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Abstract

Cassava is a good source of carbohydrates and a staple diet in many countries. It has a high-calorie count but a low protein and fat content. Microalgal biomass is increasingly being used in the food business industry due to its ease of production, low carbon requirements, and small footprint. The usage of microalgae in combination with cassava is becoming more common as it can boost the amount of nutrients in processed cassava products. In this chapter, we discuss the development of cassava products that combine cassava with microalgae. Furthermore, cassava waste contains carbohydrates, which can be used as a carbon source for the development of microalgae. Cassava starch, when modified to become cationic cassava starch, has the potential to be used as a flocculant agent for the separation of microalgal biomass. Cassava starch is also well-known for being a low-cost source of bioplastics. This chapter also addresses the possibilities for microalgae and cassava to be used as bioplastics in the same way.

Keywords: cassava, microalgae, cationic, food, bioplastics

1. Introduction

Cassava is cultivated in more than one hundred countries and is a primary source of nutrition for millions of people living in tropical areas of Africa, Asia, and America. The average amount of cassava that can be harvested from one hectare in Nigeria is 10.6 tons, making the country the largest cassava producer in the world [1]. Cassava, in addition, is considered to be one of the staple foods in Indonesia. After Nigeria and Thailand, Indonesia has emerged as one of the world’s leading producers of cassava, making it one of the top three countries in this regard. Up to 53% of cassava production is used for food items, with the remaining amount being used for animal feed and as sources of bioethanol. Cassava-based food items such as boiled or fried cassava, chips, fermented cassava (tape, peyeum), gatho, and tiwul are examples of these.

About 70% of the cassava root is water. If the roots are not treated within 2–3 days, they will fully oxidize. Therefore, the drying procedure is a necessary post-harvest
treatment for preserving the quality of the roots. Roots of cassava that have been peeled, then cut into chips, and then dried in the sunlight. Cassava flour can be produced by grinding dried cassava chips in a mill. The locals of Java, Indonesia refer to it as “gaplek” flour. In addition to drying the roots directly, we can alter the cassava by soaking the chips in water containing bio-starter after it has been chopped. This is done after the root has been dried. There will be a three-day period of fermentation. After being fermented, the cassava chips were exposed to the sun to finish drying. In Indonesia, this type of flour is referred to as “mocaf.” The acronym mocaf stands for “modified cassava flour,” which is the full meaning of the term “mocaf” [2]. Mocaf flour is already being put to use as a gluten-free alternative to regular flour. It can be used as a wheat flour replacement in gluten-free baking, as well as in the preparation of gluten-free noodles and snacks. The non-food industry relies heavily on cassava flour and starch as its primary raw materials. Paper, textiles, plywood, glue, and biofuels are just some of the products that can be made with them. The gelatinization temperature of cassava starch is lower than that of other types of starch, and it also has a higher water-binding capacity and viscosity than other types of starch. These characteristics make it valuable in the culinary, chemical, and pharmaceutical industries [3]. These days, one of the components utilized in the production of biodegradable packaging is cassava starch, which is obtained from the root of the cassava plant [4].

Cassava roots have a significant amount of dietary fiber, which helps to improve heart health and eliminate atherosclerosis and the associated concerns, such as heart attacks and strokes. Cassava is also beneficial to digestive health. It contains vitamins and minerals such as vitamins C and K, as well as potassium, calcium, iron, copper, and zinc [5]. Despite the fact that cassava roots are a source of carbs, they are quite low in protein and fat content [6]. To meet the nutritional requirements for consumption, cassava root products must be coupled with foods that provide a source of protein. A protein source derived from microalgae is one of the forms of protein that are compatible with cassava food products and can be integrated with them. Microalga *Spirulina* sp. is a widespread type of microalgae that is frequently combined with foods that people consume on a regular basis, such as cookies, chocolates, energy drinks, crackers, and instant noodles [7–10]. The cassava cake and the cassava doughnut are the two cassava items that have been reported to combine with *Spirulina* sp. [11, 12]. After the addition of *Spirulina* sp., all the research revealed an increase in the product’s protein content [11, 12].

The relationship between cassava and microalgae goes beyond food products. Cassava starch that has been modified to make it cationic cassava starch can be used effectively as a flocculant agent in the microalgae harvesting process [13]. Waste products from cassava processing can be used for the cultivation of microalgae seeds or for fermentation. Achi, et al. [14] reported that waste products from the processing of cassava are a significant source of pollution. Cassava peels are a significant source of waste, and in most areas, 91% of them are piled up in trash landfills [15]. Additionally, Zhang et al. [16] found that the physical and chemical properties of waste cassava were comparable to those of biomass derived from woody plants. This made waste cassava an interesting option for bioconversion into products with additional value [17]. These results imply that the waste generated during cassava processing is a significant contributor to environmental pollution and that cassava waste has the potential to be converted into value-added products. However, additional research is needed to determine whether it is possible to generate value-added commodities from cassava waste.

