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Sustainable Biorefinery Approach for Cassava: A Review

N.M.L. Fernando, A.P.S.M. Amaraweera, O.H.P. Gunawardane, W.M.D.B. Wanninayaka, A. Manipura, W.A.R. Manamperi, C.A. Gunathilake and K.M.A.K. Kulathunga

Abstract: Biorefineries combine essential technologies between bio-based raw materials, intermediate products, and final products. Cassava is considered to be one of the major food crops in Sri Lanka, which has numerous industrial applications. Besides, cassava plant can be cultivated at a lower cost with relatively low labour and fertilizer. There are many industrially relevant products which can be developed using cassava tubers and plant as main ingredients; they are starch (about 20% by w/w), fibre, cellulose, and hemicellulose. The applications of the cassava plant range from food, feed, textile, pharmaceutical, detergent, alcohol, organic acids, glucose, and bio-plastic industries. Moreover, the waste generated during the production of cassava-based products, including wastewater, bagasse, pulp, etc., can be converted into valuable products such as biofuel, organic acids, biosurfactants and biochemicals via bioprocessing. Therefore, cassava plant should be explored to fully maximize its potential as an industrial crop for interested entrepreneurs to provide economic and environmental sustainability to cassava-based industries in Sri Lanka. This paper presents more effective and efficient conversion processes for converting the cassava root, leaves and stem into high-value products. Therefore, maintenance of sustainability during production is also analysed in cassava-based industries with prime importance.

Keywords: Biorefinery, Cassava plant, Product; Sustainability, Waste management

1. Introduction

1.1 Biorefinery Systems

Sustainable economic growth requires safe and sustainable resources for industrial production [1]. Environmental safety, sustainable life and safe working places for the public can be achieved by renewable natural resources [2]. Fossil resources are not sustainable, and the average annual oil prices per barrel for Organization of the Petroleum Exporting Countries (OPEC) crude oils have varied from 40 to 110 USD during the past ten years [3]. Therefore, it is important to seek solutions which reduce the consumption of fossil resources such as petroleum, natural gas, coal, minerals etc., which are not renewable [2].

An oil refinery mostly generates transport fuels and energy, and only a relatively small fraction for chemical products such as plastics and fertilizer, etc. [2]. Therefore, in a petrochemical refinery, a number of value-added products are manufactured using crude oil and their related derivatives. Similar to crude oil refinery, a biorefinery is a facility that joins biomass conversion processes and equipment to produce fuels and energy such as bioethanol, biodiesel, biogas and hydrogen, and chemicals and biopolymers from biomass [2][4].

*Eng. **N.M.L. Fernando**, B.Sc. Eng. (Hons) (Moratuwa), Research Assistant in Faculty of Engineering, University of Peradeniya Sri Lanka, Email:nimashamf@gmail.com*
https://orcid.org/0000-0002-4176-4854
***Mrs. A.P.S.M. Amaraweera**, B.Tech. (Special) (Uva Wellassa University), Research Assistant in Faculty of Engineering, University of Peradeniya Sri Lanka, Email:sumedha.sma@gmail.com*
https://orcid.org/0000-0002-6572-7804
***Miss. O.H.P. Gunawardane**, B.Sc. Eng. (Hons) (Peradeniya), Research Assistant in Faculty of Engineering, University of Peradeniya Sri Lanka, Email:hishendri1995@gmail.com*
https://orcid.org/0000-0001-9745-1665
***Mr. W.M.D.B. Wanninayaka**, B.Sc. Eng. (Hons) (Peradeniya), Research Assistant in Faculty of Engineering, University of Peradeniya Sri Lanka, Email:darshana.wanninayaka1992@gmail.com*
https://orcid.org/0000-0003-3541-5153
***Dr. A. Manipura**, B.Sc. Eng. (Peradeniya), M.Eng. (Moratuwa), Ph.D. (South Africa), Senior Lecturer in Faculty of Engineering, University of Peradeniya Sri Lanka, Email:amanipura@yahoo.com*
https://orcid.org/0000-0003-0372-9289
***Dr. W.A.R. Manamperi**, B.Sc. Eng. (Moratuwa), M.Sc. (Moratuwa), Ph.D. (USA), Senior Lecturer in Materials Engineering Department, California Polytechnic State University, USA Email:wmanampe@calpoly.edu*
***Dr. C.A. Gunathilake**, B.Sc. Special (Hons) (Peradeniya), Ph.D. (USA), Senior Lecturer in Faculty of Engineering, University of Peradeniya Sri Lanka, Email:chamilag@pdn.ac.lk*
https://orcid.org/0000-0001-7912-3940
***Prof. K.M.A.K. Kulathunga**, B.Sc. Eng. (Hons) (Peradeniya), Ph.D. (Australia), Senior Lecturer in Faculty of Engineering, University of Peradeniya Email:aselakk@eng.pdn.ac.lk*
https://orcid.org/0000-0002-9241-3149

Basic principles of a biorefinery are illustrated in Figure 1. Oil crops (such as soybean, sunflower, rape, palm, and jatropha), sugar crops (such as sugarcane and beet), starch crops (such as corn, potato, wheat, cassava, and sorghum), woody plantation (such as hardwoods and softwoods), grasses and herbs (such as switch grass and alfalfa), can be used as the feedstock to develop biorefinery [2][5].

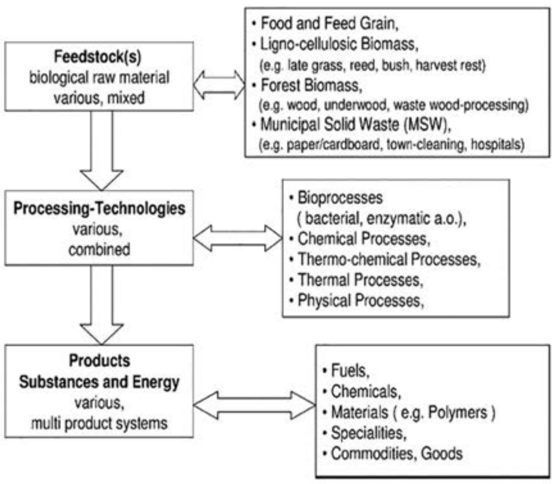

Figure 1 - Basic Principles of a Biorefinery [2]

Recent advances have prompted this review on exploring the development of a biorefinery based on cassava plant in order to add more value to the whole plant of this low value crop in Sri Lanka. Therefore, this review focuses on industrial uses of cassava, utilization of cassava as a biorefinery feed stock in order to convert the cassava root, leaves and stem into high-value products, waste management processes, and finally, the problems and challenges associated with cassava-based biorefinery system.

1.2 Cassava Plant

Cassava (*Manihot esculenta* Crantz) is one of the major tuber crops grown in more than 80 countries. Cassava is usually referred to as "manioca" in Latin America, "manioc" in Madagascar and French-speaking Africa, "tapioca" in India and Malaysia, "cassava" or "cassada" in English-speaking regions in Africa, Thailand, and Sri Lanka [6].

