct feed materials and the annualized salvage value of equipment and structures. Table 2 itemizes all annualized costs and benefits included in the model; greater detail regarding the model, as well as a full reference list, is found in (Rosentrater, 2001).

2.2.4. Economic analysis

A general balance sheet (Table 2) was implemented within the model to account for all annualized fixed and variable costs, as well as all annualized benefits, for each reprocessing option, as well as for landfilling. By determining these values, the required byproduct feed sales price ($/Mg) needed for each reprocessing option to reach the annual breakeven point could be determined via Eq. (1):

$$\mathrm{BBSP} = \frac{\sum \mathrm{AFC} + \sum \mathrm{AVC} - \sum \mathrm{AB}}{\mathrm{AMBP}} \tag{1}$$

where BBSP is the byproduct breakeven sales price ($/Mg), AFC is the annualized fixed costs ($/yr), AVC is the annualized variable costs ($/yr), AB is the annualized benefits ($/yr), and AMBP is the annual masa byproduct production rate (Mg/yr).

For the landfilling case, however, the only annualized benefit was salvage value. Consequently, total annualized costs to landfill were determined (i.e. breakeven never occurs for the landfilling scenario).

2.2.5. Model implementation

All processing, equipment, structure, energy consumption, and cost information was programmed into a FORTRAN computer model (Lahey Computer Systems, Inc., 1995). The complete model is given in (Rosentrater, 2001). The user must specify input values for the five extrinsic variables: interest rate, electricity price, gasoline

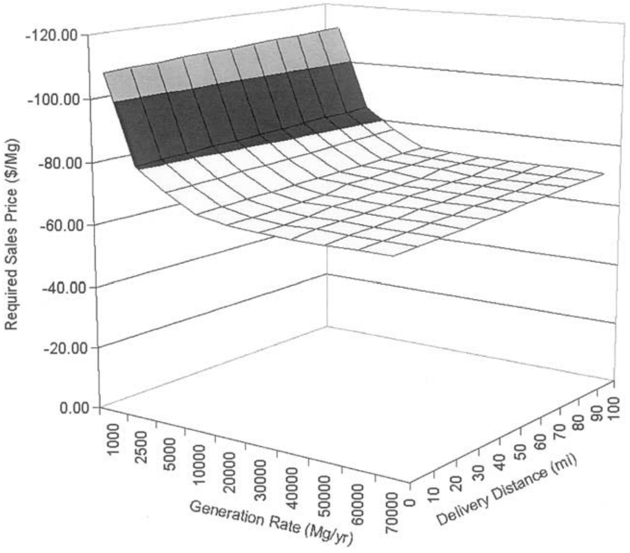

Fig. 6. Effect of byproduct generation rate and delivery distance on landfilling cost.

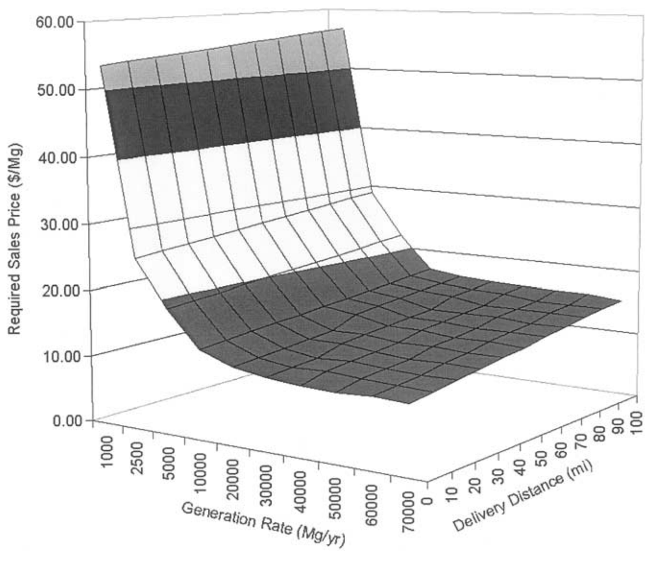

Fig. 7. Effect of byproduct generation rate and delivery distance on byproduct sales price for direct shipping option.

price, blending agent (soybean meal for this study) price, and landfill tipping fee. Additionally, the user must specify which recycling option to use, as well as type of feed product desired (bagged or bulk) for the extrusion, pelleting, and dehydration options. The model then calculates total annualized costs ($/Mg) (for the landfilling