One example of a sustainable cycle is the integration of the cassava industry with microalgae biorefinery. It could reduce the amount of cassava wasted and the cost of
microalgae biorefinery. Microalgae as a protein source has the potential to be a staple dietary fortification against malnutrition. There is also the prospect of developing cassava-microalgae bioplastics as a long-lasting, functional, and environmentally beneficial packaging material.

2. Foods derived from cassava and microalgae

Cassava production in Indonesia can reach 20 million tons per year, allowing cassava to become one of the staple foods in Indonesia. Cassava, on the other hand, is unpopular as a food source due to its stigma as a meal for marginalized people [2]. In order to increase consumer acceptance of cassava, innovation in the processing of products based on cassava is required. There have been a number of advancements made in the processing of cassava flour into food products. These include the modification of the structure of the cassava flour through the use of fermentation, as well as the transformation of well-known dishes such as cookies, cheese sticks, and noodles using cassava flour [18–21].

Cassava is a source of carbs and contains a negligible amount of protein [6]. The nutritional value of processed food products made from cassava can be improved by the incorporation of various protein sources into their composition. Microalgae are a potential source of protein that might be added to this cassava product after it has been processed. *Spirulina* sp. is by far the most common type of microalgae used.

- **Product using cassava flour**

Cassava flour has been used to replace wheat flour in doughnut recipes. The microalgae *S. platensis* has been utilized to boost the nutritional value of cassava doughnuts. The compositions of the formulation’s proximal, sensory, and technical components were assessed. When *S. platensis* was introduced to doughnuts, the protein, lipid, and fiber content increased linearly by 2.59, 3, 4, 5, and 5.41% (w/w). It also increases shearing force, making the doughnut more resistant to deformation and more difficult to chew. However, the doughnut with the highest *S. platensis* inclusion is still acceptable by the consumer, according to the acceptance test. As a result, this product can be utilized to provide improved nutrition to patients suffering from celiac disease [12].

Cassava flour can also be used to make cassava cake. Microalgae *S. platensis* was introduced to compensate for the absence of protein in cassava products. The addition of *S. platensis* at 1% and 2% boosted the protein content without affecting consumer acceptance [11].

- **Product using modified cassava flour (mocaf)**

Food products made from modified cassava flour are becoming increasingly popular in Indonesia. The usage of mocaf can replace the use of wheat flour, which is still imported. Furthermore, an increasing number of people are concerned about gluten-free foods. The fermentation procedure used to create modified cassava flour influenced the physical quality but not the protein content. The protein content of mocaf and cassava flour is 1.2% [22]. The use of *Spirulina* sp. is one approach to boosting the protein content of these products. Commercially available mocaf and *Spirulina*-based products include ‘Nasamie’ mocaf *Spirulina* noodles and “Garmil” mocaf sticks as shown in Figure 1. In Nasamie, the addition of *Spirulina* sp. to mocaf noodles...
could elevate the protein level up to 8 g in an 80 g serving size (data from ‘Nasamie’s nutrition fact’). Therefore, in Garmil, the protein content is 3 g per 25 g serving size (data from ‘Garmil Spirulina’ nutrition facts) after the addition of *Spirulina* sp. to a mocaf-based stick. Furthermore, the protein content of Garmil mocaf *Spirulina* sp. sticks was higher than that of mocaf sticks reported by Kusumaningrum, Miitakhussolikah, Herawati, Susanto, and Ariani [18]. This indicates that the addition of *Spirulina* sp. improves the nutritional quality of mocaf sticks. Al-Baarri, et al. [23] reported that the combination of 2% *Spirulina* sp. and 5% basil leaf can reduce the level of mocaf noodle hardness by as much as 50%.

Pie susu as shown in Figure 1, a Balinese culinary icon, is another example. It was a short pastry dough with milk and topping. Pastry dough made with a 1:2 ratio of flour and mocaf mocaf and flour. *Spirulina* sp. addition is 0.5% of the total dough. It is the maximum amount of *Spirulina* sp. that can meet the pastry requirement [22].

- Product using cassava starch (tapioca)

Tapioca is widely used in Indonesian cuisine, particularly in a variety of dishes. *Pempek*, *cireng*, *cimol*, *bika ambon*, *ongol-ongol*, *kue lapis*, and *cenil* are just some of the delectable dishes that are traditionally prepared in Indonesia with tapioca as one of the main ingredients. Tapioca pearls are among the most well-known foods that are generated from tapioca, and their use can be found all over the world. Tapioca in the form of balls, with a diameter of 2–8 mm [6]. Tapioca is commonly used as a topping in desserts and beverages. Frutea, a Colombian bubble tea maker, has launched Espirulitea, a bubble tea variety. Tea, milk, tapioca, and *Spirulina* sp. are among the ingredients. A franchise café in the United States created a dessert with phycocyanin extract from *Spirulina* sp., also known as blue spirulina. They create a sorbet out of coconut, pineapple, and blue spirulina. Toppings included strawberry tapioca pearls, crunchy honey GF granola, banana, strawberries, and kiwi (Figure 2).

