CHAPTER 24

Producing Hydrated Bioethanol from Cassava

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Introduction

Bioenergy, and biofuels in particular, have become priority topics on the research and development agenda of world agriculture. Their significance lies in their enormous potential towards overcoming problems related to using the world's oil reserves such as shrinking volumes, growing use, price increases, and increasing emissions of greenhouse gases with resultant climate change. Bioenergy can also help answer the growing urgency to promote sustainable socioeconomic development. In particular, it can provide farmers with additional employment and incomes opportunities.

The world is demanding economic and social sustainability from the various biofuel production systems currently operating. Although the technology for producing bioethanol has partially met these expectations, the same cannot be said of other components of biofuel production systems. Most ethanol-producing systems are characteristically based on monocultures (e.g., sugarcane and maize), which create serious environmental problems in terms of biodiversity loss, excessive use of water, and generation of considerable quantities of effluents with high potential for contamination. Furthermore, to implement these systems, large investments are required, thus preventing rural communities of few resources from participating and benefiting from these technologies. Indeed, such communities, usually found in developing countries, suffer severe increases in food prices that put them at risk of reduced food security and increased poverty.

A major reason for giving priority to the generation of bioenergy and the use of biofuels on the global agricultural development agenda is the possibility that these technologies can become strategies for reducing poverty and overcoming the social inequalities that exist in many developing countries. More than 2000 million people around the world are estimated to lack access to any modern energy source (UNDP 2004). Hence, production technologies, and the use and marketing of biofuels, must be designed and implemented to help rural communities of few resources minimize their dependence on fossil energy, and permit a more equitable distribution of the benefits available along the entire agricultural production chain for biofuels.

Rural Social Biorefineries: An Approach to Small-Scale Biofuel Production

Since 2006, CLAYUCA has been implementing a research and development project to establish a technological platform for processing hydrated ethanol at the level of small rural communities. The raw materials used were cass ava (*Manihot esculenta* Crantz), sweet potato (*Ipomoea batatas* (L.) Lam.), and sweet sorghum (*Sorghum bicolor* (L.) Moench).

This initiative, called Rural Social Biorefineries (RUSBI)[5], seeks to promote the development of rural communities of few resources and located in the marginal regions of Latin America and the Caribbean (LAC). The idea is to produce and use a biofuel—

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5. For an explanation of this and other abbreviations and acronyms, see *Appendix 1: Acronyms, Abbreviations, and Technical Terminology*, this volume.

hydrated ethanol—as the starting point for establishing a level of agroindustrial development that will have a social impact on these regions. That is, it will help farmers stimulate the economies of their regions, create productive employment and opportunities for income, increase security of energy, food, agriculture, and improve their families' quality of life (CIAT 2011).

The local production and use of hydrated ethanol is the principal focus of the RUSBI approach. It involves five technological components (Figure 24-1), and integrates modern concepts of agronomic management, processing engineering, and effluent management. The strategy is to promote, in marginal regions, self-sufficiency in energy, agricultural development, and food security (Figure 24-1).

The CLAYUCA research on bioethanol production from cassava began in 2006 with a project financed by the Ministry of Agriculture and Rural Development (MADR, its Spanish acronym) of Colombia. The MADR's support enabled the construction and operation of a prototype processing plant for hydrated ethanol. In this project, evaluations were also carried out to assess the potential of different cassava varieties as raw materials for ethanol processing.

Several private- and public-sector groups showed interest in bioethanol production from cassava, including farmers, businesses, universities, and research centers, both national and international. They were given firsthand access to the technologies developed (Ospina et al. 2008).

Based on preliminary results, a small biorefinery was established in 2009 at CIAT's facilities in Palmira, Colombia. Technological support was received from Usinas Sociais Inteligentes (USI, a Brazilian private enterprise) and the Universidade Federal do Rio Grande do Sul (UFRGS, Brazil) (Patino et al. 2009). Figure 24-2 shows the equipment used in the rural social biorefinery, including (1) a plant to dry and refine the flours of cassava and sweet potato, and a plant to mill sweet sorghum; (2) a pilot plant to produce hydrated ethanol (96%) at a capacity of 10 to 20 L/h; and (3) a plant to treat effluents. Other equipment used in the biorefinery included a stationary plant to generate bioelectricity from hydrated ethanol and an ethanol-fueled stove for cooking (Figure 24-3).

The small-scale operational prototype for processing hydrated ethanol was inexpensive to construct, operate, and maintain. It is based on the use of saccharine (e.g., sweet sorghum) and/or amylaceous (e.g., cassava and

1. Sustainable and competitive cassava production
2. Evaluation of processing technologies for obtaining fermentable biomasses
3. Development of a model pilot plant to produce bioethanol
4. Evaluation of local uses for hydrated ethanol
5. Sustainable management of wastes and effluents generated during processing

Self-sufficiency in energy

Agricultural development

Food security

Figure 24-1. Technological components of the Rural Social Biorefinery (RUSBI) approach.

Figure 24-2. Equipment used in the Rural Social Biorefinery (RUSBI) established at CLAYUCA.

"Clean-cook" stove

Energy generator

Flex tek kit

Vehicle powered by ethanol from cassava

Figure 24-3. Validated uses of hydrated ethanol biofuel.

sweet potato) bioenergy crops as sources of substrata. During 2009–2011, the prototype was evaluated, its operation validated, and adjustments made to perfect the process.

CLAYUCA is now attempting to disseminate the model to rural communities that have limited access to electrical power, are highly dependent on fossil fuels, and, usually, depend entirely on agriculture for subsistence and income. The pilot plant's installations can be used for demonstrations and training activities for groups of farmers and technicians from Colombia and other countries in LAC, as well as other regions in the world facing similar problems.

The RUSBI approach (Figure 24-4) could have high impact on LAC's marginal regions. Biofuel production from energy crops would provide access to electrical power and thus open up opportunities for establishing value-added processing of crops such as flour and starch products for human and animal consumption or industrial use, and organo-mineral fertilizers for restoring soils and improving crop yields.

Producing Bioethanol

Figure 24-5 illustrates how hydrated ethanol is produced from cassava, using the RUSBI methodology. The cassava crop is among the richest sources of fermentable substrata for ethanol production, having high starch content (between 70% and 85%, dry basis).

To produce bioethanol, cassava roots are first converted into flour, after which, during biomass pretreatment, water is added. The resulting liquid biomass is known as starch milk. At this stage, incubation environmental conditions (pH and temperature) must be adjusted for the next stages: hydrolysis and fermentation. This stage can also be carried out with fresh cassava roots, which are very finely grated to facilitate the later stages of hydrolysis and fermentation. When fresh cassava roots are used, less water is needed, as root water content is used. However, the mash obtained after fermentation must be filtered, as it has high fiber content. Also, when cassava flour is used instead of fresh roots, drying leads to two byproducts that can be sold for use in animal feed, thus helping to reduce the additional costs for the energy needed to convert roots into flour.