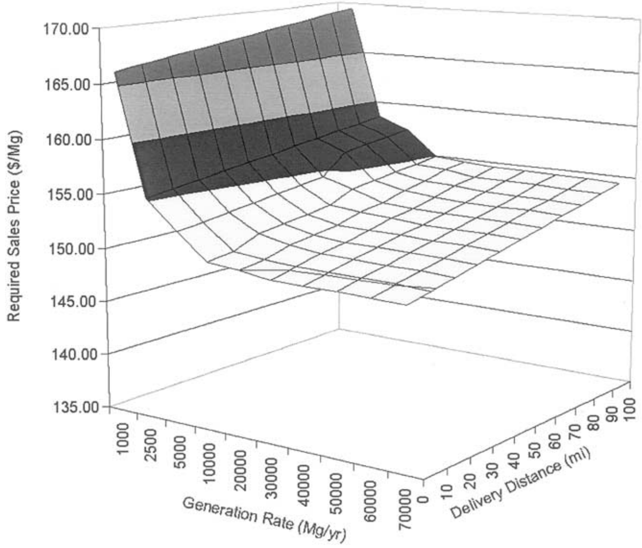

Fig. 8. Effect of byproduct generation rate and delivery distance on byproduct sales price for blending option.

option) or feed sales price required to breakeven ($/Mg) (i.e. for all five other reprocessing options).

The current study entailed a series of simulation runs with the model. Values of the five user-specified variables were chosen based on values representative of those found in the central United States during the summer of 2000. Values chosen included an interest rate of 9.50% (Federal Reserve, 2000; HSH Associates, 2000), an electricity price of 0.07 $/kW h (EIA, 2000a, EIA, 2000b), a gasoline price of 1.50 $/gal (0.40 $/l) (EIA, 2000c), a soybean meal price of 150.00 $/ton (165.35 $/Mg) (TFC, 2000), and a tipping fee of 50.00 $/ton (55.12 $/Mg) (Goldstein, 1992; Ackerman, 1997; Johnson and Carlson, 1991; Jones, 1992).

2.2.6. Sensitivity analysis

A sensitivity analysis was subsequently conducted with the model by altering the values of three input variables (interest rate, electricity price, and gasoline price); each were changed, in turn, by $\pm 10\%$, and the resulting model outputs were compared with the previous results.

3. Results and discussion

Output results from the economic model simulation runs (i.e. byproduct feed sales price ($/Mg) required for each recycling option to reach the breakeven point annually), using the aforementioned values for the input variables, are presented in Figs. 6–11. The results are given as a function of the two intrinsic variables,

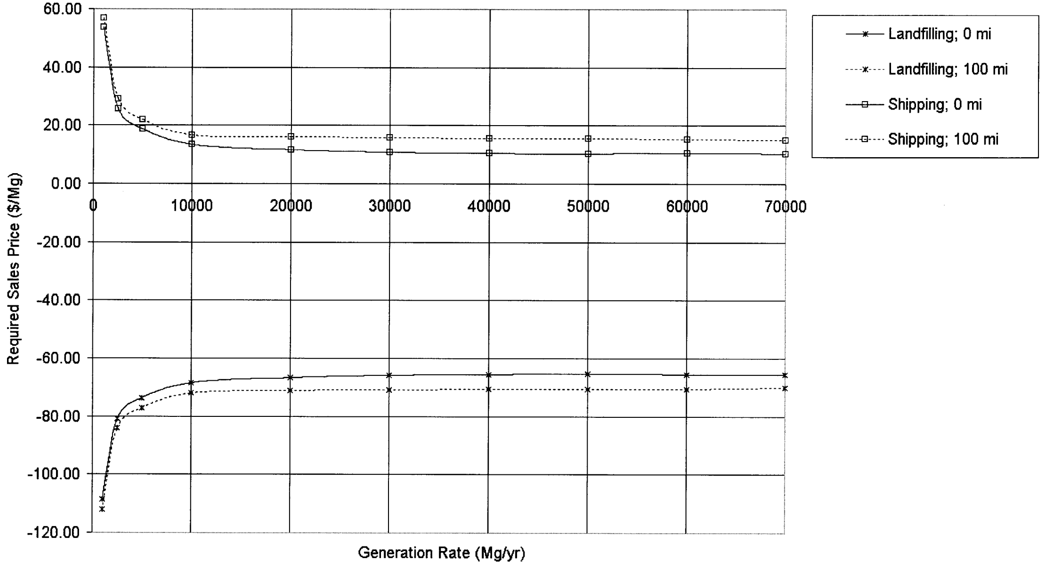

Fig. 9. Effect of byproduct generation rate and delivery distance on byproduct sales price for landfilling and direct shipping options.