Cassava products are grown in over 100 countries and feed millions of people in Africa, Asia, and some part of America. Nigeria is the world’s largest cassava producer, with an average yield per hectare of 10.6 tons per acre [1]. The top three countries in terms of cassava production are Nigeria, Thailand, and Indonesia [24]. However, because of its low protein content, cassava necessitates the development of new methods of processing in order to improve its nutritional value and make it suitable for consumption as a food source in the fight against stunting. In order to
Cassava and Microalgae Use in the Food Industry: Challenges and Prospects
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boost the nutritional value of cassava, one of the supplementary substances that may be used is microalgae, which is abundant in both protein and antioxidants.

3. Bioplastics from cassava and microalgae

Currently, the world faces global plastic waste contamination. Innovation is required to reduce this pollution. In contrast, plastics derived from fossil fuels have dropped. Bioplastics were utilized as an alternative to polymers derived from fossil fuels. Bioplastics are a type of plastic that can be derived from natural materials like starches and vegetable oil. The use of plant-based bioplastics is anticipated to reduce petroleum use by 15–20% by 2025, with Asia and Europe holding the biggest market share for bioplastics [25].

Bioplastics can be categorized into three groups: those made from recycled materials, those modified from naturally occurring polymers, and those made from synthetic biobased monomers. Biopolymers can be made from a wide variety of renewable but non-biodegradable raw materials, such as bio-polyethylene (Bio-PE), biobased polyethylene terephthalate (PET), and polytrimethylene terephthalate (PTT), as well as biodegradable but non-renewable materials, such as polybutylene adipate-co-terephthalate (PBAT), polybutylene succinate (PBS), and polycaprol. Starch-based polymers are the most prevalent bioplastics polymers worldwide [26]. Indonesia has mass-produced cassava starch and tapioca, for bioplastics under the brand name Telobag as shown in Figure 3. A Telobag is a bag constructed from telo-cassava.

Furthermore, microalgae-based bioplastics have been developed. The production of microalgal bioplastics could involve the use of microalgal biomass, bio- or petroleum-based polymers, and additives. The alternate method depends on the...
**Species** | **Production methods*** | **Materials** | **Characteristic** | **Publication**
---|---|---|---|---
*Species Production methods*
Spirulina platensis | Melt mixing, hot molding | Glycerol, polyvinyl anhydride, maleic anhydride | Microalgal as composites | [27]
C. vulgaris | Melt mixing, hot molding | Glycerol, polyvinyl anhydride, maleic anhydride | Microalgal as composites | [28]
Chlorella sp. | Melt mixing, hot molding, compression molding | Polyethylene, maleic anhydride | synthesize new compound | [29]
Nannochloropsis gaditana | Melt mixing, injection molding, twin screw extrusion | Poly (butylene adipate-co terephthalate) | residual biomass, microalgal as composites | [30]
Nannochloropsis sp., Spirulina sp., Scenedesmus sp. | Melt mixing, compression molding, solvent casting | Corn starch biocomposites | Microalgal as composites | [31]
Spirulina sp., Chlorella sp. | Compression molding | Polyethylene polymer | Microalgal as composites | [32]
Spirulina platensis | Compression molding | Gluten | Microalgal as filler | [33]
Spirulina sp. | Compression molding | Poly (butylene succinate) | Microalgal as composites | [34]
Nannochloropsis sp. | Compression molding | Polyethylene | Remove odor problem | [35]
Ankistrodesmus falcatus (NIES-2195), Chlamydomonas reinhardtii 11-32A, Parachlorella kessleri (NIES-2152), C. reinhardtii (DW15), Scenedesmus obtusus (NIES-2280), Chlorella sorokiniana (NIES-2173), Chlorella variabilis (NC-64A), C. vulgaris (NIES-227), Scenedesmus acutus (NIES-94), Scenedesmus sp. | Twin screw extrusion | Glycerol | intracellular starch production microalgae in sulfur-deprived medium | [36]
Chlorella sp. | Solvent casting | Chlorellapolyvinyl alcohol (PVA) | Microalgal as composites | [37]
Spirulina sp. | Solvent casting | Poly (vinyl alcohol) (PVA) | hazardous high-salt microalgal residues | [38]
Microcystis sp.; Haematococcus pluvialis | Solvent casting | Polyhydroxybutyrate (PHB) | Using high-rate algal ponds (HRAP) for algal biomass production | [39]

*Based on Onen Cinar, Chong, Kucuker, Wieczorek, Cengiz, and Kuchta [26].

Table 1. Development of microalga-based bioplastics.
intracellular synthesis of biopolymers in microalgae cells, such as polyhydroxybuty- 
rates (PHBs) and starch (Table 1) [26].