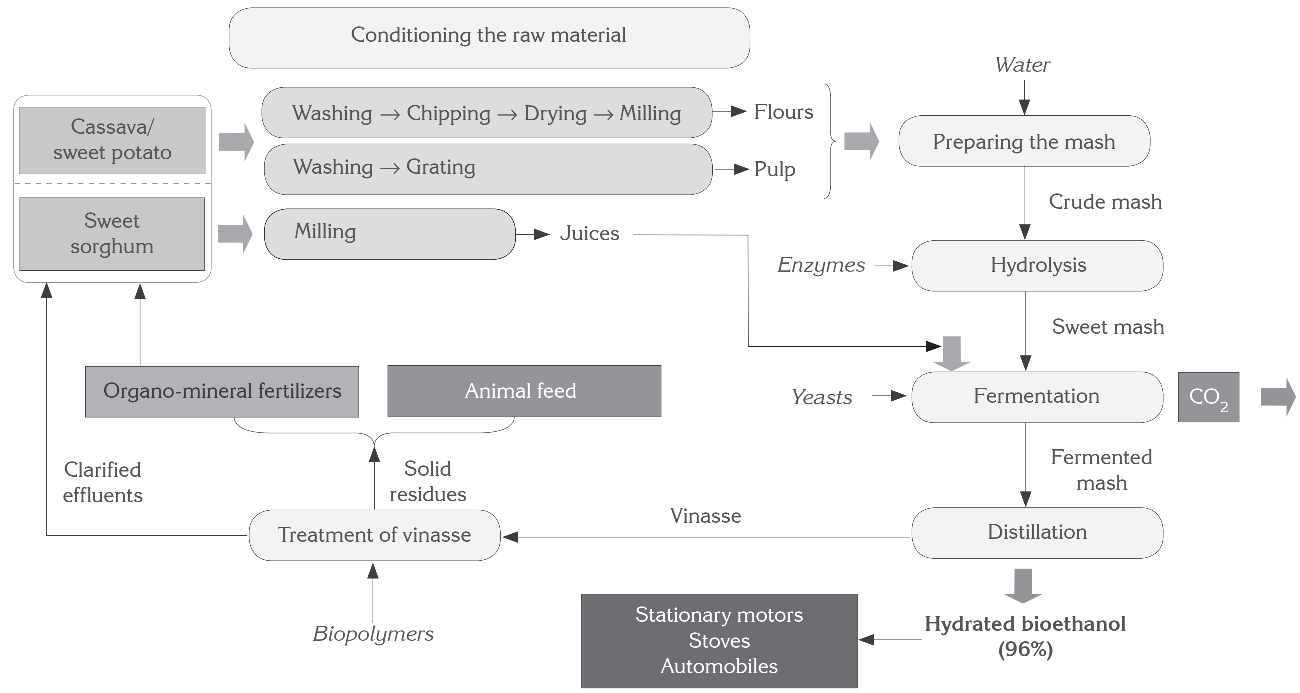

Figure 24-4. Schematic concept of the RUSBI approach, showing procedures, inputs, and products.

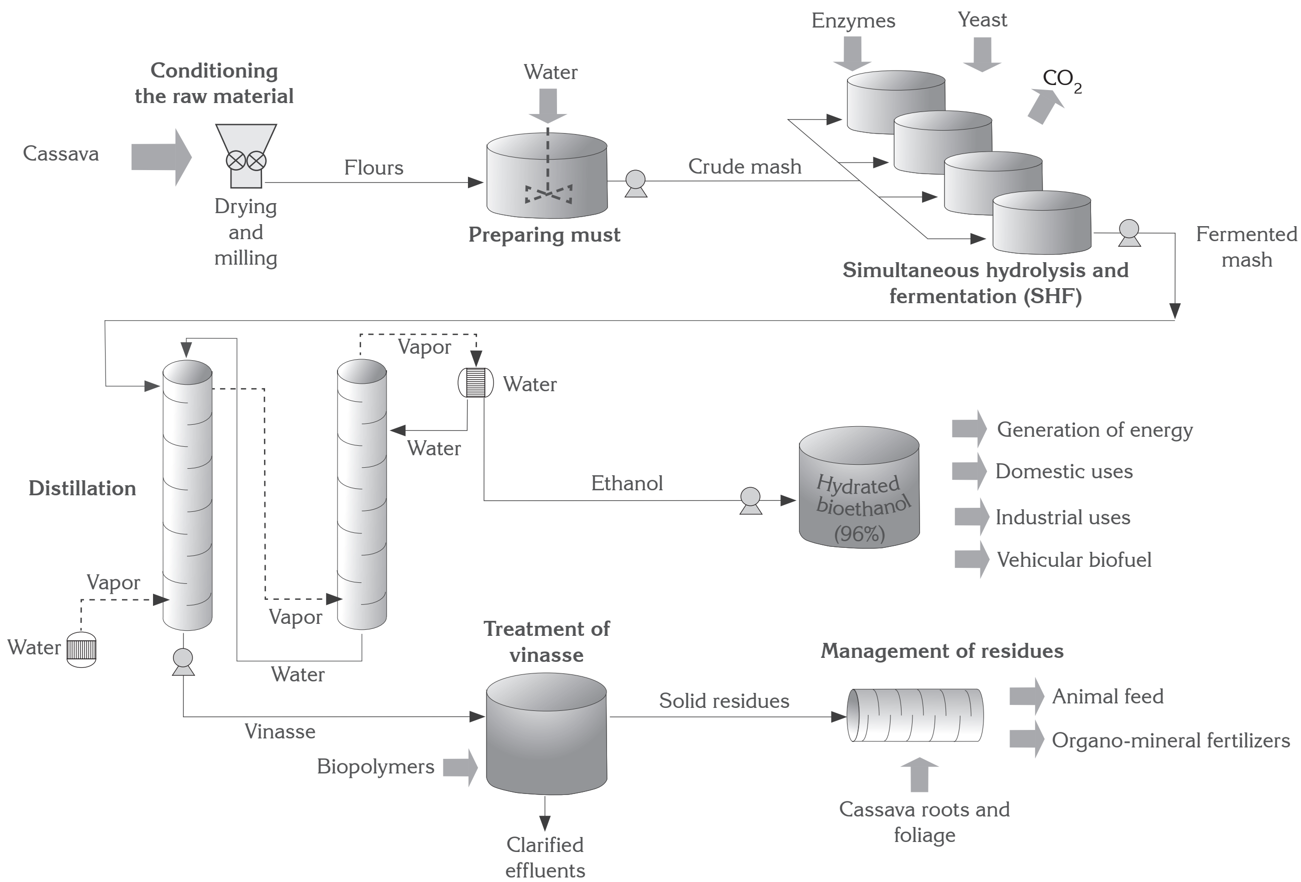

Figure 24-5. Flow chart for the production of hydrated ethanol from cassava.