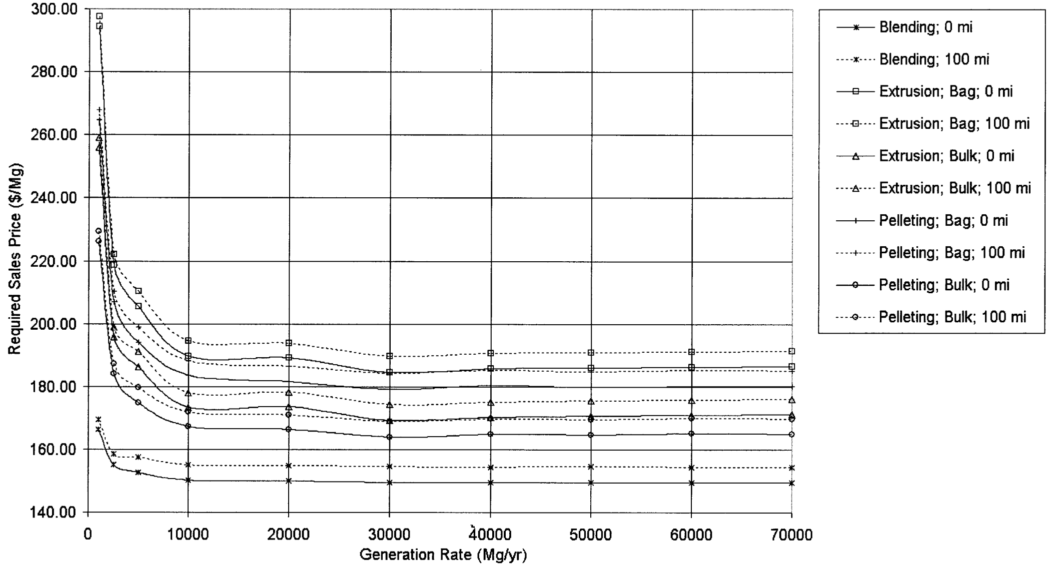

Fig. 10. Effect of byproduct generation rate and delivery distance on byproduct sales price for blending, extrusion, and pelleting options.

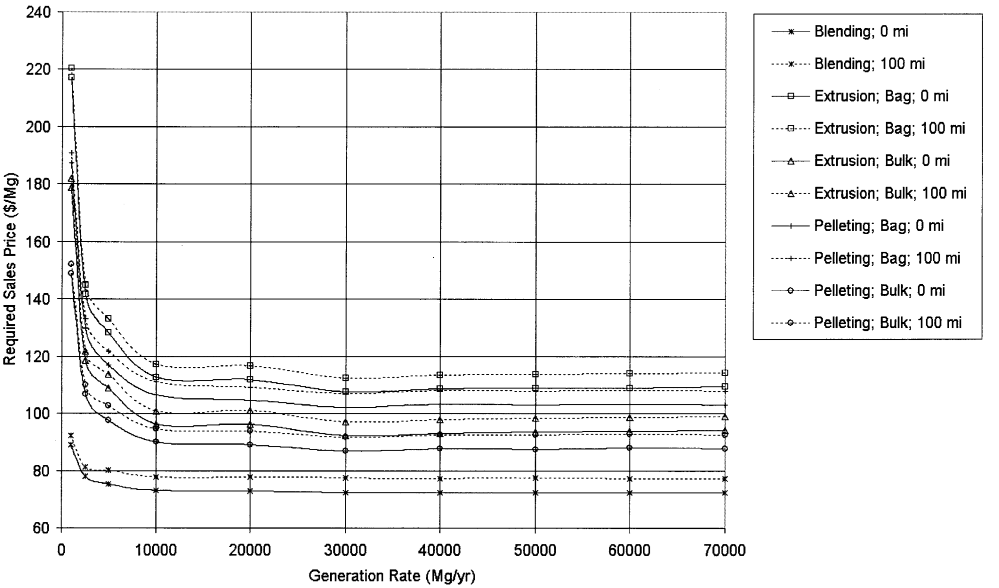

Fig. 11. Effect of byproduct generation rate and delivery distance on byproduct sales price for blending, extrusion, and pelleting options, using a blending agent at 50 $/Mg.

byproduct generation rate and delivery distance, which varied at the same rate for all recycling options.

3.1. Landfilling

Landfilling results are shown in Fig. 6. As the results show, breakeven will never occur for the landfilling option, because the only annualized benefit derived from this process is the annualized salvage value from equipment and facilities (i.e. the byproduct is never sold). Additionally, the results show that as distance to the landfill increases the total cost for landfilling ($/Mg) increases. This occurs due to increased gasoline consumption and labor costs associated with transporting the byproduct. As generation rate increases, at a given delivery distance, however, the total cost to landfill decreases, because economies of scale are achieved at the higher production rates. This occurs because production costs and capital investments vis-à-vis byproduct output are comparatively lower (McConnell, 1987). Because the costs associated with landfilling are usually considered ‘avoided’ costs, the breakeven sales price calculated for the subsequent recycling options could, in fact, potentially be reduced to this amount and still be considered economically feasible.