Although the production of cassava-microalgae-based bioplastics is feasible, no 
research on cassava bioplastics based on microalgae has been reported. Nevertheless, 
Cardoso, et al. [40] have developed biobased films from cassava bagasse and 
*Spirulina platensis*. This biofilm has a total solid content of 7%, with 4% cassava starch, 1% 
glycerol, and 2% cassava bagasse/*S. platensis*/gelatin mixture. The greatest elon- 
gation value was discovered in a mixture of cassava bagasse: *S. platensis*: gelatin 
(0.34:1.32:0.34). The inclusion of *S. platensis* raised the color (the value of $a^*$) and 
opacity, but the addition of cassava bagasse increased the viscosity. The films’ green 
color makes them perfect for packing meals of the same color.

The study reported that the biobased films made from cassava bagasse and *S. 
platensis* are applied to Cambuci peppers (*Capsicum* sp.). For 14 days, the peppers are 
stored at room and refrigerator temperatures. At room temperature, peppers coated 
with cassava bagasse-*S. platensis* biobased films lose less bulk. The temperature of the 
refrigerator delays the maturity of the peppers. In addition, cambuci peppers’ shelf 
life can be extended by combining coating with low temperature [41].

4. Cassava wastewater as a substrate for microalgae

The cassava industry generates a large number of byproducts and leftovers that 
are rich in organic matter and particulate debris [42]. In addition, cassava process- 
ing generates a lot of effluents. It should be noted that processing one ton (1000 kg) 
of cassava roots may result in between 250 and 600 kilos of wastewater [43]. de 
Carvalho, et al. [44] reported that cassava wastewater has high quantities of numer- 
ous mineral nutrients. The ash level of cassava waste ranges between 2.5% and 3.5% 
[17]. The biological oxygen demand (BOD), chemical oxygen demand (COD), and 
total suspended solids (TDS) found in cassava wastewater are all above average 
[45, 46]. Wastewater’s excessive TDS, BOD, and COD levels are directly correlated to 
the organic matter and chemical content of the water, which poses serious threats 
to the environment and the well-being of living things [47].

Microalgae are dependent on the chemical composition and organic matter of 
cassava wastewater. COD reflects the quantity of oxygen that can be consumed by 
reactions in a measured solution. The biological oxygen demand (BOD), also known as 
biological oxygen need, is the amount of dissolved oxygen required by aerobic 
biological organisms to decompose organic material present in a given water sample at 
a particular temperature over a certain time period. BOD and COD can be utilized to 
assess the effectiveness of wastewater treatment plants [48]. Nitrogen is an important 
factor in the growth of microalgae. Nitrogen is essential for the formation of DNA, 
proteins, and pigments [49]. Phosphorus is also an essential component of numerous 
metabolic activities, such as the transfer of energy across cell membranes and cells, 
the production of nucleic acids, and the encouragement of cell growth and photosyn- 
thetic activity [50].

Microalgae can naturally absorb nutrients from the water in order to grow. Thus, 
laboratory studies have shown that nutrient removal via microalgae cultivation is 
possible [51]. Microalgae can be autotrophic or heterotrophic. If they are autotrophic, 
they obtain their carbon from inorganic molecules. Autotrophs are classified into two 
types: chemolithotrophic and photoautotrophic (photolithotrophic). Photoautotrophs 
use light as an energy source, whereas chemoautotrophs (chemolithotrophs)
oxidize inorganic substances for energy. Furthermore, heterotrophic microalgae employ organic molecules for growth. Heterotrophs are classified into two groups: photoheterotrophs (photoorganotrophs) and heterotrophs (chemoorganotrophs). Photoheterotrophs use light as an energy source, whereas chemoheterotrophs (chemoorganotrophs) oxidize organic substances for energy. Furthermore, heterotrophic microalgae can absorb complete food particles into food vesicles for processing. They may, on the other hand, be osmotrophic, absorbing dissolved nutrients through the plasma membrane. Some photosynthetic algae are mixotrophic ( facultatively heterotrophic). They rely on organic chemicals found in the media [52]. Sorgatto, Soccol, Molina-Aulestia, de Carvalho, de Melo Pereira, and de Carvalho [53] reported that microalgae grew faster in cassava wastewater and produced lipids similar to synthetic mixotrophic cultures. Another research by Nwanko and Agwa (2021) showed that the optimal ratio of cassava peel water to cassava wastewater (CP: CW) for growth was 160:40.

Nutrients in cassava wastewater can be removed using microalgae. For wastewater treatment, the microalgal genera Chlorella, Haemotococcus, Arthrospira, and Dictyosphaerium have been studied [45, 47, 54–57]. Chai, et al. [58] reported that microalgae are effective at removing nitrogen, phosphate, and toxic metals from wastewater. de Faria Ferreira Carraro, Loures, and de Castro [46] demonstrated cyanide removal efficacy approaching 99% and average CO$_2$ biofixation of 0.19 g L$^{-1}$ d$^{-1}$ from cassava wastewater. The efficacy of wastewater treatment varies according to the species as shown in Table 2.