1.3 Morphology of Cassava Plant

The cassava plant is a woody shrub and it reaches 2 to 4 m in height. The principal parts of the mature cassava plant are leaves, stem and storage roots (tubers), and the percentages of them are 6%, 44%, and 50%, respectively, from the whole plant. The roots and leaves contain nutrition which is used as a feed source. Roots are the main storage part in a cassava plant and only few fibrous roots become tubers and the majority continue their function of nutrient absorption [7]. The protein and starches are produced by the cassava leaves. The stems transfer the produced food to different plant parts for the development and growth. There are three types of roots in cassava plant which are classified as thick roots, tuberous roots, and fine white roots. The thick roots help attaching the plant to the ground while the tuberous roots store carbohydrates and the fine white roots absorb nutrients and water [8].

Every plant has 5 to 20 starchy stretched tubers and they are 5–10 cm in cross sectional diameter and 20–80 cm long. The weight of the tuber is 4-7 kg. There is a significant difference in the chemical composition of cassava root and leaves due to variety, age of plant and processing technology. There are more than 7000 cassava varieties and the number and size of tubers is highly variable between cultivars and growing conditions [7][9].

1.4 Harvesting and Production Capacities of Cassava

The cassava plant is believed to have originated in Brazil, from where it spread to the rest of Latin America and then to Africa, brought by Portuguese colonizers [6]. Cassava cultivation areas are increasing rapidly because it grows easily at the expense of minimum labour and fertilization, has large yields and is little affected by diseases and pests. The cassava farming areas have increased by 91.7% and cassava production has increased globally by 67.83% during the past 30 years. In 2019, the annual production of cassava in the world was more than 303 million tons. Nigeria has produced the world's largest cassava production which was 59 million tons in 2019 [10]. Cassava farms spanned more than 27 million hectares in over 105 countries in 2019 [10] [11]. In Asia, cassava is produced in Thailand, Indonesia, Cambodia, Viet Nam, China, India, Philippines, Laos, Myanmar, Sri Lanka, and Malaysia [10]. Cassava is now grown widely as a food crop or for industrial purposes as the industrial utilization of cassava roots is increasing [6].

1.5 Cassava Cultivation in Sri Lanka

In 1796, Mauritius introduced cassava to Sri Lanka [12]. Cassava cultivation is abundant in Sri Lanka due to its ability to grow in any kind of soil. In traditional farming, 5-6 t/ha cassava yield can be obtained without fertilizers, on soils that would not support other crops. However, on easily crumbled, light textured and well-drained soils containing sufficient moisture and a balanced amount of plant nutrients, 40-60 t/ha cassava yield can be obtained [6] [13].

Farmers grow cassava as a backyard crop in the wet zone (Figure 2) in Sri Lanka and the area cultivated as a backyard crop varies from 100-1000 plants per farmer. Those backyard crops are rarely fertilized and the root yields depend on the soil conditions, hence the cultivation cost of cassava is negligible [14].

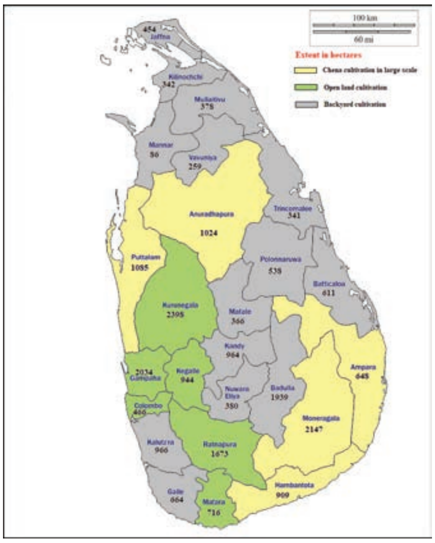

Figure 2 - Extents of Cassava Crop – 2018

In most cassava harvesting systems, planting material is not purchased, land is not prepared specially for cassava planting and inorganic fertilizer is not applied. But fertilizers such as Urea, TSP (Triple Super Phosphate) and MOP (Muriate of Potash) are recommended by Horticultural Crop Research and Development Institute (HORDI), Sri Lanka (Cassava, n.d.). Three improved cassava varieties named MU-51 (var. Peradeniya), CARI-555 and Kirikawadi which have high yield are recommended by HORDI for cultivation [13]. Mean yield of cassava has increased during the past years in Sri Lanka as shown in Figure 3.

2. Usage of Cassava Plant

Most important industrial uses of cassava plant are glue production, pharmaceutical products, confectionery, spices, textile, dry cell batteries, paper cartons, animal feed, biodegradable products and toothpaste [15]. The demand for cassava for bioenergy sectors has arisen as the cassava utilization for production of ethanol is expanded. Development and increase in use of cassava for production of ethanol helped the incremental demand of cassava for bioenergy. Using one ton of cassava, 280 litres of ethanol with a purity of 96% can be produced [16].

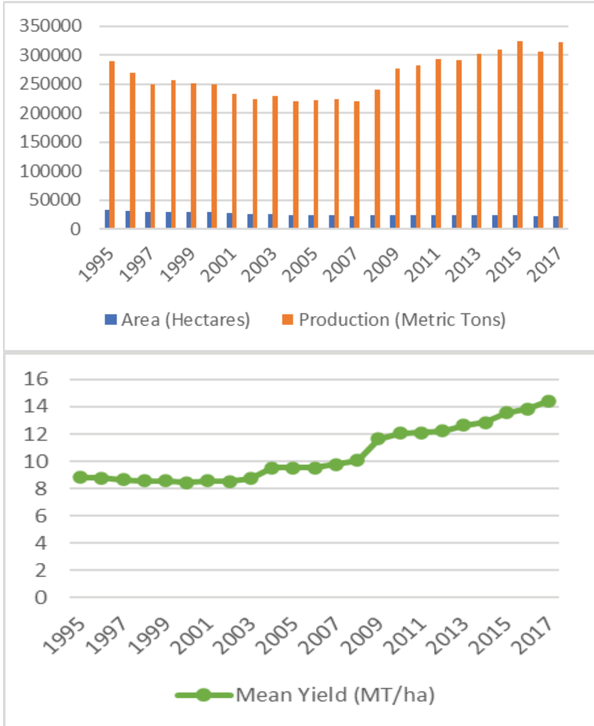

Figure 3 - Area, Production, and Yield of Cassava in Sri Lanka [13]

Leaves of the cassava plant can be eaten as a vegetable or in a soup. They can also be dried and given as feed to animals for extra protein. Cassava leaves can be used to produce biofuel as well as fertilizer.

The cassava roots can be eaten after cooking. The cassava roots can be processed into many valuable end products such as: cassava starch which can be added as an ingredient for making paper and clothing textiles; cassava flour which can be used to make cakes, bread, and biscuits; cassava chips which can be used for animal feed; ethanol which can be used as biofuel when combined with additives; and fructose which is used in industry for sweetening fizzy drinks [15]. In contrast, cassava stem can be used as material for biofuel and to produce partisan boards.