Hydrolysis is a significant phase in the process. It transforms starches into fermentable sugars, which are then metabolized and assimilated by yeasts during fermentation, thus generating ethanol. Enzymatic hydrolysis, or saccharification, breaks up the large starch molecules to obtain units of glucose. Glucose syrups or sweet mash are obtained from starch through the liquefaction and later saccharification of starch. Two methods of hydrolyzing starch can be used:

1. *Liquefaction, saccharification, and conventional fermentation (LSF)*. The starch is first liquefied, then converted into glucose (i.e., saccharified), and, finally, fermented, using the yeast *Saccharomyces cerevisiae* (Figure 24-6).

   Heat-stable enzymes used for liquefaction and saccharification are, respectively, alpha-amylose and glucoamylase. Table 24-1 describes the

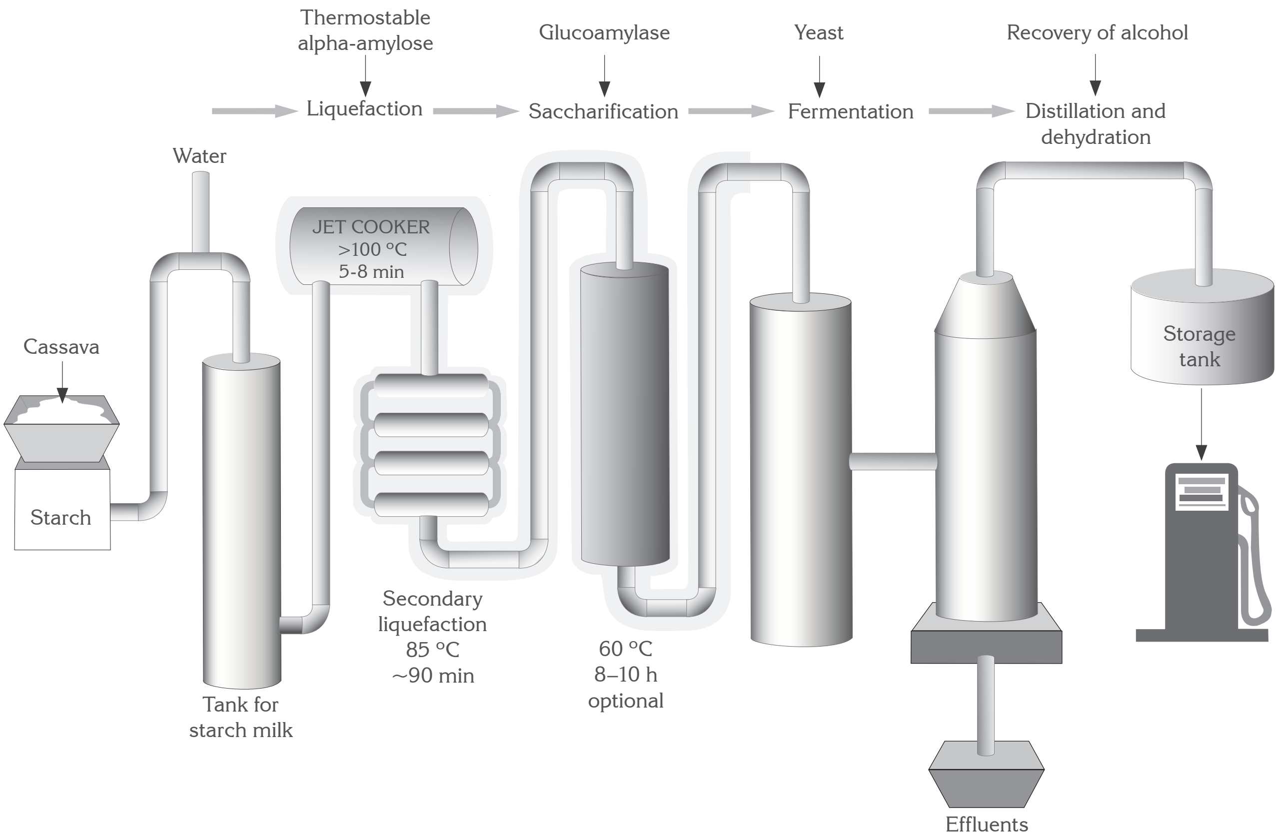

Figure 24-6. Conventional process for producing bioethanol from cassava (from Genencor International, a Danisco company; see www.genencor.com).

Table 24-1. Operating conditions for the hydrolysis and fermentation of organic biomass in conventional processing and simultaneous hydrolysis and fermentation (SHF) processing.

Conventional processing:			
Condition	Hydrolysis (liquefaction, followed by saccharification)		Fermentation
T (°C)	82–86	65–70	32
pH	5.7–6.0	4.3	4.5
SHF processing:			
Condition	Hydrolysis (liquefaction + saccharification)		Fermentation
T (°C)	30–33		30–33
pH	4.0–4.5		4.5

operating conditions conventionally used with this method.

2. *Simultaneous hydrolysis and fermentation (SHF)*. A mixture of enzymes allows the saccharification and liquefaction processes to occur simultaneously (Figure 24-7).

   This method uses STARGEN™ enzymes (which enable hydrolysis at low temperatures) and combines saccharification and fermentation within a single stage, because the enzymes function under the same conditions of temperature and pH as does the yeast (i.e., *S. cerevisiae*). Table 24-1 indicates the operating conditions used with this method.

In the RUSBI methodology to produce bioethanol, CLAYUCA used the SHF method to reduce processing time, energy consumption, and installation costs (i.e., no need to install a heating system for the mash). The end product of the SHF process—fermented mash—was distilled at 78 °C, and its steam—ethanol—captured and condensed. The distillation products were therefore ethanol at 96% purity and an organic liquid byproduct known as vinasse. Finally, the hydrated ethanol was evaluated as a biofuel in suitably adapted equipment, selected for being commonly used by rural communities such as kitchen stoves, electrical power generators, and other motors (Figure 24-3).

The validated uses of hydrated ethanol as a biofuel produced from the cassava crop will help rural communities have access to electrical power, enabling them to establish processing enterprises to add value to their crops, and thus link with markets that will afford them higher incomes and improved food security and quality of life.

Bioethanol Production Trials

The preliminary results obtained by CLAYUCA for cassava variety evaluation in ethanol production showed that enormous potential exists to exploit the crop's genetic diversity and improve the processing of cassava biomass into ethanol. Considering the average value of starch found in the varieties analyzed, we could estimate a theoretical value of 220 L/t and determine an experimental value of 118 L/t to convert biomass into ethanol. This means that real processing efficiency represented only 54% of the theoretical potential (Table 24-2; Arriaga 2008).