3.2. Direct shipping

The only difference between direct shipping and landfilling option is the final destination for the byproduct (i.e. landfill or livestock feeding facility). Of all reprocessing options in this study, direct shipping resulted in the lowest sales price required to reach breakeven (i.e. this was the most economical option for any masa production facility, because capital investment and production costs were minimized). These results are shown in Fig. 7. As the results show, the required sales price slightly increased as delivery distance increased, but drastically decreased as byproduct generation rate increased (i.e. economies of scale occurred). ‘Ripples’, however, can also be seen in the graph; these are actually due to the competing effects of the economics of scale and the ‘diseconomies of scale’, which occur due to increased equipment costs at increased production rates.

3.3. Blending

Blending and shipping results (Fig. 8) are similar to that of direct shipping, but the levels of required sales price are considerably higher, due to both the higher equipment investments, energy consumption, and the costs associated with the acquisition and addition of a blending agent. Required sales prices are between 3 and 15 (with an average of 10) times greater than those of direct shipping alone. Diseconomies of scale can also be seen in the graph, primarily due to increased equipment costs at greater production rates.

Because all reprocessing options exhibited similar behavior (i.e. slightly increased costs as delivery distance increased (at a given byproduct generation rate) and substantially decreased costs as byproduct generation rate increased (at a given delivery distance)), all results have been subsequently projected into two-dimensional scatterplots (Figs. 9–11) to simplify the presentation of the simulation results. In these graphs, the entire range of byproduct generation rates are presented, but only two delivery radii are presented: 0 and 161 km (0 and 100 miles).

3.4. Extrusion

Extrusion processing, as Fig. 10 shows, exhibits behavior similar to the previous options (slightly increased costs at increased delivery distances and drastically decreased costs at increased byproduct generation rates). Additionally, a few diseconomies of scale can be seen; but, the majority of behavior can be attributed to the economies of scale being achieved, and thus lower production costs as byproduct generation rate is increased. Due to the equipment-intensive nature of this processing option, however, production costs are considerably greater than those for the direct delivery option. Extrusion processing, with the bagged feed option, has production costs 5–18 (with an average of 12) times greater than those of direct shipping alone. Extrusion processing with the bulk feed option has production costs between 5 and 17 (with an average of 11) times the costs of direct shipping alone. The results also indicate that bagged feed has production costs 1.1 times greater than the bulk feed option. This is due to increased capital expenditures for bagging equipment and the associated energy costs to operate these machines. Because the costs associated with extrusion processing are so high, this reprocessing option may be cost-prohibitive, especially because the marginal nutritional gain resulting from this process is relatively small compared to the inherent composition of raw soybean meal (i.e. the masa byproduct slurries alter the nutrient content minimally, due to their high moisture content) (NRC, 2000)

3.5. Pelleting

Pellet mill processing is also very process-intensive. In fact, this option is very similar to extrusion processing vis-à-vis equipment and energy required. The simulation results for this option also reflect the trends shown by all previous options, as shown in Fig. 10. The graph also shows both economies of scale being achieved and slight diseconomies of scale occurring. Pellet mill processing, with the bagged feed option, has production costs 5–18 (with an average of 12) times greater than those of direct shipping alone, while pellet mill processing with the bulk feed option incurs production costs 4–16 (with an average of 11) times the costs of direct shipping. As with the extrusion processing option, bagged feed is 1.1 times more expensive to produce than bulk feed. Although pellet mill processing is slightly less expensive than extrusion processing, this reprocessing option is also cost-prohibitive compared to direct shipping of the masa byproduct stream.

3.6. Dehydration

Dehydration, or drying, was by far the most expensive reprocessing option studied. Although this option was not as equipment-intensive as either extrusion processing or pellet mill processing, the major cost factor associated with this option was the quantity of dryer fuel required to dry the wet byproduct slurry (i.e. from $\approx$ 90% m.c. (w.b.) to $\approx$ 10% m.c. (w.b.)). Compared to direct shipping, drying with the bagged feed option incurred production costs 46–81 (with an average of 60) times greater, while drying with the bulk feed option had costs 33–79 (with an average of 55) times greater, respectively. As with the extrusion and pellet mill processing options, bagged feed was 1.1 times more expensive to produce than bulk feed. Thus, dehydration is not an economical choice for the recycling of corn masa byproducts. These results were so high, in fact, compared to all other reprocessing options, that the values were not plotted in Fig. 10, because it would have adversely impacted the readability of the graph. Although not shown graphically, the dehydration results exhibited similar trends vis-à-vis generation rate and delivery distance as all other reprocessing options studied.