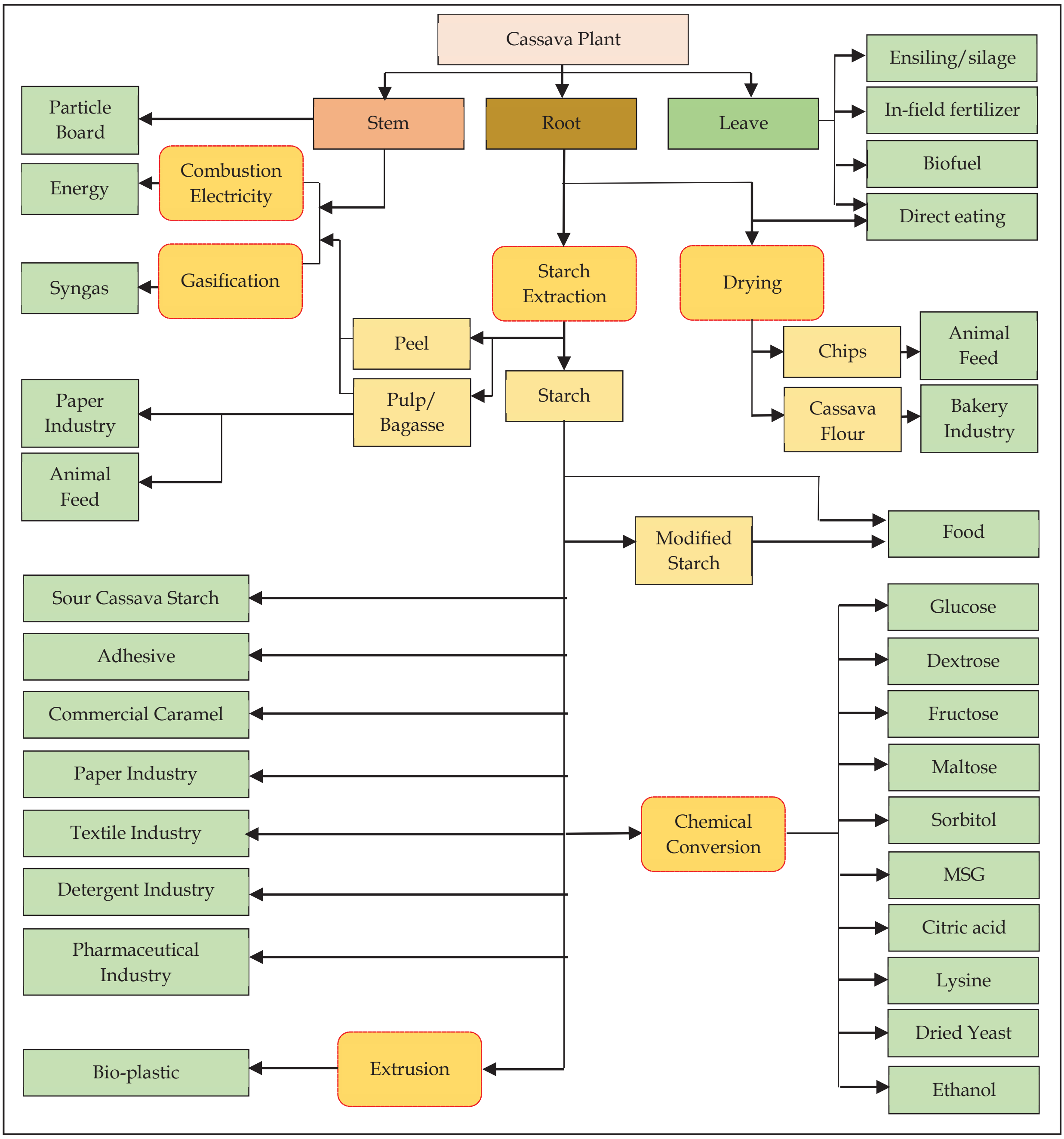

Figure 4 – Biorefinery Based on Cassava Plant

2.1 Cassava Plant-based Biorefinery

Cassava plant and the wastage produced by cassava-based industries can be converted into various value-added products. Figure 4 represents the biorefinery based on cassava plant. The production processes for each product are described in the rest of this paper.

2.2 Cassava as a Food Source

Cassava roots contain high energy and high levels of some vitamins, minerals and dietary fibre and contain no trypsin inhibitor when comparing with other tuber crops. In 100g tubers, 160 kcal energy can be found in cassava while potato contains 69 kcal, sweet potato contains 86 kcal and yam contains 118 kcal [17]. The cyanide presence in the roots is removed by post-harvest treatments and cooking.

Cassava is classified into sweet and bitter flavours and only the varieties with sweet flavours are grown. Cassava is a very nutritious food for toddlers and especially for underweight children because it contains a high starch content. Cassava leaves are edible and they are a good source of protein, vitamins and minerals. Cassava leaves are rich in calcium and vitamin C. Cassava tubers as well as cassava leaves are very good for cancer and worm diseases. Cassava flour also helps to control blood cholesterol levels because it is free of gluten and cholesterol. Cassava contains iron which reduces the risk of anaemia. Cassava contains 'vitamin K' which helps to increase bone strength. Potassium in cassava protects humans from high blood pressure. Cassava is reported to have the potential to cure many eye-related issues. The antioxidants in cassava help to relieve fatigue and stress. Cassava being a high-fibre food, alleviate constipation and facilitates proper digestion [13].

2.3 Cassava Starch in Food Industry

Starch is produced from a variety of raw food materials such as wheat, potato, sweet potato, maize, rice, cassava, sago palm and waxy maize. Starches from different food materials have different granular structures which affect their physical properties. Starches are mostly consumed in food applications in food industries. Also, large quantities of small packages of starch are sold in the market for household cooking. Corn, potato, rice, cassava and wheat are the major commercially produced starch and they have been categorized as gluten-free starch which suits well for people with allergies towards gluten [18]. Figure 5 illustrates the production process of cassava starch from cassava tubers [19].

A case study done by Aji et al. [20] reported cassava starch yield based on 50 ton of cassava as raw material. By processing 50,000 kg cassava roots, 10,706 kg amount of cassava starch could be produced and the yield was 21.412%. Total 31% cassava rods were removed in root cutting process. Sand and peels (25% from cassava tubers) were removed during washing stage. About 120 m^3 fresh water was used for the process. Production capacity of selected plant was 10 ton of cassava starch using cassava roots about 50 tons. Production process runs 7 hours daily with average 40 workers.

Unmodified starch and modified starch are used in the food industry either as food products or additives for thickening, preservation and quality enhancer in baked foods, confectioneries, pastas, soups and sauces, and mayonnaises. In confectioneries, starch is used mainly for manufacturing of gums, pastes and other types of sweets as an ingredient, in the making of moulds or for dusting sweets to prevent them from sticking together. Starch is used for biscuits to increase volume and crispness of the products. Cassava starch is used in biscuit and cream sandwich manufacturing in Malaysia. Adding 5% to 10% cassava starch to biscuits softens texture, reduces stickiness of biscuit and adds distinctive taste [6].