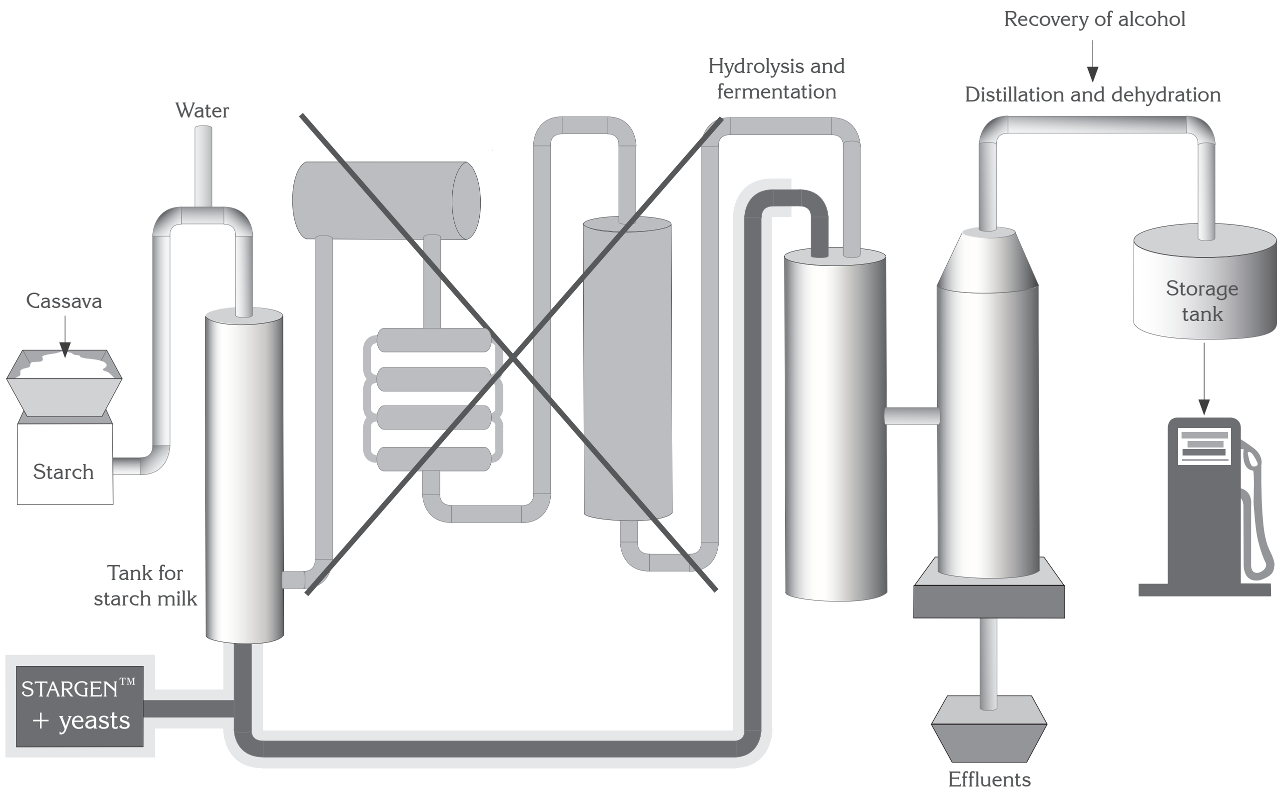

Figure 24-7. Simultaneous hydrolysis and fermentation (SHF) (from Genencor International, a Danisco company; see www.genencor.com).

Table 24-2. Comparing cassava varieties for ethanol production.

Variety	Production (t/ha)	Starch (%)	Theoretical conversion (L/t)	Real conversion (L/t)	Efficiency (%)	Ethanol production (L/ha)
CM 4574-7	25	32.3	230.6	118 .0	51	2950
CM 6438-14	26	33.3	237.8	129.8	55	3374
M TAI 8	29	31.6	225.6	129.1	57	3743
Verónica	29	29. 0	207.1	99.9	48	2897
Ginés	27	27.9	199.2	114. 7	58	3096
Average	27 ± 1. 8	31 ± 2. 3	220 ± 16. 3	118 ± 12.2	54 ± 4.2	3212 ± 350

More recent work carried out on the CLAYUCA biorefinery model aimed to optimize the enzymatic hydrolysis of the starch present in cassava (Cajamarca 2009). The efficiency of bioethanol production from cassava flour was also estimated at a pilot scale by calculating the balances of materials and energy in the process (Martínez 2009). Table 24-3 presents trials carried out with cassava flour in the pilot plant, using the SHF method at room temperature.

According to the results shown Table 24-3, the best results were for Trial 3. Yields were 372.5 L of ethanol per ton of flour, and 106.4 L per ton of fresh roots. These values are slightly lower than those reported in the literature (Vinh 2003; Atthasampunna et al. 1990). A relatively low value (61%) was also obtained for the efficiency of the process in terms of real ethanol production versus the theoretical conversion. This implies the presence of polluting agents, especially during fermentation, which either reduced or limited the fermentative glycolysis of ethanol.

Table 24-4 shows the results of two trials with fresh cassava roots, using the same conditions of simultaneous hydrolysis and fermentation at room temperature.

Initially, in the real results of hydrated ethanol production from fresh cassava roots, no notable

Table 24-3. Results of three trials for producing hydrated bioethanol from cassava flour at the CLAYUCA pilot plan.

	Trial		
	1	2	3
Raw materials			
Refined flour (kg)	75	86	120
Enzymes (STARGEN™) (kg)	0.375	0.428	0.600
Yeast (Ethanol Red®) (kg)	0.250	0.286	0.400
Urea (kg)	0.175	0.200	0.300
Water (kg)	400	400	400
Generated product			
Hydrated ethanol at 96%, v/v (L)	21.8	27.3	44.7
Quantitative analyses[a]			
Total production (liters of ETOH)	21.8	27.3	44.7
Yield (L ETOH per ton of flour)	290.7	317.4	372.5
Yield (L ETOH per ton of roots)[b]	83.1	90.7	106.4
Yield (L ETOH per hectare)[c]	2076.4	2267.4	2660.0
Efficiency in production of ETOH[d]	48%	52%	61%
Ratio of vinasse to ethanol (v/v)	25.3	19.81	14.1

a. ETOH refers to hydrated ethanol at 96% (v/v).
b. Conversion factor for fresh cassava roots to refined flour is 3.5:1.
c. Average yield of cassava roots is 25 t/ha.
d. Calculated as the ratio of real production to theoretical conversion.

Table 24-4. Results of two trials on hydrated bioethanol production from fresh cassava roots at the CLAYUCA pilot plant.