Table 3
Sensitivity analysis of direct shipping option ($\pm$10% of original variable values)

	Avg. change (%)	Max. change (%)	Min. change (%)	Range (%)
Interest rate	0.89	2.40	0.25	2.15
Electricity price	0.11	0.18	0.06	0.12
Gasoline price	0.72	1.61	0.00	1.61

3.7. Sensitivity analysis

Sensitivity analysis is used to examine the effects of changes in input variables on model outputs. Results from a sensitivity analysis are important because it gives an indication of the relative robustness of the model to changes in the input economic parameters, which are due, in reality, to exogenous factors in the actual, greatly fluctuating, marketplace. Because only direct shipping was economically feasible in this study, a sensitivity analysis was conducted on this option only. To conduct the sensitivity analysis, the three appropriate input variables (interest rate, electricity price, and gasoline price) were each changed by $\pm 10\%$, and the resulting model outputs were compared with the baseline results. Table 3 summarizes the results of this sensitivity analysis, and as shown in the table, interest rate, electricity price, and gasoline price each had only a small effect on model output (2.15, 0.12 and 1.61%, respectively). Thus, the model was fairly robust vis-à-vis the input (i.e. economic) variables.

Along a similar vein, the effect of using a lower-cost blending agent (such as grain dust or other dry processing byproducts, was investigated, because the relatively high cost of soybean meal (165.35 $/Mg) led to high breakeven values for the blending, extrusion, and pelleting options, which could thus preclude their implementation in a production setting. To examine this scenario, an arbitrary blending agent price of 50 $/Mg was selected, with all other model input variables set at the original levels. The simulation results from this case are shown in Fig. 11. As shown, the data curves for the blending, extrusion, and pelleting options were all shifted downward substantially, but were still much higher than the direct shipping option results: blended byproduct feed (2–7 times greater, with an average of 5 times), extruded/bagged feed (4–11 times, with an average of 8 times), extruded/bulk feed (3–9 times, with an average of 6 times), pelleted/bagged feed (3–10 times, with an average of 7 times), and pelleted/bulk feed (3–9 times greater, with an average of 6 times). Thus, these simulation results still show that direct shipping is the economically-optimal option for recycling masa processing byproducts.

4. Conclusions

This study modeled the economics associated with the recycling/reprocessing of corn masa byproducts using a computer program developed specifically for this purpose. The costs associated with traditional disposal (i.e. landfilling) are actually ‘avoided’ costs and, thus, the breakeven sales price calculated for all recycling options considered could potentially be reduced to this amount and still be considered economically feasible. Through use of this model, it was determined that direct shipping of masa byproducts is the most economical choice for the corn masa manufacturer. Blending masa byproducts is a more expensive recycling option, but still may be economically feasible, depending on the blending agent used. Extrusion processing and pellet mill processing are substantially more expensive.

Thus, these options are cost-prohibitive. Furthermore, dehydration is far too expensive to justify economically.

With regard to the blending, extrusion, and pelleting options, because masa byproducts are approximately 90% water (w.b.), even blending at a ratio of 30%/70% with a dry blending agent, such as soybean meal, the addition of the byproduct alters the nutrient makeup of the blending agent minutely (i.e. only 3% of the blend's solids originate from the masa byproduct). Thus, the byproduct feed is essentially soybean meal, or whatever blending material has been used, and has been altered very little. Blending may be economically feasible because it only adds 4 $/Mg (at most) to the original cost of the blending agent. The benefits of this option can be realized if the masa byproduct is blended with a low-cost dry material, instead of high-cost soybean meal. Extrusion adds a maximum cost of 94 $/Mg (bulk feed) and 132 $/Mg (bagged feed), while pelleting adds a maximum cost of 64 $/Mg (bulk) and 103 $/Mg (bagged) over the original cost of the blending agent. Thus, the increase in costs utilizing extrusion and pelleting is exorbitant relative to the costs of direct shipping, and is not economically warranted at current feed prices. It must be mentioned, however, that dry feed (e.g. extruded or pelleted) has a long shelf-life, whereas blended or raw (i.e. directly shipped) materials have very limited storability due to higher moisture content. The ability to store feed for a length of time may indeed be a benefit to livestock producers.

Even so, the most economically feasible recycling option for corn masa byproducts is direct delivery. Blending may also be feasible, just somewhat more costly, depending on the blending agent used. Both options should be studied further in a real manufacturing setting. However, extrusion, pelleting, and dehydration are too cost-prohibitive to implement.

The intent of this project was to examine the economics associated with the development of a livestock feed ingredient produced from corn masa processing byproducts. Because the scope was limited to the production of a single feed ingredient only, the development of an entire feed ration for a particular animal species is left to future studies, and may possibly entail the incorporation of corn, vitamins, minerals, etc., and will require feeding trials before the effectiveness of this type of feed ration is known.

It should also be noted that the price of soybean meal, as with all other agricultural commodities, fluctuates drastically over time (TFC, 2000). Consequently, these changes will need to be taken into consideration, and can be easily inputted into this model to accommodate these price changes, and should shift the results slightly up or down the price scale. The fundamental behavior exhibited should remain the same: recycling costs increase as delivery distance increases, and costs decrease as masa byproduct generation rate increases.