Microalgae-treated wastewater has the potential to be used in pollution removal, agriculture, aquaculture, biogas production, bioproducts, and biomaterials [58, 60]. One method for producing biomass and metabolites at a cheaper cost is to cultivate

<table>
<thead>
<tr>
<th>Species</th>
<th>Efficiency of waste removal</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chlorella minutissima</td>
<td>COD, TS, and nutrient removal efficiency are about 30, 75, and 92%, respectively. In addition, cyanide removal was 99% and average CO$_2$ biofixation was 0.19 g L$^{-1}$ d$^{-1}$</td>
<td>[46]</td>
</tr>
<tr>
<td>Dictyosphaerium sp.</td>
<td>TS for heterotrophy was 79.32% and for mixotrophy was 89.78%, respectively. For heterotrophy and mixotrophy, the BOD was 72.95% and 89.35%, the COD was 72.19% and 84.03%, and the cyanide level reduces from 450 mg/L to 93.105 (79.31%) and 85.365 mg/L (81.03%), respectively.</td>
<td>[47]</td>
</tr>
<tr>
<td>Arthrospira platensis</td>
<td>Over 99% of ammonia, nitrates, and nitrites, could be reduced.</td>
<td>[54]</td>
</tr>
<tr>
<td>Chlorella sorokiniana</td>
<td>COD, total phosphorous (TP), and total inorganic nitrogen (TIN) are reduced by 63.42, 93.68, and 70.66%, respectively, in P21 culture. While WBRDG culture reduced COD, TP, and TIN by up to 73.78, 92.11, and 67.33%, respectively.</td>
<td>[59]</td>
</tr>
<tr>
<td>WB1DG and C. sorokiniana P21</td>
<td>COD and nutrient removal efficiency in WCF supernatant ranged between 80 and 94%.</td>
<td></td>
</tr>
<tr>
<td>C. sorokiniana WCF</td>
<td>COD and nutrient removal efficiency in WCF supernatant ranged between 80 and 94%.</td>
<td></td>
</tr>
<tr>
<td>Haematococcus pluvialis and Neochloris oleoabundans</td>
<td>COD, TN, and TP are reduced by 60.80, 51.06, and 54.68%, respectively, in HP culture. While in NO culture reduced COD, TN, and TP by up to 69.16, 58.19, and 69.84, respectively.</td>
<td>[53]</td>
</tr>
</tbody>
</table>

Table 2. Microalgal waste removal efficiency.
microalgae in wastewater [53, 61]. Table 3 depicts the cassava wastewater treatment product based on microalgae. Wastewater from cassava processing can be utilized to cultivate microalgae, which can be used to produce biodiesel or biogas [44, 63]. Microalgae can also be used as a bio stabilizer to boost biogas production from cassava starch effluent [64]. The use of cassava wastewater can also increase astaxanthin accumulation and reduce the toxicity caused by this agro-industrial effluent in *H. pluvialis* [56].

### 5. Cationic cassava starch as flocculants for microalgae harvesting

The most difficult challenge in collecting biomass for subsequent usage is efficiently collecting microalgae biomass from their growth substrate. According to Al-Hattab, et al. [65], it accounted for 20–30% of overall biomass production expenses. We are aware that harvesting using filtration techniques is one of the most cost-effective methods available, despite the fact that it is limited to microalgae with a large size, such as *Arthrospira* sp. This method is widely used, even in industrial production. Indeed, microalgae harvesting strategies consider species characteristics, size, density, downstream biomass processing, and sometimes medium recycling needs [66–68]. The greater the size or length of the microalgae, the greater the number of potential screening options available. In actuality, single-cell and small-sized microalgae predominate in our environment, and we constantly interact with them. These factors encourage the development of harvesting systems that are sustainable, cost-effective, suited for industrial production, and safe based on the final product’s intended use.

Researchers have studied various methods of harvesting microalgae biomass, including filtration with specific treatments, centrifugation, dispersed air flotation, sedimentation, flocculation, bioflocculation, coagulation, and fluidic oscillation [67, 69–71]. The previously researched bioflocculation harvesting method was regarded as a viable approach for gathering microagal biomass since it was acceptable with regard to sustainability, large-scale production, low-cost energy, and environmental friendliness [47]. When bioflocculant is utilized, however, microbiially contaminated biomass products may be produced [72]. In contrast to microbial-based flocculants, plant-based coagulants enable the harvesting of microalgal biomass that is biodegradable and less contaminated by microorganisms, as mentioned previously. Apart from *Moringa oleifera*, neem, cactus, orange (peels),