	Trial 1	Trial 2
Raw materials		
Fresh cassava roots (kg)	300	300
Enzymes (STARGEN™) (kg)	0.380	0.380
Yeast (Ethanol Red®) (kg)	0.500	0.500
Urea (kg)	0.300	0.300
Water (kg)	300	450
Generated product		
Hydrated ethanol at 96%, v/v (L)	48	48
Quantitative analyses[a]		
Total production (liters of ETOH)	48	48
Yield (L ETOH per ton of roots)	160	160
Yield (L ETOH per hectare)[b]	4000	4000
Efficiency in production of ETOH[c]	89%	89%
Ratio of vinasse to ethanol (v/v)	13.6	16.7

a. ETOH refers to hydrated ethanol at 96% (v/v).
b. Average yield of cassava roots is 25 t/ha.
c. Calculated as the ratio of real production to theoretical conversion.

variation is observed for the treatments tested, resulting in a production of 160 L for 1 t of fresh roots. For Trial 1, 13.6 L of vinasse were obtained per liter of ethanol, indicating that the quantity of effluents produced per liter of ethanol was reduced. This aspect is of utmost importance, as the disposal or management of these effluents is critical in ethanol production.

Furthermore, Del Ré et al. (2010) conducted an experiment at CLAYUCA/CIAT to evaluate the effect of the amount of water used to produce ethanol and effluents. Six fermentation tanks, each having a capacity of 1000 L, were used in a randomized complete block experiment design replicated over time, with four replications per treatment. Results showed a 37.5% reduction in the amount of water used (i.e., from 800 to 500 L), a 107% increase of ethanol production (i.e., from 21.75 to 44.94 L), and a 33% increase in processing yield (i.e., from 268.8 to 357.5 L/t) (Table 24-5).

Results for processing yield, using less water in the fermentation tanks, were 62% higher than the theoretical value estimated for the evaluation of cassava varieties (357 versus 220 L/t). They were very close to the values used internationally to evaluate ethanol production from cereal grains (400 L/t) (Jansson et al. 2009).

The 37.5% drop in the amount of water used reduced the ratio of vinasse to ethanol by 44% (25.34 versus 14.09 L/L) ($P < 0.05$) (Table 24-5). These results are highly significant as the competitiveness of the biofuel chain in small agribusinesses is highly sensitive to the management of generated effluents, as additional resources must be used to manage them according to the environmental standards in force.

Analyses of the hydrated bioethanol produced (Table 24-6) demonstrated that this is a crude redistilled alcohol of industrial use. It can be easily converted into a neutral rectified alcohol that meets technical standards for pharmaceutical and potable use.

Table 24-5. Production of ethanol (L), yield of ethanol (L/t of dry matter), and quantity of vinasse generated per liter of produced bioethanol.

	Treatment[a]		
	1	2	3
Raw materials			
Refined flour (kg)	150	150	150
Enzymes (STARGEN™) (kg)	0.714	0.714	0.714
Yeast (Ethanol Red®) (kg)	0.500	0.500	0.500
Urea (kg)	0.350	0.350	0.350
Water (kg)	800	700	500
Generated product			
Hydrated ethanol at 96%, v/v (L)	21.75 b	27. 28 b	44.94 a
Quantitative analyses[b]			
Total production (liters of ETOH)	21.75 b	27.28 b	44.94 a
Yield (L ETOH per ton of flour)	268.80 b	306.60 ab	357.50 a
Ratio of vinasse to ethanol (v/v)	25.34 b	19.81 ab	14.09 a

a. Values in the same row with different letters are significantly different, Tukey's at 5%.
b. ETOH refers to hydrated ethanol at 96% (v/v).

Table 24-6. Characteristics of hydrated bioethanol produced in the CLAYUCA pilot plant.

Characteristic	Unit	Specification ANP[a]	Result
Aspect	—	Clear[b]	Clear
Color	—	Colorless to yellow	Colorless
Total acidity (e.g., acetic acid), max.	mg/L	30.0	17.0
Alcoholic percentage	% (v/v)	93.2 ± 0.4	91.3
pH	—	6.0 to 8.0	
Aldehydes (e.g., acetaldehyde), max.	mg/L	60	29
Esters (e.g., ethyl acetate), max.	mg/L	100	47.3
Methanol, max.	mg/L	500	No data
Higher alcohols, max.	mg/L	500	163.8

a. National Petroleum Agency (ANP, its Portuguese acronym).
b. Clear in color and free of water or materials in suspension.

Energy Balance

Figure 24-8 shows the energy balance for producing 250 L of hydrated ethanol. The electrical power consumed by equipment is recorded according to operating time for producing cassava flour and ethanol, and the thermal energy required for the boiler to generate steam.

Total energy consumption indicates that the consumption of electrical power was 95.3 kWh or 342.9 MJ (1 kWh = 3,600,000 joules = 3.6 MJ), while thermal energy consumption, as according to the wood consumed, was 3932.5 MJ. In short, total energy consumption (electrical + thermal) to produce 250 L of hydrated ethanol was 4275.4 MJ. Consequently, energy consumption for processing 1 L of ethanol at the biorefinery is 17.1 MJ/L.