Reuse of organic residuals as livestock feed captures both the energy and nutrient value of these byproducts and, thus, offers important benefits from both economic and environmental perspectives. The cost advantages identified by this study, for both direct shipping and proximity to livestock feeding operations, suggest there is an opportunity for closer integration of food processors and other bio-based industries with livestock producers. This is particularly important for high moisture residual generation, due to both inherent material biodegradability and the high costs for water removal or transport. Organizational strategies, ranging from contractual agreements to cooperative ownership, have historically been used to support such integration in the agricultural and food processing sectors, most recently in the rapidly expanding ethanol industry. Such integration, if structured in an equitable and environmentally sound manner, can offer significant benefits for organic byproduct recycling and reuse.

Acknowledgements

The authors would like to thank the Iowa Biotechnology Byproducts Consortium for financial assistance. Others whose help was essential for the completion of this project include K.P. Rosentrater, for assistance with the economic analysis, and also various equipment vendors for equipment information. This is Journal Paper No. J-19680 of the Iowa Agricultural and Home Economics Experiment Station, Ames, Iowa, Project No. 3465, and supported by Hatch Act and State of Iowa funds.

References

Ackerman F. Recycling: looking beyond the bottom line. BioCycle 1997;38(5):67–70.
AFIA. Feed Manufacturing Technology III, In: R.R. McEllhiney (Ed.), American Feed Industry Association, Arlington, VA, 1985.
Allen DT, Behamanesh N. Wastes as raw materials. In: Allenby BR, Richards DJ, editors. The greening of industrial ecosystems. Washington, DC: National Academy Press, 1994:68–96.
Ayers RU, Ayers LW. Industrial ecology: towards closing the materials cycle. Cheltenham, UK: Edward Elgar Publishing Ltd, 1996.
Bandoni JA, Rotstein E, Romagnoli JA. Simulation modelling and optimal operation of an apple juice concentrate plant. J Food Eng 1988;7(3):159–75.
Barbosa-Canovas GV, Vega-Mercado H. Dehydration of foods. New York, NY: International Thomson Publishing, 1996.
Beers, A.R., Getz, T.J. Composting biosolids saves $3.3 million in landfill costs. BioCycle 1992; 33(5): 42, 76–77.
Beauchat LR. Microbial stability as affected by water activity. Cereal Foods World 1981;26(7):345–9.
Byström S, Lönnstedt L. Paper recycling: a discussion of methodological approaches. Resour, Conserv Recycling 2000;28:55–65.
Bressani R, Paz y Paz R, Scrimshaw NS. Corn nutrient losses: chemical changes in corn during preparation of tortillas. J Agric Food Chem 1958;6(10):770–4.
Clarke WP. Cost-benefit analysis of introducing technology to rapidly degrade municipal solid waste. Waste Manage Res 2000;18:510–24.
Council for Agricultural Science and Technology (CAST). Waste Management and Utilization in Food Production and Processing. CAST, Ames, IA, 1995.
Derr DA, Dhillon PS. The economics of recycling food residuals. BioCycle 1997;38(4):55–6.
EIA. Iowa: Energy Information Administration, 2000a. Available from: http://www.eia.doe.gov/cneaf/electricity/st_profiles/iowa/ia.html (accessed September 9, 2002).
EIA. United States: Energy Information Administration, 2000b. Available from: http://www.eia.doe.gov/cneaf/electricity/st_profiles/us/us.html (accessed September 9, 2002).

EIA. August 2000: Energy Information Administration, 2000c. Available from: http://www.eia.doe.gov/emeu/steo/pub/steotext.html#prices (accessed August 19, 2000).

Federal Reserve. Federal funds daily rates. Federal Reserve Bank of New York, 2000. Available from: http://www.ny.frb.org/pihome/statistics/dlyrates.html (accessed August 19, 2000).

Ferris DA, Flores RA, Shanklin CW, Whitworth MK. Proximate analysis of food service wastes. Appl Eng Agric 1995;11(4):567–72.

Finnveden G, Ekval TL. Life-cycle assessment as a decision-support tool—the case of recycling versus incineration of paper. Resour, Conserv Recycling 1998;24:235–56.

Flores RA, Posner ES, Milliken GA, Deyoe CW. Modeling the milling of hard red winter wheat: estimation of cumulative ash and protein recovery. Trans ASAE 1991;34(5):2117–22.

Flores RA, Posner ES, Phillips R, Deyoe CW. Modeling the economic evaluation of wheat flour milling operations. Trans ASAE 1993;36(4):1143–9.

Fontenot, J.P. Nutrient recycling: the North American experience. In: Proceedings of the 8th World Conference on Animal Production: Special Symposium and Plenary Sessions, pp. 457–468. Seoul National University, Seoul, Korea, 1998.

Glatz BA, Floetenmeyer MD, Hammond EG. Fermentation of bananas and other food wastes to produce microbial lipid. J Food Prot 1985;48(7):574–7.