Cassava starch has low protein content, but it is a good source in forming soft and transparent gel. Cassava starch is highly suitable for food industry due to its lack of smell, clarity of paste and stickiness [21]. Sour cassava starch can be used in bread/pastry production or as an alternative for gluten-free bread. Sour cassava starch is produced by chemical and enzymatic

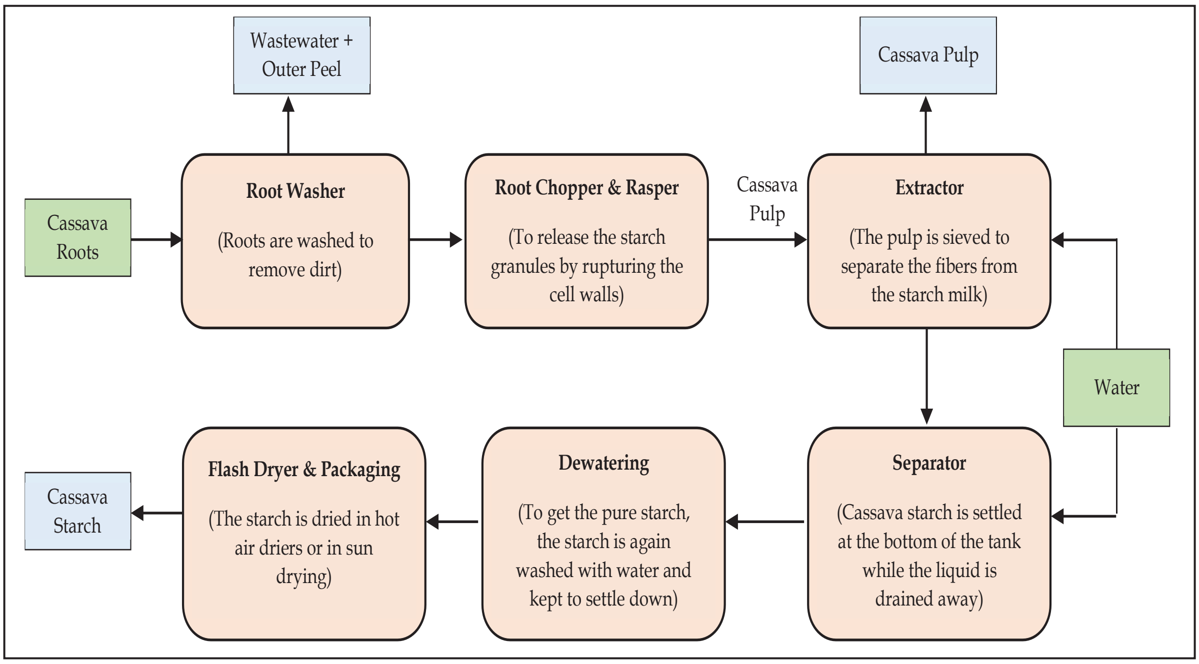

Figure 5 – Cassava Starch Production Process [19]

modification through a predominantly natural fermentative process [22]. In manufacturing Brazilian cheese bread, sour cassava starch is widely used, as bread can be made without the addition of baking soda [23]. Cardenas and Buckle [21] have described the production process of sour cassava starch.

Modified starch is produced mostly by physical and chemical methods. Physical modification methods such as superheating, dry heating, osmotic pressure treatment, multiple deep freezing and thawing, instantaneous controlled pressure-drop process, stirring ball milling, vacuum ball milling, pulsed electric fields treatment, corona electrical discharges, etc., are simple and cheap; whereas chemical modification consists of introducing new functional groups into the starch molecules changing the physicochemical characteristics. Chemical modification is mostly performed through chemical derivatization, such as etherification, esterification, acetylation, cationization, oxidation, hydrolysis, and cross-linking. These modification methods are used to produce different types of modified or converted starch to obtain starch with appropriate physicochemical characteristics such as gelatinization, retrogradation, heat stability, solubility, transmittance, colour, texture, etc., for different industrial applications [24]. Table 1 and Table 2 show lists of specific modified starches used in various food systems and applications.

2.4 Baked Cassava Products

Tapioca fancies or tapiocas are the commercial baked products which use cassava flour as the basic ingredient. These products are also known as 'sago products' in Malaysia. Tapioca fancies are manufactured in different shapes and forms in medium and larger scale factories all around the world. Irregular shape lumps are named as flakes and perfectly round beads are called seeds or pearls which are also commonly known as 'sago'. Lastly, residual tapioca flour is named as grist.

Partially gelatinized cassava starch, which is obtained by heat treatment of the moist flour in shallow pans, is used for making tapioca fancies. When cassava starch is heated, the wet granules gelatinize, burst, and stick together. The mass is stirred to prevent scorching.

Table 1 - Roles of Starches in Various Food Systems [25]

Function	Foods
Adhesion	Battered and breaded foods
Binding	Formed meat, snacks seasonings
Clouding	Beverages
Crisping	Fried and baked foods, snacks
Dusting	Chewing gum, bakery products
Emulsion stabilization	Beverages, creamers
Encapsulation	Flavours, beverage clouds
Expansion	Snacks, cereals
Fat replacement	Ice cream, salad dressings, spreads
Foam stabilization	Marshmallows
Gelling agents	Gum drops, jelly gum centres
Glazing	Bakery, snacks
Moisture retention	Cakes, meats
Thickening	Gravies, pie fillings, soups

Quality of the cassava flour is very important for baked products. To obtain high quality white flour, sulphurous acid can be added in the first sedimentation, however this chemical should be washed out as completely as possible by a second sedimentation in clean water. If any acid is left in the flour, it will spoil the quality of the end product. Active chlorine preparation methods should not be used because it influences the accumulation of the starch into pearls and other forms.

During manufacturing of tapioca fancies, gelatinization is kept at a moderate temperature to make sure gelatinization only occurs in the surface layer of the lumps of moist starch. Gelatinization is the process where starch undertakes a radical modification in molecular arrangement, with a concomitant change in properties. Starch becomes an amorphous substance from a practically insoluble product of semicrystalline structure, miscible with water in any proportion at suitable high temperatures, giving viscous solutions. This viscous solution becomes a semisolid elastic mass just like a jelly or gel, after cooling. Cassava starch gelatinization occurs at about 60 °C, and the process is completed at about 80 °C. Modern technology performs gelatinization with the direct application of steam to ensure uniform gelatinization. Final drying process should be followed after gelatinization to bring down the moisture level to about 12%. The temperature may be raised to 60-70 °C for 1 1/2-2 hours to obtain the final product[6].