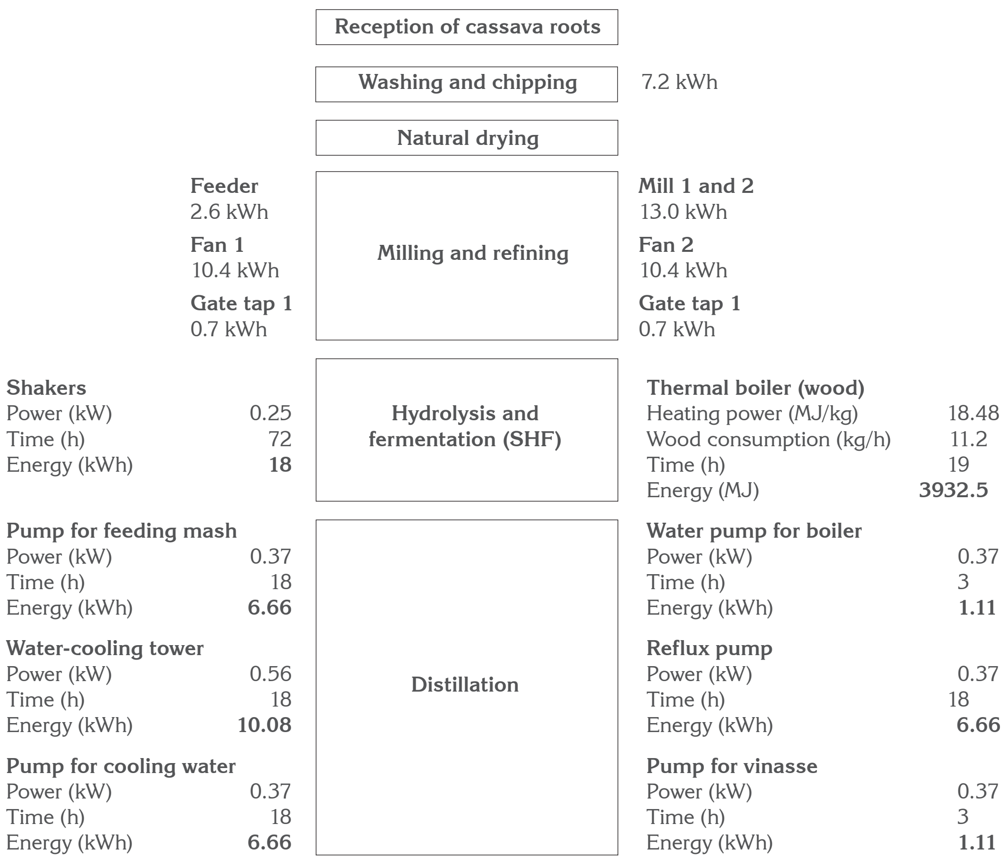

Figure 24-8. Energy balance for producing 250 liters of hydrated bioethanol at the CLAYUCA biorefinery.

If we assume a value of 1.54 MJ/L for the principal agronomic operations to produce 1 L of ethanol from cassava (Assis 2008), a total value (i.e., agronomic + industrial consumption) of 18.64 MJ/L is reached. This indicates that if we obtain 23.375 MJ from 1 L of ethanol, then the rate of return for energy is positive at 1.25.

Costs of Producing Hydrated Bioethanol

Based on the data obtained for the CLAYUCA biorefinery model (500 L/day), total production costs for hydrated ethanol (96%, v/v) was US$1.34/L. This includes the costs of raw materials, processing, depreciation, and maintenance, as well as the possible profits derived from the sale of byproducts (Table 24-7).

Finally, Gomes (2010) evaluated the technical and economic viability of implementing a biorefinery (500 L/day) in three rural areas of Colombia with problems of self-sufficiency and/or high energy costs: Puerto Carreño, La Macarena, and Leticia. The study concluded that the project was not viable in Puerto Carreño and Leticia, as production costs of ethanol were not competitive with the prices of local fuels brought in at low cost from Venezuela and Brazil, respectively. In contrast, in La Macarena, the project could indeed be viable, depending on the cost of gasoline and the possibility of tax exemption (Table 24-8). Moreover, the study concluded that if a biorefinery were implemented in La Macarena, it would provide 0.5% of the rural population with access to electrical power and that 7.3% of the volume of gasoline currently sold in the rural area could be mixed at 30% with ethanol.

The study also recommended that, to improve the project's efficiency, improved cassava varieties must be introduced and technological improvements in converting cassava into ethanol must be identified. Also, farmers should receive training and support, and their associations or small groups should be promoted.

Table 24-7. Estimate of the costs of producing hydrated bioethanol from cassava at the CLAYUCA pilot plant.

Item	Cost (US$)[a]	
	(per liter)	(%)
Raw materials		
Cassava roots (US$0.055/g)	0.51	38.0
Flour production		
Electricity	0.02	1.5
Labor	0.06	4.5
Ethanol production		
Water	0.01	0.7
Electricity	0.02	1.5
Wood	0.04	3.0
Reagents	0.41	30.6
Labor	0.06	4.5
Subtotal for process	**1.13**	
Sale of byproducts[b]	-0.08	
Depreciation, maintenance[c]	0.29	15.7
Total production costs	**1.34**	100.0

a. US$1.00 = Col$ 1800 in 2010.
b. Cost recovery through sale of byproducts (375 kg at US$0.11/kg).
c. Depreciation: 5 years at 250 days/year; maintenance: annual at 4.

Managing Effluents

When hydrated ethanol is being produced as a biofuel from cassava, one aspect of considerable environmental and energy sensitivity is the huge quantity of effluents resulting from the process. On average, for every liter of ethanol obtained, 10 to 15 L are generated of an effluent, known as vinasse. As described previously, vinasse is the organic liquid byproducts resulting from the fermentation of carbohydrates (e.g., sugarcane juice and molasses or cassava starch milk) and later distillation of the fermented mash. The composition of vinasse is variable and depends on the characteristics of the raw materials (e.g., cassava flour or fresh cassava roots) used to produce the alcohol, and on the type and efficiency of fermentation and distillation (CIAT 2011).

Vinasse is usually made up of water, mineral salts, organic matter, residual yeast, and non-fermentable constituents. Table 24-9 presents the bromatological composition, *in vitro* dry matter digestibility, organic matter content, and starch content of vinasse obtained from fermenting fresh cassava roots. Table 24-10 indicates the mineral concentration (dry basis).

Table 24-8. Data for current gasoline prices, potential market, and costs of biofuel for each of three regions in Colombia.

Site	Potential market (L/year)	Current gasoline price (US$/L)	Cost of ethanol (US$/L)
Puerto Carreño	1,364,000	0.92	1.14
La Macarena	4,548,000	1.41	1.19
Leticia	6,503,640	1.17	1.21

Table 24-9. Bromatological composition (%) of vinasse produced during the processing of cassava into bioethanol.

Crude protein	Ash	Ether extract	Crude fiber	Moisture	IVDMD[a]	OM[b]	Starch
11.60	5.23	4.86	60.35	8.49	64.70	93.52	0.74

a. IVDMD refers to *in vitro* dry matter digestibility.
b. OM refers to organic matter.

Table 24-10. Mineral contents present in vinasse produced during the processing of cassava into bioethanol.

P	K	Ca	Mg	S	Zn	B	Mn	Fe	Cu	Al	Na
		(%)						(ppm)			
1.42	1.49	5.38	0.40	0.48	40.4	15.5	104.5	3305.1	14.2	3120.6	38,398.2

Mineral concentrations in vinasse from cassava processing are low except for Ca (5.38%), limiting their use as an individual product. García and Rojas (2006) reported that these effluents are deficient in elements, implying low fertilizer power. To supply crop needs, large quantities must therefore be applied. However, they are extremely acid and have a high electrolytic concentration, which may favor their use over other byproducts.

Most of the chemical components of vinasse are chelants, enabling the formation of organic complexes with nitrogen and other minerals of greater bioavailability for animal nutrition. However, vinasse also contain typical chemical components, including soluble inorganic substances (particularly ions of K, Ca, and SO_4), dead yeast cells, organic substances resulting from the metabolic processes of yeasts and polluting microorganisms, alcohol and residual sugars, insoluble organic substances, and volatile organic substances.

Vinasse is one of the most polluting organic wastes for the planet's flora and fauna, as they present high organic matter contents, which are measured in terms of chemical oxygen demand (COD) and biological oxygen demand (BOD). Values range from 24,635 to 65,457 and 26,500 to 33,600 mg of O_2 per liter, respectively. Effluents also contain high concentrations of fixed soluble solids (1400 to 2000 mg/L), low electrical conductivity (2.6 to 4.2 mS/cm), very low pH (3.6 to 3.8), high concentrations of phenols (478 to 541 mg gallic acid equivalents/L), absence of a buffer capacity because of low pH, and contents of phosphates and sulfates that range between 290 and 1705 mg/L, and 308 and 946 mg/L, respectively (Robles and Villalobos n.d.).