<table>
<thead>
<tr>
<th>Type</th>
<th>Species</th>
<th>Metabolites</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassava water processing</td>
<td><em>Neclochlois oleobundans</em> UTEX 1185 and <em>Haematococcus pluvialis</em> SAG 34 – 1h and</td>
<td>Fatty acid methyl esters (FAME)</td>
<td>[53]</td>
</tr>
<tr>
<td>Non-detoxified cassava bagasse hydrolysate (CBH)</td>
<td><em>Chlorella pyrenoidosa</em> and yeast <em>Rhodotorula glutinis</em></td>
<td>FAME, sugar</td>
<td>[62]</td>
</tr>
<tr>
<td>Cassava water waste</td>
<td><em>H. pluvialis</em></td>
<td>Astaxanthin</td>
<td>[56]</td>
</tr>
<tr>
<td>Cassava water waste</td>
<td><em>Dictyosphaerium</em> sp. LCI72264</td>
<td>Lipid</td>
<td>[47]</td>
</tr>
</tbody>
</table>

Table 3. Metabolites formed during the processing of cassava waste.
pomegranate (peels), banana (peels), *Canavalia ensiformis*, *Strychnos potatorum*, and *Azadirachta indica*, a cassava starch-based coagulant has previously been examined for microalgal harvesting [73–77]. Moreover, considering biodegradability, renewability, and cost-effectiveness, it becomes attractive to use cassava starch as a natural flocculant [78].

The flocculation harvesting concept is driven by the fact that most microalgae cells have a negative surface wall charge; hence, their stability in suspension is a result of their mutual repulsion [74]. With a positive charge, flocculant The so-called cationic flocculant can absorb and react with the naturally negatively charged microalgae, which results in charge cancelation and cell agglomeration, also known as charge neutralization [79, 80]. Natural flocculants that are positively charged are presumably able to agglomerate the microalgae cells in suspension by means of the mechanism [81]. Moreover, another flocculation mechanism, namely bridging, occurs when natural flocculants with long polymers and a large molecular weight are unable to build polymer bridges with negatively charged ions [82]. Charged cationic biopolymers are also using the mechanism to construct the bridge between the cell walls by means of neutralization of the charge or through electrostatic path agglomeration [83]. Bioflocculant mechanisms are illustrated in Figure 4.

Cassava starch has been reported as a flocculant in numerous applications, including kaolin suspension, water treatment, water purification, and wastewater treatment [84–88]. X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) characterizations and chemical analysis confirmed that double helix configurations in cassava starch result from the amorphous crystalline distribution of starches and influence the growth of flocs and, thus, sedimentation [89, 90]. Cassava starch with a range of unique modified structures has been used to harvest valuable microalgae from their culture medium due to its promising application. When applied to *Chlorella* sp., the harvesting efficiency of cationic cassava starch in composite magnetic form was able to reach 98.09% with 1.67 g microalgae per g flocculant harvesting capacity [78]. In addition, according to Chittapun, Jangyubol, Charoenrat, Piyapittayanun, and Kasemwong [13], a 1000 mg/L dose of