Table 2 - Chemical Modification Processes of Starch and their Food Applications [24]

Chemical treatment	Function	Food application
Acid hydrolysis	Reduce hot-paste viscosity, improve gelling or gel strength, enhance textural properties	Gum, pastilles, jellies
	Encapsulate volatiles aromatic compound such as limonene, isoamyl acetate, ethyl hexanoate and β-ionones	Flavour encapsulator in seasonings
Oxidation	Lower viscosity, improve whitening of granules, high paste clarity, low temperature stability, and increase adhesion, reduce retrogradation of cooked starch pastes	As binder in battered meat and breading, film former and binder in confectionery, crispy coating in various fried food stuffs, texturizer in dairy products
Esterification	Improve quality of any fat/oil-containing products, reduce rancidity by preventing oxidation, increase viscosity	Snack foods, stabilizer and thickener in most foods, cholesterol-free salad dressings, flavour encapsulating agents in clouding agents, creamer and beverage.
	Improve viscosity and juice taste, freeze-thaw stability, improve emulsification properties	Soups and frozen/refrigerated food products, meat and fried products to improve juicy or smooth taste and retain flavour
	Increase paste viscosity, emulsion stabilizer and lower gelatinization temperature, reduce glycaemic response after consumption of beverages	Beverage emulsion stabilizers, and mayonnaises, flavour encapsulating agent for battered meat and meat products
Etherification	Improve clarity of starch paste, greater viscosity, reduce syneresis	As stabilizer in wide range of food applications such as gravies, dips, sauces, fruit pie fillings and puddings, flavour encapsulating agent in beverages clouds
	Cold-water solubility	Candy foods, sweets
	Improve freeze-thaw stability, water holding properties, lower the swelling temperature, increase solubility	Salad dressings, ice creams, refrigerated and frozen foods, and dairy products
Crosslinking	Volume expander. Delay retrogradation and reduce paste clarity	In bread and dough products as an expander and to improve rheological properties
	A smooth, viscous, clear thickener and freeze-thaw stability	Gravies, dips, sauces, fruit fillings, canned foods and puddings
Pregelatinized starch	Cold-water solubility and thickening	Instant soups, sauces, dressings, desserts and bread mixtures, thickener in food that receive minimal heat processing such as pastas

2.5 Cassava in Composite Flours

In Sri Lanka, wheat flour is the main ingredient used for breads and it is imported. But usage of starch from tubers such as cassava, yam or sweet potatoes and cereals such as maize, millet or sorghum for bread manufacturing would be economically beneficial because imports of wheat could be reduced and the demand for bread could be met using domestically grown products instead of wheat [6].

The Food and Agriculture Organization of the United Nations initiated a composite flour program in 1964 to develop bakery products from locally available raw materials. They could obtain good quality bakery products like wheat-flour bread. However, the texture and sweetness of the new bakery products was different from those made from wheat flour. Bread has a softer crust and crumbs as in cakes when they are made using gluten free flour. The soft crumb of wheat flour bread is caused by the swelling properties of wheat-flour gluten in water. If pure starch of other tubers or cereals is used, the product becomes more rigid because gases in the dough are not sufficient. To overcome this issue, a swelling or binding agent such as egg white or gum should be added during the preparation of the dough to bind the starch granules. Though it was found that, non-glutenous starch such as cassava starch can be added only 10% for wheat flour bread, recent studies have shown that it is possible to increase the nonglutenous flour amount significantly without changing the bread characteristics using certain bread improvers such as calcium stearyl lactylate or a relatively high percentage of fat and sugar.

Also, 30% of cassava starch can be used for making bread with wheat flour. Tapioca macaroni was developed using cassava flour in India and the nutrition content of the macaroni is higher than rice. Also, when using cassava flour with wheat flour for breads, conventional fermentation system can be replaced. This is known as mechanical leaving of bread doughs and it is capable of producing a bread of good quality [6].

2.6 Products Manufactured by Chemical Conversion of Starch

Products manufactured using cassava starch and their manufacturing process and uses of those products are depicted in Table 3. Glucose is a monosaccharide found in honey and sweet fruits such as grapes. Shelf life of glucose syrup is relatively longer than most sweeteners, five to six months [26]. Glucose is less sweet than sucrose and usually produced as a solid or a syrup.

The common name for the syrup is glucose and dextrose is used for solid sugar. Corn starch, cassava starch, sweet potato starch, and sorghum are widely used to produce glucose, but the glucose yield from cassava starch is higher than from corn starch. The physical properties of the glucose syrup depend on the dextrose equivalent and the manufacturing method. Among the glucose production processes, acid conversion method is the most economical process and the enzymatic process is the most common process.

The manufacturing process of glucose syrup production contains mainly three sub processes, namely, liquefaction, saccharification, and purification. In the liquefaction process, starch slurry is prepared by mixing starch with calcium hydroxide or calcium chloride solution and pH value is adjusted to 6.0-6.4. α-amylase heat stabilizer is added to the starch slurry and the slurry is instantly heated to 100 °C and kept for 10 minutes. Then the slurry is kept at 90 °C for 1-3 hours for further hydrolyzation [27]. Then the thick white starch solution changes into brown caramel dilute [28]. In the saccharification process, pH value is reduced to between 4.2 and 4.5 and the solution is cooled to 60 °C. A glucoamylase, which releases single glucose units from the ends of the dextrin molecule, is added to the solution and 24-48 hours reaction time is required for saccharification. Herein, the produced syrups contain 95% or higher glucose contents [27]. Samaranayake et al. [29] investigated on optimization of liquefaction and saccharification times for production of glucose syrup in pilot scale and introduced an effective process method for the industry to produce glucose syrup in Sri Lanka. In the purification process, excess moisture from glucose is removed to obtain a standard concentration. Also, the decolourization process is carried out to produce colourless and transparent glucose syrup. Activated carbon is used to remove colours and other impurities from the solution by surface adsorption. The application of enzymatic technology to the production of glucose has helped to reduce the production cost [30].

In dextrose manufacturing process, starch hydrolysate (hot thick glucose syrup) from saccharification process is purified and discoloured and is run from an evaporator into crystallizers. The crystals are separated from mother liquor using centrifugal separators and dried using fluidized bed dryer [31]. In fructose manufacturing process, the best glucose product is mixed with Magnesium sulphate and the pH value is maintained at 7.5. Then glucoisomerase enzyme is added to the mixture and incubated for 3 hours at 60 °C [28].

Johnson and Padmaja [32] have used cassava fibrous residue to produce glucose syrup by hydrolysing starch and cellulose with various enzyme treatments and converted glucose to high fructose syrup. Araujo-Silva et al. [33] has used cassava bagasse to produce maltose.

In the sorbitol manufacturing process, cassava starch is first converted into the monosaccharide dextrose. Then the dextrose syrup is hydrogenated in the presence of a catalyst. The hydrogenated solution is purified by carbon treatment and ion exchange. The catalyst is reused by recycling. The purified solution is evaporated and the sorbitol syrup is crystallized to obtain a powder [34].