The principal problems are that, for each hectoliter (hL) of ethanol produced, about 15 hL of vinasse are obtained as residues (Lezcano and Mora 2008). Because of its high production, storing this byproduct is not easy. Hence, in many places, the effluents are poured directly on to the soil and/or into water sources without treatment, polluting large extents of surface and ground water and heavily affecting the environment.

With the growth in the production and use of biofuels, the search for methods to treat and use vinasse has increased. This means that technologies for their use are available, such as fertilizer applications; production of biogas, compost, unicellular protein (i.e., SCP), and animal feed; energy generation; brick production; concrete reinforcement; and production of chemical compounds. Technologies for managing vinasse include recirculation to reduce volumes to 2 L of effluents per liter of ethanol, with 60% total solids content, thus facilitating transport, storage, and use.

Concentrating vinasse by evaporation has high energy cost and requires chemical compounds to periodically wash the system to eliminate deposits of non soluble salts in the evaporation tubes. Another technology for treating vinasse is methanization or anaerobic degradation, which not only removes more than 90% of the BOD and 70% of the COD, but also generates methane gas, which can be used as fuel. A further alternative is composting for use as fertilizer. This use, despite being more environmentally friendly, demands high levels of capital, area, and time to operate.

To treat and use effluents generated in ethanol production, no simple techniques of bioremediation (filtration) are available that comply with environmental standards, as the particle sizes of most of the solids found in solution are extremely fine. In the RUSBI methodology, vinasse is treated with biopolymers. These electrically charged chemical compounds are prepared from starch, and are used to guarantee the controlled release of nutrients from fertilizers, reduce erosion, increase the penetration of water into soil, and improve the germination rate of seeds.

When biopolymers come into contact with solutions carrying high loads of ionic solids and basic pH, they foster flocculation and later coagulation of these loads. After the organic matter in the effluents flocculates and coagulates and the resulting sludge is removed, the clarified liquids may be used for other activities in the distillery or irrigation.

To flocculate and coagulate vinasse, the biopolymers used are prepared to a concentration of 1000 ppm and added to the effluents, generating clarification. The products obtained are called clarified vinasse and clarified sludge. Figure 24-9 illustrates the decanting of solids from the effluents, and Table 24-11 lists the nutrient contents present in each clarified product, from sugarcane biofuel processing (Patino et al. 2007).

CLAYUCA in collaboration with Soil Net–Polymer Solutions (a private U.S. company in Madison, WI, USA; www.soilnetllc.com) and the Universidade Federal do Rio Grande do Sul (UFRGS, Porto Alegre, Brazil),

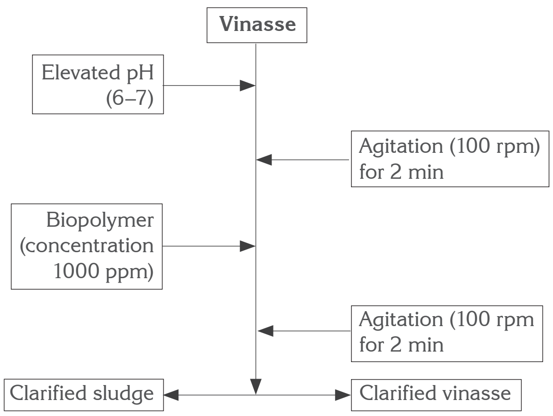

Figure 24-9. Sequence of clarification of vinasse, using biopolymers.

generated new ecological alternatives for managing wastes generated by alcohol distilleries at the national level. One was to process cassava products (i.e., roots and foliage) on an industrial level, together with vinasse. That is, they are incorporated into protein and energy supplements for ruminants, or are prepared fertilizers from agroindustrial residues of cassava production. The effluents and substrate wastes can therefore be used for irrigation and soil fertilizer applications, and the production of compost, biogas, yeasts, and animal feed (Figure 24-10).

The first efforts were directed towards preparing solid organo-mineral fertilizers (Tables 24-12 and 24-13 and Figure 24-11). Table 24-13 shows the values, obtained in laboratory, for the chemical composition of organo-mineral fertilizers prepared from vinasse produced during cassava processing, plus the addition of minerals, cassava wastes, and polymers. Because

Table 24-12. Experimental formula of an organo–mineral fertilizer based on vinasse produced during the processing of cassava into bioethanol.

Raw material	Inclusion (%)	Contribution (%) of:		
		N	P_2O_5	K_2O
Vinasse	15.80	0.27	0.51	0.80
Cassava wastes	25.00	0.10	—	—
Urea	20.00	9.20	—	—
KCl	19.00	—	—	9.50
Triple superphosphate	20.00	—	9.20	—
Polymer	0.20	—	—	—
Total	**100.00**	**9.57**	**9.71**	**10.30**

Table 24-13. Chemical composition (%) of an organo–mineral fertilizer, based on crop wastes and vinasse produced during the processing of cassava into bioethanol.

Moisture	Ash	C	N	P	K	Ca	Mg	Total S
9.22	28.58	30.10	6.48	6.04	1.26	6.55	0.33	0.40

Table 24-11. Nutrient contents present in vinasse and clarified byproducts formed during the processing of sugarcane into bioethanol.

Description	Total P	Total K	Total Ca	Total Mg	S	Fe	Cu	Na	Zn	Protein (%)	OM[a] (%)
			(%)				(mg/kg)				
Sugar cane vinasse	2.97	10.24	0.88	1.14	1.23	986.0	6.0	3066.0	54.0	6.95	56.83
Clarified sugar cane vinasse	0.00	1.06	0.48	0.12	0.14	32.0	0.0	366.0	3.0	0.81	6.79
Sugar cane clarified sludge	2.75	2.99	14.26	0.20	9.30	525.0	47.0	467.0	19.0	5.15	27.51

a. OM refers to organic matter.