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**Figure 4.**
Mechanisms of bioflocculants that interact with microalgae cells: A. charge neutralization mechanism; B. bridging mechanism (reconstructed according to Ogbonna and Nwoba [47]).
<table>
<thead>
<tr>
<th>Flocculant</th>
<th>Microalgae species</th>
<th>Operating condition</th>
<th>Dose; Time (min.)</th>
<th>Harvesting efficiency/ Harvesting capacity (g algae/g flocculant)</th>
<th>Cell density</th>
<th>Marine (M)/ Freshwater (F)</th>
<th>Flocculant form</th>
<th>Microalgae properties after recovery</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cassava starch</td>
<td><em>Chlorella</em> sp. (TISTR8236)</td>
<td>pH 9.5; 0.76 DS</td>
<td>500 mg/L; 2</td>
<td>98.09%/1.67 ± 0.01</td>
<td>1 g/L</td>
<td>F</td>
<td>Composites, magnetic-cationic cassava starch</td>
<td>NA [78]</td>
<td></td>
</tr>
<tr>
<td>Cassava starch</td>
<td><em>Chlorella</em> sp. (TISTR8236)</td>
<td>pH 10; 0.76 DS</td>
<td>200 mg/L; 2</td>
<td>93.77 ± 0.26 (%) ± 0.26 /4.69 ± 0.01</td>
<td>1 g/L</td>
<td>F</td>
<td>Composites, magnetic-cationic cassava starch</td>
<td>NA [78]</td>
<td></td>
</tr>
<tr>
<td>Cassava starch</td>
<td><em>Chlorella</em> sp. (TISTR8236)</td>
<td>pH 9, 0.04 DS</td>
<td>1000 mg/L; 2</td>
<td>92.86 (%) ± SD/1.58 ± 0.01</td>
<td>1 g/L</td>
<td>F</td>
<td>Commercial cationic starch</td>
<td>NA [13]</td>
<td></td>
</tr>
<tr>
<td>Cassava starch</td>
<td><em>Chlorella</em> sp. (TISTR8236)</td>
<td>pH 9; 0.040 DS</td>
<td>500 mg/L; 2</td>
<td>67.89 ± 0.48 (%) ± SD / 2.31 ± 0.02</td>
<td>1 g/L</td>
<td>F</td>
<td>Commercial cationic starch</td>
<td>NA [13]</td>
<td></td>
</tr>
<tr>
<td>Cassava starch</td>
<td><em>Chlorella</em> sp. (TISTR8236)</td>
<td>pH 9.5; 0.040 DS</td>
<td>200 mg/L; 2</td>
<td>60.12 ± 0.74 (%) ± SD / 2.56 ± 0.03</td>
<td>1 g/L</td>
<td>F</td>
<td>Commercial cationic starch</td>
<td>NA [13]</td>
<td></td>
</tr>
<tr>
<td>Cassava starch</td>
<td><em>Chlorella</em> sp. (TISTR8236)</td>
<td>pH 9.5; 0.04</td>
<td>200 mg/L; 2</td>
<td>56.65 ± 0.30 (%) ± SD / 2.41 ± 0.01</td>
<td>1 g/L</td>
<td>F</td>
<td>Composites, magnetic-cationic cassava starch</td>
<td>NA [13]</td>
<td></td>
</tr>
<tr>
<td>Cassava starch</td>
<td><em>Chlorella</em> sp. (TISTR8236)</td>
<td>pH 9.5; 0.76</td>
<td>200 mg/L; 2</td>
<td>80.15 ± 0.29 (%) ± SD / 3.41 ± 0.01</td>
<td>1 g/L</td>
<td>F</td>
<td>Composites, magnetic-cationic cassava starch</td>
<td>NA [13]</td>
<td></td>
</tr>
<tr>
<td>Potato starch</td>
<td><em>Scenedesmus dimorphus.</em></td>
<td>pH 7; 0.14 and 0.31 DS</td>
<td>10 mg/L; 90</td>
<td>&gt; 95% /</td>
<td>0.12 g/L</td>
<td>F</td>
<td>Cationic starch batches were synthesized using CHPTAC</td>
<td>NA [91]</td>
<td></td>
</tr>
<tr>
<td>Potato starch</td>
<td><em>S. dimorphus.</em></td>
<td>pH 7; 0.41 and 0.64 DS</td>
<td>10 mg/L; 90</td>
<td>&gt; 95% /</td>
<td>0.12 g/L</td>
<td>F</td>
<td>Cationic starch was created using EPTAC</td>
<td>NA [91]</td>
<td></td>
</tr>
<tr>
<td>Potato starch</td>
<td><em>Scenedesmus obliquus.</em></td>
<td>pH 7; 0.82 DS</td>
<td>0.0053 coagulant/algae ratio; 72</td>
<td>85% / 0.2–0.25 g/L</td>
<td>F</td>
<td>Cationic starch was using MAPTAC</td>
<td>NA [92]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flocculant</td>
<td>Microalgal species</td>
<td>Operating condition</td>
<td>Dose; Time (min.)</td>
<td>Harvesting efficiency/ Harvesting capacity (g algae/g flocculant)</td>
<td>Cell density</td>
<td>Marine (M)/ Freshwater (F)</td>
<td>Flocculant form</td>
<td>Microalgal properties after recovery</td>
<td>Ref.</td>
</tr>
<tr>
<td>------------</td>
<td>--------------------</td>
<td>---------------------</td>
<td>------------------</td>
<td>---------------------------------------------------------------</td>
<td>-------------</td>
<td>-------------------------</td>
<td>----------------</td>
<td>------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>Potato starch</td>
<td><em>S. obliquus</em></td>
<td>pH 7; 0.82 DS 1.4 coagulant/ algae ratio; 72</td>
<td>60% /</td>
<td>0.035–0.05 g/L</td>
<td>F</td>
<td>Cationic starch was using MAPTAC</td>
<td>NA</td>
<td>[92]</td>
<td></td>
</tr>
</tbody>
</table>

*DS=Degree of Substitutions.