In MSG (Monosodium glutamate) manufacturing process, glutamic acid is produced using glucose by bacterial fermentation. The fermentation is carried out as a batch process to confirm appropriate digestion of the carbohydrate. The glutamic acid accumulates in the fermentation broth and is separated from the broth by microfiltration. The glutamic acid is treated with caustic soda and centrifuged and dried in drum dryers. The resulting crystals are the monosodium

Table 3 – Products manufactured by Chemical Conversion of Starch and their Uses Application

Product	Manufacturing process	Uses	Local/ Global demand
Glucose	Acid conversion method, enzymatic process, and carbon free method	As sweetening agents in confectioneries, pharmaceutical industries (Glucose prevents crystallization in boiled sweets and reduces hvdroscopicity in the finished product) [30]	In Sri Lanka, glucose syrup is mainly imported and the annual expenditure on the importation is about 450 million Sri Lankan rupees [29]
Dextrose	Enzyme hydrolysis of starch	100% pure dextrose crystals -pharmaceutical-grade sugar. Crystalline dextrose - bakery (to supply fermentable carbohydrates), confectionery (to prevent crystallization of the sucrose, jams, and ice cream), fruit canning (to increase the solids without causing an undue increase in the total sweetness), beverages and alcohol production (for fermentation)	Global market – 34.810 billion USD (2020/2021)
Fructose	Enzymatic reaction of starch	Production of drinks	Global market – 5.45 billion USD (2020)
Maltose	Enzymatic hydrolyzation of the starch	Pure maltose - pharmaceutical industry for the manufacture of antibiotics, vaccines, maltitol, etc. Food industry due to its functional properties such as low hygroscopicity, low viscosity, resistance to crystallization, low sweetness, reduce browning capacity, and good heat stability [40]	
Sorbitol	Hydrogenation of dextrose syrup	Food (as a sweetener), pharmaceutical applications (as a carrier), cosmetics applications (as an emulsion stabilizer) [41]	Global - about 800.000MT per year [34]
Monosodium glutamate (MSG)	Fermentation of starch	Flavour enhancer for foods such as vegetables, meats, and sauces	Global market – 3.8 billion USD (2020)
Citric acid	Fermentation process of starch-based media	Organic acid used in pharmaceutical, beverage, agricultural and chemical industries	Global - about 0.7 million [38]
Lysine	Fermentation of starch	An essential amino acid for humans and warm-blooded animals because their body cannot produce it [42]	Global – 2.8 Mt (2020)
Dried yeast	Yeast is propagated using starch	Food industry [13]	Global – about 3.7 billion USD (2020)
Ethanol	Fermentation process of starch-based media	Biofuel	Global market – 26.06 billion gallon (2020)
Commercial caramel	Heating glucose alone and heating glucose with a certain catalyst	For flavouring purpose, to colour food, confectionery and beverages [43]	Global – about 2 billion USD (2020)

glutamate and it is usually at least 99% pure [35].

In citric acid production, Indigenous *Aspergillus niger* bacteria is used for the fermentation process [36]. Cassava starch can be used for the production of citric acid. In Thailand, one factory uses cassava pulp as the raw material while the other uses cassava chips as the raw material. When producing citric acid using cassava chips, about 40 tons of cassava chips are required to manufacture 6 tons of citric acid per day. Cassava starch, after gelatinization and liquefaction, is fermented for 4 days to produce citric acid [15]. Prado et al. [37] used treated cassava bagasse for manufacturing citric acid. The wastewater, which is a by-product of the process, can be treated in an anaerobic reactor and treated effluent can be recycled [38].

Cassava is used to produce alcohol since it is rich in fermentable materials. In Malaysia and many other countries, fresh cassava roots which contain 30% starch and 5% sugar, and dried cassava roots which contain 80% fermentable materials, are used to produce Ethyl alcohol. Cassava roots are washed, peeled, milled, and fibre is removed. Cassava starch slurry is cooked at a temperature greater than the gelatinization temperature to rupture the granular structure. Then, starch slurry is hydrolysed to glucose using α-amylase and glucoamylase. The liquefaction process is done by α-amylase at high temperatures and liquefied slurry is cooled down to an optimum temperature for glucoamylase hydrolysis. Then, the glucose is fermented using yeast and, after fermentation, the product contains 10% ethanol. This product is distilled to concentrate ethanol. Anhydrous ethanol is produced by removing water by dehydration process [39]. According to Sriroth et al. [39], 150,000-liter fuel ethanol can be produced using 362.17-ton cassava chips per day. During this process, carbon dioxide gas, fuel oil, and thick slop are produced as by-products. Wastewater can be treated and re-used. Solid waste can be used to produce biogas to feed the burner or as a supplement in animal feed [39].

2.7 Industrial Uses of Cassava

2.7.1 Adhesive Production

Adhesives are polymeric materials and they are capable of joining two materials together by surface attachment. In 1804, Lagrange was trying to find a substitute for gum and prepared adhesive by roasting starch. Dextrins, which were discovered accidentally in 1921, were prepared by moisturizing dried starch with a dilute mixture of hydrochloric acid (HCl) and nitric acid (HNO_3) [44]. Starch from corn, potato, or cassava can be used as main raw materials. The mixture is spread on corrugated iron sheets and heated in the oven until they are dried and become slightly yellow. Characteristics and mechanical properties of dextrins depend on the time of roasting, use or non-use of converting agent, character of wavering agents, raw materials, concentration of acid used or mixtures of different starches. Some dextrins are different in viscosity and some grades are highly adhesive and dry quickly [44]. British gums, white dextrins and yellow dextrins are the three primary groups of dextrins [44].

Cassava-based adhesives are stickier, more viscous and their joints exhibit higher tensile strength than the starch from cereal and other tuber crops. The gelatinization temperature of cassava-based adhesive ranges between 49 °C and 70 °C and it is very low when compared to cereals such as corn (62 - 73 °C). Energy is saved due to the lower heat requirement for gelatinization when using cassava starch for making adhesives [45]. Agboola et al. [46] prepared adhesive from cassava starch. Azeez [44] investigated the effects of acid concentration, roasting temperature and time on dextrin produced using cassava starch as main raw material. Opara et al. [47] produced various adhesives using modified cassava starch such as oxidized, hydrolysed and dextrinized starch. It was identified that adhesives produced using hydrolysed and oxidized starch showed greater and good adhesive qualities. Olusola et al. [48] measured adhesive properties using four cassava varieties: 'Red stick', 'Butter stick', 'Maracas Black stick', and 'M Col 22', in Trinidad and Tobago. After the experiment, they identified that Maracas Black Stick and Butter Stick varieties have better stickiness and resistance to degradation than the other two varieties. Furthermore, Oghenejoboh [45] studied the effects of natural fermentation on the stability or shelf life of adhesives produced from starch of two cassava varieties and identified that, when the cassava starch acidity is high, viscosity is low, whereas the drying time is high and has a longer shelf-life.

Oghenejoboh [45] learned about the relationship of natural fermentation on the shelf life of adhesives manufactured using two variations of cassava starch. In this study, it was revealed that, cassava starch acidity has an inverse relationship with viscosity and drying time, and shelf-life has a direct relationship. Wang et al. [49] prepared a new starch-based adhesive using crosslinked cassava starch with high solid content, high binding force and low viscosity. Moreover, Xing et al. [50] prepared a new and environmentally friendly wood bio-adhesive using cassava starch and bio-oil, which showed better liquidity, longer storage period and higher shear strength. The effects of various preservative agents (formaldehyde, benzoate and butraldehyde) on starch adhesives prepared from cassava starch were investigated by Akhabue et al. [51].