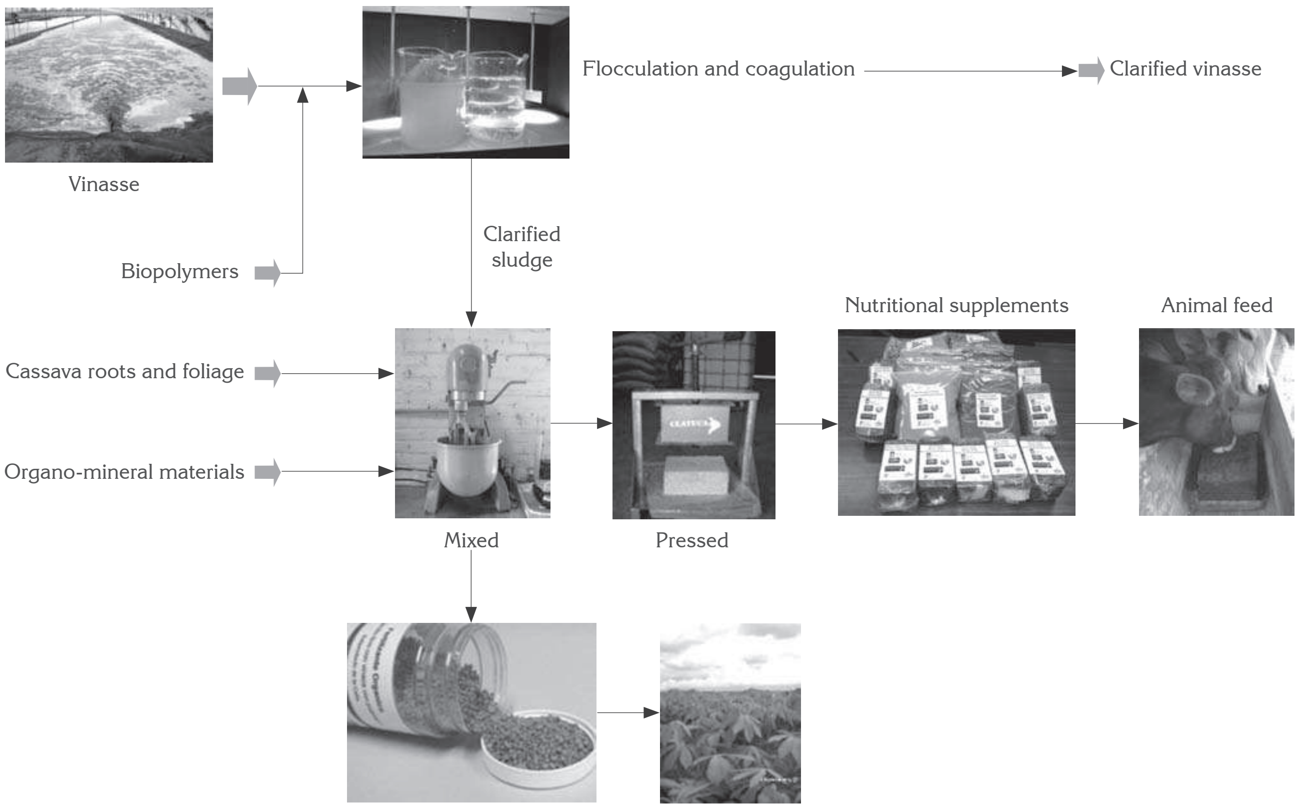

Figure 24-10. Management of wastes and effluents in the RUSBI methodology, established at CLAYUCA.

Figure 24-11. Final appearance of the organo-mineral fertilizer produced from crop wastes and vinasse produced during the processing of cassava into bioethanol.

the mineral contents of the vinasse are low, minerals must be added to the end product.

Animal feed prepared from vinasse has been mostly directed towards ruminants and, to a lesser extent, pigs and poultry. For cattle, the vinasse is used as a raw material to prepare nutritional supplements, which may have various presentations according to the type of production. Organic matter is sourced from vinasse, other byproducts, derivatives, and leaves, stems, and bagasse from sweet potato, cassava, and sweet sorghum. These, together with urea, minerals, and additives, are incorporated into supplement preparations for ruminants (Figure 24-12).

Table 24-14 presents the results of bromatological analyses of the prepared supplements (protein-mineral and energy-mineral), using the strategy described above.

Nutritional blocks prepared from vinasse and wastes of ethanol production are highly palatable to animals (Torres 2010). They also present high levels of *in vitro* dry matter digestibility (ranging between 71 and 78%), which is very attractive to the national market. When levels of crude protein increase in vinasse, this may be attributed to the presence of yeast wastes. These enrich the product, enhancing its value (Loaiza 2008).

The microbiological quality of prepared supplements made from vinasse is adequate, according to Loaiza (2008) and Torres (2010). Their observations of the products under different storage conditions suggested that their microbiological quality complied with the guidelines established by the Colombian Institute of Agriculture (ICA, its Spanish acronym, and entity that governs the standardization of animal feed in Colombia; see www.ica.gov.co). That is, the products, stored under conditions established by the Good Manufacturing Practices for Animal Feed (BPFA, its Spanish acronym), maintained acceptable microbiological status for 40 days.

Adding protein-mineral supplements in feed for calves (Gil et al. 2007) and young bulls (Campos et al. 2007) consuming poor quality feed led to liveweight gains of between 350 and 550 g/day. This is similar to gains obtained with the more costly commercial supplements found on the market.

Table 24-14. Bromatological composition (%) of supplements for ruminants and prepared from byproducts, derivatives, and effluents of ethanol production.

Nutrient	Protein		Energy	
	Block	Salt	Block	Salt
Dry matter	78.01	93.44	78.99	94.15
Organic matter	67.59	59.43	67.67	65.04
Protein	33.07	39.51	9.61	17.20
Fat	0.82	2.20	1.30	1.59
TDN[a]	65.54	64.26	69.91	65.54

a. TDN refers to total digestible nutrients.

Conclusions

The goal of a Rural Social Biorefinery (RUSBI) is to use several types of biomass (e.g., cassava, sweet potato, and sweet sorghum) to produce ethanol for energy generation and, at the same time, use the various derivatives and wastes generated to obtain a range of byproducts, thus maximizing the added value of the raw materials.

Partial results from studies conducted by CLAYUCA in Colombia to evaluate cassava in the production of hydrated ethanol suggested that enormous potential exists. The cassava crop's genetic diversity must be explored and the processing of the biomass into ethanol in the pilot plant optimized. Further, more detailed, studies are needed on the balance of mass and energy and on bioeconomic efficiency to define energy expenditure and the cassava crop's economic viability as a raw material for ethanol production.

The economic and environmental sustainability of the RUSBI will depend on the correct use of byproducts and wastes generated by the process. Hence, more studies are needed to characterize these materials and propose alternative uses.

Nutritional blocks Pellets Meal

Figure 24-12. Animal feed products manufactured from crop wastes, byproducts, and vinasse produced during the processing of cassava into bioethanol.

The incorporation of the biorefinery concept into biofuel production has high potential to revitalize social-inclusion programs, adding value to products, and fostering the socioeconomic development of family agriculture. Hence, the RUSBI approach obviously implies the inclusion of sustainability of the environment and the socioeconomic development of rural communities where such biorefineries are established.

Rural social biorefineries can, in the future, become key components for the development of integrated production models for food, raw materials, feed and fuels, especially at the level of small rural communities located in marginal areas and with little access to conventional energy sources.

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