Glenn J. Marketing food residuals as animal feed. BioCycle 1997;38(4):43–50.

Godfrey T. Effluent, byproduct and biogas. In: Godfrey T, Reichelt J, editors. Industrial enzymology: the application of enzymes in industry. New York, NY: Nature Press, 1983:294–304.

Goldstein N. Composting the commercial organic stream. BioCycle 1992;33(5):46–52.

Gomez MH, Rooney LW, Waniska RD, Pflugfelder RL. Dry corn masa flours for tortilla and snack food production. Cereal Foods World 1987;32(5):372–7.

Gonzalez de Palacios, M. Characteristics of corn and sorghum for tortilla processing. Unpublished M.S. Thesis. Texas A&M University, College Station, TX, 1980.

Gonzalez-Martinez S. Biological treatability of the wastewaters from the alkaline cooking of maize (Indian corn). Environ Technol Lett 1984;5(8):365–72.

Graedel TE, Allenby BR. Industrial ecology. Englewood Cliffs, NJ: Prentice Hall, 1995.

Gunjal K, Owusu-Manu M, Ramaswamy HS, Amankwah F. Minimal processing of fish and pork in Quebec: a financial feasibility study. Can Agric Eng 1999;41(4):247–51.

HSH Associates. ARM indices: The prime rate. HSH Associates, Financial Publishers, 2000. Available from: http://www.hsh.com/indices/prime.html (accessed September 9, 2002).

Huang W. A framework for economic analysis of livestock and crop byproducts utilization. Am J Agric Econ 1979;61(1):91–6.

Johnson M, Carlson WL. Calculating volume-based garbage fees. BioCycle 1991;32(2):48–50.

Jones BJ. Composting food and vegetative waste. BioCycle 1992;33(3):69–71.

Hyde MA, Consolazio GA. Composting of food processing waste sludges. BioCycle 1982;23(1):58–60.

Kashmanian, R.M., Kluchinski, D., Richard, T.L., Walker, J.M. Quantities, characteristics, barriers, and incentives for use of organic municipal by-products. pp. 127–167. In: J. F. Power, W. A. Dick (Eds.), Land Application of Agricultural, Industrial, and Municipal Byproducts. Soil Science Society of America, Madison, WI, 2000, p. 653.

Katz SH, Hediger ML, Valleroy L. Traditional maize processing techniques in the new world. Science 1974;184(4138):765–73.

Khan MN, Des Rosiers MC, Rooney LW, Morgan RG, Sweat VE. Corn tortillas: evaluation of corn cooking procedures. Cereal Chem 1982;59(4):279–84.

Krause VM, Tucker KL, Kuhnlein HV, Lopez-Palacios CY, Ruz M, Solomons NW. Rural-urban variation in limed maize use and tortilla consumption by women in Guatemala. Ecol Food Nutr 1992;28(4):279–88.

Kuchenrither RD, Martin WJ, Smith DG, Psaris PJ. An economic comparison of composting and dual utilization. BioCycle 1984;25(5):33–7.

Lahey Computer Systems, Inc. 1995. LP77 Personal FORTRAN v. 3.00. Lahey Computer Systems, Inc., Incline Village, NV.

Liu MC, Flores RA, Deyoe CW, Posner ES. Assessment of a computer simulation model for the flour-milling industry. Cereal Foods World 1992;37(8):649–54.

Logsdon G. Pomace is a grape resource. BioCycle 1992;33(2):40–1.

Luzier JM, Summerfelt RC. Partial replacement of fish meal with spray-dried blood powder to reduce phosphorous concentrations in diets for juvenile rainbow trout, Oncorhynchus mykiss (Walbaum). Aquacult Res 1995;26(8):577.

Martins SN, Guzman EC. Effect of drying method of bovine blood on the performance of growing for tambaqui (Colossoma macropomum, Curier 1818) in experimental culture tanks. Aquaculture 1994;124(1–4):335–41.

McCartney DM. An analysis of the costs of the collection and debugging systems for residential yard (garden) waste used in Canada. Waste Manage Res 1998;16(4):389–400.

McConnell CR. Economics principles, problems, and policies. New York, NY: McGraw-Hill Book Company, 1987.

McEllhiney RR. Shrink control in feed manufacturing. In: McEllhiney RR, editor. Feed manufacturing technology III (Chapter 65). Arlington, VA: American Feed Industry Association, 1985:522–7 (Chapter 65).

Mercier C, Linko P, Harper JM, editors. Extrusion cooking. St. Paul, MN: American Association of Cereal Chemists, 1989.

Minsa, Corporate Information-Manufacturing. Minsa Southwest Corporation, 2000. Available from: http://www.minsa.com/english/htm/ci-man.htm (accessed January 17, 2002).

National Research Council (NRC). Biobased Industrial Products: Priorities for Research and Commercialization. National Academy Press, Washington, DC, 2000.