Table 4. Characteristics of cassava and other bioflocculants for algae harvesting.
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Flocculant</th>
<th>Cost</th>
<th>Level</th>
<th>Toxicity</th>
<th>Application</th>
<th>Advantages</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>[78]</td>
<td>Composites, magnetic-cationic cassava starch</td>
<td>NA</td>
<td>Laboratory</td>
<td>Potentially</td>
<td>Another source of raw materials for making biofuels.</td>
<td>Low detachment ability may limit the use of collected algal cells.</td>
<td></td>
</tr>
<tr>
<td>[13]</td>
<td>Commercial cationic starch</td>
<td>NA</td>
<td>Laboratory</td>
<td>Potentially</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[13]</td>
<td>Commercial cationic starch</td>
<td>NA</td>
<td>Laboratory</td>
<td>Not</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[13]</td>
<td>Composites, magnetic-cationic cassava starch</td>
<td>NA</td>
<td>Laboratory</td>
<td>Potentially</td>
<td>Low dosage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[91]</td>
<td>Cationic potato starch batches were synthesized using CHPTAC</td>
<td>NA</td>
<td>Laboratory</td>
<td>NA</td>
<td></td>
<td>Low dosage</td>
<td></td>
</tr>
<tr>
<td>[92]</td>
<td>Cationic potato starch was synthesized using epoxide equivalent 2,3-epoxypropyl trimethyl ammonium chloride (EPTAC)</td>
<td>NA</td>
<td>Laboratory</td>
<td>NA</td>
<td></td>
<td>Low dosage</td>
<td></td>
</tr>
<tr>
<td>[92]</td>
<td>Cationic potato starch</td>
<td>NA</td>
<td>Laboratory</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>[92]</td>
<td>Cationic potato starch</td>
<td>NA</td>
<td>Wastewater from Lagoons</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.
Application of cassava flocculants for microalgae harvesting.
commercial cationic starch enabled harvesting of the same species of microalgae at the maximum harvesting capacity of 92.86% (Table 4). For comparison, potato starch, on the other hand, has been applied for *Scenedesmus dimorphus* flocculation. Cationic starch was used to precipitate more than 95% of the microalgae. Cationic starch was generated using N-(3-chloro-2-hydroxypropyl) trimethyl ammonium chloride (CHPTAC), and epoxide equivalent 2,3-epoxypropyl trimethyl ammonium chloride (EPTC) was used to make cationic starch [91]. While Anthony and Sims [92] investigated different forms of potato starch flocculant using 3-methacryloyl aminopropyl trimethyl ammonium chloride (MAPTAC) and discovered disparate results as shown in Table 4. This research has already demonstrated the effects of dose, pH, and degree of substitution on the efficiency of cassava starch as a harvesting aid for microalgae. Additionally, the ionic strength of the medium, hydrophobicity and net charge, phase of cellular growth, CO$_2$ concentration, particle size, and zeta potential will influence flocculation processes [93, 94].

The use of cassava starch as a microalga harvesting agent has already been tested in the laboratory as shown in Table 5. The volume of microalgae cultures that have been employed in numerous industries (food, feed, and cosmetics). According to FAO [95], 56,456 tons of microalgae were produced, with 99.56% coming from *Spirulina* (Arthrospira) and the remaining 248 tons derived from other single-celled microalgae such as *Haematococcus pluvialis*, *Chlorella vulgaris*, *Tetraselmis* spp., and *Dunaliella salina*. One of the reasons for the low production of other single-celled macroalgae could be the inefficiency of the harvesting technique. In light of this, it appears that studies on flocculation harvesting techniques, including the use of cassava starch as a natural material-based flocculant agent, are still in great demand. However, laboratory research on cassava starch as a harvesting agent for microalgae is still limited to microalgae and cassava species. Only two literatures, namely Jangyubol, Kasemwong, Charoenrat and Chittapun [78] and Chittapun, Jangyubol, Charoenrat, Piyapittayanun, and Kasemwong [13] have intensively investigated cassava starch as a flocculant agent. Some additional research is required, such as increasing microalgae volume levels, toxicity analysis, marine microalgae species utilization, end product nutrient analysis, and until microalgae production is economically feasible. Cassava starch's economic worth, renewable availability, and biodegradability have attracted industrial levels despite the fact that starch is only the planet's second most plentiful natural polymer [13].

6. Future prospective

The integration of the cassava industry and the microalgae biorefinery is a promising and sustainable technology. Using cassava waste to grow microalgae can help to reduce the environmental impact of the cassava flour industry. Additionally, using cassava waste as a substrate for microalgae can reduce manufacturing costs. Microalgae can generate useful products comprising protein, lipids, antioxidants, and vitamins. In addition, harvesting microalgae with cassava starch is highly effective and minimizes the cost of producing microalgae biomass. In addition, the development of fortified staple foods is necessary for the future improvement of public health. Trends in health and fitness increase demand for microalgae and cassava products. Microalgae can be added to cassava products to improve their nutritional value. The addition of microalgae to cassava products can help the sustenance of the community. Furthermore, the addition of microalgae to baby food items helps prevent
infant stunting. Moreover, biomass derived from microalgae and cassava can be used to produce plant-based proteins. The development of high-protein and mineral-rich plant-based proteins is primarily motivated by the desires of vegetarian and vegan societies.

In conclusion, the integration of the cassava industry with microalgae biorefinery has numerous environmental and social benefits. It contributes to the implementation of clean technology within the cassava industry. Additionally, it adds to the nourishment of the population. Responsible consumption and production, ending hunger, protecting terrestrial and marine ecosystems, and preserving biodiversity are just a few of the Sustainable Development Goals that benefit from this work.
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