Dextrins are used in many industries. In corrugated cardboard manufacturing, dextrins are used to manufacture cartons, boxes and other packing materials. There, the layers of board are glued together with a suspension of raw starch in a solution of the gelatinized form, and for strong bonding, the board is pressed between hot rollers where gelatinization of the raw starch happens. Remoistening gums are applied and dried on surface, and when required, the surface can be moistened by adding water or water-based solution. These types of adhesives can be seen on postage stamps and envelope flaps. Cassava dextrins in aqueous solution are very suitable for the remoistening gums. In the manufacture of castings for metals, starch is used as the adhesive. Starch-based adhesives are used for coating the sand grains and binding them together in making cores which are placed in moulds. Starches and modified starches mixed with clay are used in drilling oil wells or water wells to give the correct viscosity and water-holding capacity in bores for the trials [52].

2.7.2 Uses of Cassava in Paper Industry

In paper manufacturing industry, starch is used as an adhesive, a bonding regent, a retention aid, a binder for coatings, and a flocculant, due to its unique properties such as low-cost renewable adhesive, controlled viscosity, specific rheological characteristics, water-holding properties, electrostatic charge, film formation and bonding after drying [53]. In the paper industry, different types of starches such as potato, maize, and cassava are used at different stages of the manufacturing process for different purposes. Among these, cassava starch has great properties that are highly necessary for paper manufacturing. In West Africa, cassava starch is mostly used for paper industry because it possesses a strong film, clear paste, good water holding properties, stable viscosity and low cost.

Besides, cassava starch is largely used during the paper and board manufacturing processes. The strength of the finished paper is increased by beating the cellulose fiber to a desired pulp using starch and starch imparts body and resistance to scuffing and folding. Oxidized or modified starch is added to one or both sides of the paper sheet or board when the paper sheet or board is partially dried at the size press. This improves the finishing, appearance, strength, and printing properties of the paper sheet or board. Also, starch acts as a coating agent when a pigment coating is required for the paper [53]. Some research has been conducted to investigate whether other parts of the cassava plant such as cassava peel and bagasse can be utilized for paper industry as raw materials. For instance, Aripin et al. [54] studied whether cassava peel can be used as an alternative fibre in pulp and paper. The amount of holocellulose content in cassava peels is lower than that of the wood and canola straw which are the raw material for paper industry. But the value was still within the limit. Therefore, they suggested that cassava peel can be used as an alternative fibre source for pulp and paper making industry by altering the chemical properties and morphological characteristics. Matsui et al. [55] prepared the composite that is similar to cardboard using a mixture of 90% cassava bagasse and 10% of kraft paper. The characteristics of the resulting material were similar to the moulded fibre packaging made using recycled paper, as used in egg boxes.

2.7.3 Uses of cassava in plywood industry

In plywood industry, cassava starch is widely used as a glue [56]. The starch is used in order to permit the plywood to attach in thick layers and develop strength and durability. The use of starch as an ingredient for glue manufacturing also helps to reduce the production cost since it uses up to 50% of the total ingredients. Moreover, cassava starch also has a smooth and charming superficial surface that forms no precipitation in the glue manufacturing process, and a low price [57].

2.7.4 Uses of Cassava in Textile Industry

Starch is used in the textile industry for warp sizing, cloth finishing and printing. In warp sizing, a protective coat is applied to prevent the single yarns from disintegrating during weaving. The size contains an adhesive and a lubricant and is removed after weaving. Warp is produced by coating starch in the surfaces of the twisted single fibres of yarn when passing through a sizing solution. Then the coated yarn is heated and dried. Cassava starch or maize starch, binder, softener, water, wax and oil are the key raw materials used during sizing of yarn, and maize starch is the major competitor for cassava starch.

In cloth finishing, fabric is made firmer, stiffer and heavier, to feel the fabric. In textile printing, designs in various colours are printed on the smooth surface of a finished fabric. The printing pastes should not change on ageing and should resist against the effect of added acids or alkalis as required by colour agents. Modified starches are used to provide the required viscosity and paste features [58].

2.7.5 Uses of Cassava in Pharmaceutical Industry

In pharmaceutical industry, starch is used as a filler material and bonding agent for producing tablets and capsules in powder formulations. Cassava starch is used for tablets to coat the tablet as well as to bind the constituents of the tablet [59]. A paracetamol produced using modified cassava starch by acetylation does not easily crumble during transportation and storage until reaching the consumer [60].

2.7.6 Uses of Cassava in Detergent Industries

When using starch in the manufacturing of soap and detergent, the shelf life of detergents improves and soap gets better recovery. Cassava starch is commonly used as a filler in producing soap; it is usually mixed with the particles of soap before milling [59].

2.7.7 Particle Board Production from Cassava Stalks

Cassava stalks become huge waste products when cassava cultivation is increased. The good quality stalks are used for cassava re-cultivation, but a huge amount will be available for disposal. Some research has been conducted to add value to the cassava stalk. Aisien et al. [61] produced particle boards from cassava stalks using urea-formaldehyde as a binder. Milled cassava stalks were used to produce particle board and an adhesive; cassava stalk ratio of 3:1 gave the best results. Another method is mixing small cassava stalk sections with certain resins but the strength of the board depends on the resin content and density.

2.7.8 Cassava Products for Animal Feeding

Large quantities of cassava roots and cassava waste have long been used for animal feeding in many countries. Imports of dried cassava roots and animal meal into European markets for animal feeding are also increasing. In most tropical areas, cassava products are used for feeding pigs, cattle, sheep and poultry. Dried peels of cassava roots are used to feed sheep and goats. Boiled or raw roots of cassava are mixed with a mash of protein concentrates. For the protein concentrate, we can use maize, sorghum, groundnut or palm oil kernel. On the other hand, mineral salts are also added to increase the nutrient level of the livestock feeding mixture.

Despite the fact that cassava leaves and stems are considered as a wastage, the leaves contain 17-20% protein. Imports of dehydrated alfalfa, which has been grown as feed for livestock in the Far East, have reached about 240 000 tons a year [62]. Experiments showed that dehydrated cassava leaves are equivalent in feed value to alfalfa. Therefore, dehydrated cassava leaves can be used as a substitute for dehydrated alfalfa, and there is a large possibility for the exportation of dehydrated stems and leaves of cassava as feed for livestock. In Brazil and Southeast Asian countries, large quantities of cassava roots, stems and leaves are chopped and mixed into a silage for feeding of cattle and pigs. Cassava root is especially suitable to feed young animals and fattening pigs because it entirely contains starch which is easy to digest. In the European Economic Community, the highly developed compound animal-feed industry uses cassava chips, pellets and meals. According to the type of animal (pigs, cattle, poultry) and final production of the livestock (meat, dairy, eggs), the ingredients of the animal feed varies.