Ortiz EL. The cuisine of Mexico: corn tortilla dishes. Gourmet 1985;45:62–3.

Parades-Lopez O, Saharopulos-Parades ME. Maize—a review of tortilla production technology. Bakers Dig 1983;57(5):16–25.

Pflugfelder RL, Rooney LW, Waniska RD. Dry matter losses in commercial corn masa production. Cereal Chem 1988;65(2):127–32.

Polanski J. Legalizing the feeding of nonmeat food wastes to livestock. Appl Eng Agric 1995;11(1):115–9.

Price AT, Derr DA, Suhr JL, Higgins AJ. Food waste recycling through swine. BioCycle 1985;26(2):34–7.

Ramirez-Wong B, Sweat VE, Torres PI, Rooney LW. Cooking time, grinding, and moisture content effect on fresh corn masa texture. Cereal Chem 1994;71(4):337–43.

Rooney LW, Serna-Saldivar SO. Food uses of whole corn and dry-milled fractions. In: Watson SA, Ramstad PE, editors. Corn chemistry and technology. St. Paul, MN: American Association of Cereal Chemists, 1987:399–430.

Rosentrater KA, Flores RA, Richard TL, Bern CJ. Physical and nutritional properties of corn masa byproduct streams. Appl Eng Agric 1999;15(5):515–23.

Rosentrater, K.A. Developing value-added processing techniques for corn masa processing byproduct streams. Unpublished Ph.D. Dissertation. Iowa State University, Ames, IA, 2001.

Schulte DD, Kroeker EJ. The role of systems analysis in the use of agricultural wastes. J Environ Qual 1976;5(3):221–7.

Serna-Saldivar SO, Gomez MH, Rooney LM. Technology, chemistry, and nutritional value of alkaline-cooked corn products. Adv Cereal Sci Technol 1990;10:243–306.

Shambaugh JA, Mascaro P. Composting organics at a military base. BioCycle 1997;38(1):45–9.

Smith RN, Houslay P, Whitaker A. Recycling of food wastes—microbiology and economics. J Appl Chem 1974;24(6):376–7.

Solganik H. A toast to tortillas. Food Process 1997;58(11):64–5.

Sonesson U, Dalemo M, Mingarini K, Jönsson J. ORWARE—a simulation model for organic waste handling systems, part 2: case study and simulation results. Resour, Conserv Recycling 1997;21:39–54.

Sonesson U. Modelling of waste collection—a general approach to calculate fuel and time consumption. Resour, Conserv Recycling 1998;28:335–48.

Sonesson U, Björklund A, Carlsson M, Dalemo M. Environmental and economic analysis of management systems for biodegradable waste. Resour, Conserv Recycling 2000;29:29–53.

Stapleton J, Morreale J, Kiviat E. No landfill space for apple waste. BioCycle 1984;25(3):46–7.

Steuteville R. Food residues become community asset. BioCycle 1992;33(4):56–7.

TFC. Soybean meal (CBOT) weekly price chart. TFC Commodity Charts, 2000. Available from: http://www.futures.tradingcharts.com/chart/SM/W.html (accessed August 19, 2000).

Tortilla Industry Association (TIA). Tortilla consumption continues to grow in U.S. and abroad. Tortilla Industry Association, 2001. Available from: http://www.tortilla-info.com/prrevenue98.htm (accessed September 9, 2002).

Trenkle, A., Ribeiro, C. Evaluation of a mixture of corn steep liquor and distillers solubles as a replacement for corn and supplement in cattle finishing diets, 1999. A.S. leaflet R1630, 1999 Beef Research Report, Iowa State University, Ames, IA. Available from: http://www.extension.iastate.edu/Pages/ansci/beefreports/ (accessed September 9, 2002).

Trenkle, A. Relative feeding value of wet corn steep liquor when fed to finishing cattle, 2002. A.S. Leaflet R1773, 2001 Beef Research Report, Iowa State University, Ames, IA. Available from: http://www.extension.iastate.edu/Pages/ansci/beefreports/ (accessed September 9, 2002).

Vallini G, Bianchin ML, Pera A, De Bertoldi M. Composting agro-industrial byproducts. BioCycle 1984;25(4):43–51.

Velasco-Martinez M, Angulo O, Vazquez-Couturier DO, Arroyo-Lara A, Monroy-Rivera JA. Effect of dried solids of nejayote on broiler growth. Poultry Sci 1997;76(11):1531–4.

Vellinga P, Berkhout F, Gupta J. Managing a material world: perspectives in industrial ecology. Dordrecht, The Netherlands: Kluwer Academic Publishers, 1998.

Wang L, Flores RA, Johnson LA. Processing feed ingredients from blends of soybean meal, whole blood, and red blood cells. Trans ASAE 1997;40(3):691–7.