Cassava chips are the most common form used as animal feed. Cassava chips are dried slices of roots which are mostly produced in Thailand, Malaysia, Indonesia and some parts of Africa. Cassava roots are sliced mechanically and the slices are sun dried. The yield of chips from roots is about 20-40%. However, in European markets, cassava pellets are more popular than cassava chips because the quality of cassava pellets is more uniform and they occupy 25-30% less space than chips. Therefore, the cost of transport, storage and handling charges is reduced.

Cassava meal, which is the powdered residue of the chips and roots after processing to extract edible starch, is also used as animal feed. But it has a lower starch content and usually contains more sand. Residual pulp, which is separated from the starch in the screening process during cassava flour production, is also used as an animal feed. Residual pulp is a by-product of the cassava starch industry and normally it is about 10% of weight of the cassava roots. In some industries, this by-product is sometimes sun dried before it is sold [6]. Cassava peel also can be used as feed for cattle, sheep and goats, after adding some protein and mineral [63] [64] [65].

2.8 Bio-Plastics Production

Biopolymers are usually referred to as polymers derived from biomass, a natural source of renewable materials such as cellulose, starch, chitosan and lignin [66]. First generation bio-based polymers were developed from renewable biological feedstocks such as plants and crops. Second generation bio-based polymers use alternative renewable feedstock such as waste streams or low-value by-products from food processing and agricultural industries [67] [68]. Literature reveals that, natural raw materials such as wheat, corn, sugar, rice, potatoes and soya are used to produce biopolymers [69]. Currently, bio-plastics such as starch derivatives (TPS), polyhydroxybutyrate (PHB), polylactic acids (PLA), and polycaprolactone (PCL) could be found in the market [69] [70].

Starch is a polymeric carbohydrate containing anhydroglucose units connected by glucosidic bonds. Starch has two microstructures, linear (amylose) and branched (amylopectin). Cereal grains such as corn, wheat and rice and tubers, such as potato and cassava, are the main starch sources which are used to produce bio-plastics [71] [72]. Starch has different quantities of amylose and amylopectin, ranging from about 10–20% for amylose and 80–90% for amylopectin, depending on the source [73]. Though starch is not a real thermoplastic material, it can be transformed into an amorphous thermoplastic by processing with plasticizers under special heat and shear conditions [74]. Several chemicals such as glycerol, water, urea, formamide, ethylenebisformamide, sorbitol, citric acid, N-(2-hydroxyethyl) formamide, and amino acids have been used as plasticizers for starch plasticization process in previous works. Among them, glycerol is widely used in thermoplastic starch plasticization process as the plasticizer owing to its high boiling point, availability and low cost, though water is more effective than glycerol [75].

Cassava starch is more suitable to produce thermoplastic starch due to its clarity, low gelatinization temperature and good gel stability. Cassava starch has a carbohydrate content up to 99%, and 17% amylose and 83% amylopectin content [66] [76]. Conventional processing techniques such as extrusion, injection moulding, compression moulding, thermoforming and reactive extrusion, have been adopted for processing thermoplastic starch [77]. However, extrusion is the most widely used and effective method to process thermoplastic starch. According to European Bioplastics, out of 2.11 million tons of bioplastics produced in 2020 globally, starch blends are 18.7% and the market for bioplastics has been increased. Starch-based bioplastics are used for various applications such as packaging, catering products, consumer products, electronic products, automotive, agriculture and textiles [78]. Production of starch-based bio-plastics, which is cheap and fully biodegradable, could become a possible substitute to non-biodegradable synthetic plastics while creating new markets and reducing environment pollution. Furthermore, Sharif et al. [79] have identified that cassava leaves can be used as packaging material after the mercerization treatment.

3. Waste Management Process

During production of cassava-based products, lots of waste are generated as a whole stillage containing both solid and liquid waste. This causes a series of environmental problems such as contamination of water bodies and production of offensive odours. But there is great potential to convert these wastes to value-added products. Starch and ethanol production are the major industries which are based on cassava plant. Four main cassava waste streams, such as peels, fibrous by-products from crushing and sieving, starch residues after starch settling, and wastewater effluents, are generated during the starch and ethanol production process. The solid waste from cassava starch processing is known as bagasse or pulp and is used for production of animal feed. Also, solid wastes such as cassava peels, bagasse, and stem can be used to produce biogas. The wastewater generated in cassava-based industrial plants can be recycled and reused with or without purification [80][81]. Zhang et al. [80] identified some value-added products produced by bioconversion of cassava-based industrial wastes. The industrial waste generated during production of cassava starch and ethanol can be converted into value added products: biofuels including bioethanol, biobutanol, biohydrogen and biomethane, organic acids such as short chain volatile fatty acids, citric acid, lactic acid, and succinic acid, biosurfactants and biofertilizer using bioprocess such as fermentation process [80]. Utilizing the whole cassava plant including the wastage to produce value added products will provide economic and environmental sustainability to cassava industries.

4. Problems and Challenges

The cassava value chain holds many opportunities for everyone in farming, processing and services. To improve the cassava value chain, productivity and yield of cassava should be increased, small scale farmers and farmer groups should be increased, and value-added products and by product utilization should be promoted. Farmers should be encouraged to engage in experiments in their own fields. Therefore, they can learn, adopt new technologies and spread them to other farmers. Government officials should help farmers to identify their own problems and select the technologies that might solve those problems, and then help them to test those technologies on their own fields. Farmers should gain knowledge on improving cassava productivity such as cassava varieties, land preparation, planting materials and methods, pest and disease management, fertilizer application, multiple cropping, harvesting, harvesting tools, storage, and processing. Past researchers have focused mostly in developing cassava variants which have high yield, but the starch extracted from cassava tubers are the main raw material for various industries. Therefore, research sectors should focus on developing the cassava varieties with high starch content.

Cassava will raise incomes for producers, processors and traders by adding value. Cassava will contribute to the economic development of the country. Identifying the markets that are growing or could potentially grow, and supplying the relatively uniform product to fulfil the market that meets the consumer requirements with an affordable price, will lead to the economic development of the country which is of paramount importance. Therefore, government can provide concessions and technical support for entrepreneurs and farmers who engage in cassava-based industries.

5. Conclusions

Due to the fact that the importance of cassava in the agricultural economy of many countries has grown in recent years, the cultivation of cassava for food and industrial purposes has gained greater attention. Development of industries of cassava derived products is an effective pathway to obtain a high added-value for cassava by providing significant contribution to national economies and making industries more stable. Nevertheless, the utilization of whole cassava plant and the waste generated during the production of cassava-based products is possible with the introduction of novel technologies with better expertise. Apart from the above, it is a well-known fact that cassava plant can be cultivated with minimum labour and negligible cultivation cost. Hence, there is an excellent opportunity to add value to this low-cost crop. For that, the development of enough feedstock supply is necessary. Root yield and productivity should be improved by introducing good cultivation practices and improved cassava varieties. Furthermore, the quality of the cassava-based products should be improved by lowering the production cost to compete with the existing market while maintaining the sustainability by following a zero-waste process concept. To this end, necessary research and development methods are further required in order to improve both cassava plant and the end products.

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