MT-Pallantia Publisher

Journal of Science with Technological Applications
ISSN: 0719-8647

Yam starch: approach towards agroindustry in the production of biomaterials

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Graphical Abstract

Abstract. Over the years, yam cultivation has had a significant increase in its production, obtaining an important level in the food chain and it is mainly grown as family agriculture, its main use is for food and some of the species are used in the pharmaceutical industry for the manufacture of biopolymers. On the other hand, the negative effects on the environment that synthetic polymers generate due to their excessive use and that require thousands of years for their degradation at the molecular level have been demonstrated. Due to this situation and seeking to mitigate environmental problems, efforts have been made to develop materials that replace the use of plastic. There are many residual materials in agriculture that can be used as raw materials for the production of biodegradable products, including biopolymers of plant origin that come from yams, among others. In the present work, a bibliographic review is carried out with the objective of publicizing the potential of this crop, as well as collecting information that may be of interest for the development of new technologies that generate environmentally sustainable alternatives that can be adopted by the agroindustry in a promising product.

Keywords: Starch, yam, agroindustry, bioplastics, gels.

Cite as: Mercado L.L., Polo P.C., Combatt E.M., Caraballo D.E., Rodríguez L.A., López M.J., Palencia M., Arrieta Á.Á. Yam starch: approach towards agroindustry in the production of biomaterials. J. Sci. Technol. Appl., 19 (2025), Art-112, 1-10.
https://doi.org/10.34294/j.jsta.25.19.112

Accepted: 2024-01-15 | Published: 2024-03-01 | Paper Number: 112 (STEM) | Review Article

Content

1. Introduction

The yam tuber (*Dioscorea* spp.) is one of the most important foods from the soil worldwide, occupying third place after cassava and sweet potato (Marcos et al., 2009), in addition, it is one of the genera which belongs to the *Dioscoraceae* with more than 600 species, many of them with great agro-industrial potential. It is a monocotyledonous plant whose main organ of interest is the tuber. These plants are characterized by being dioecious, herbaceous, and with small flowers. Therefore, its taxonomic classification is the following according to Janssenns (2001):

- Kingdom: Plantae
- Division: Magnoliophyta
- Class: Liliopsida
- Order: Dioscoreales
- Family: Dioscoreaceae
- Genre: *Dioscorea*

This tuber is native to tropical and subtropical regions around the world, it is mainly cultivated in continents such as Asia, Africa, and other developing countries with tropical zones (Thurston, 1989), among these developing countries is Colombia, where the yam is considered an endemic food in the Caribbean region because it has large tropical areas, with the *D. alata* and *D. rotundata* species being the most cultivated currently (Queen, 2012). Its main use is food and some of the species are used in the pharmaceutical industry and the manufacture of biopolymers (Tejada et al., 2007). However, there is little evidence for the use of yams and their by-products in areas other than food (Queen, 2012). On the other hand, currently, the food industry is looking for starches that, according to Vargas and Hernández (2013), have precise characteristics such as resistance to acidity, sterilization, mechanical stress, and other industrial processes used. In this case, yam starch has properties that are of interest to the industry, which is why its use for the production of biopolymers is being studied.

The use of polymers generates a negative impact on the environment despite the fact that they have better flexibility and resistance properties, since they derive from a material that is not biodegradable and renewable, such as petroleum (Srichuwong and Jane, 2007). At present, the negative effects on the environment generated by synthetic polymers have been evidenced due to their excessive use and that they require thousands of years for their degradation at the molecular level. Due to this situation and seeking to mitigate environmental problems, efforts have been made to develop materials that replace the use of plastic (Valarezo, 2012). There are many residual materials in agriculture that can be used as raw material for the production of biodegradable products, including biopolymers of plant origin obtained from different sources such as cassava, corn, potato, and yam, among others (López et al., 2023), in addition, yam starch, compared to potato, rice and cassava starches, has a medium amylose content (Mali et al., 2002).

On the other hand, studies have been carried out that show the presence of chemicals called diosgenin and sapogenin in varieties of yams grown in the Caribbean region corresponding to the species *D. alata* and *D. rotundata*, they are used for the preparation of steroids such as estrogen (Hata et al., 2003), these important findings may imply a strategy that would increase the sustainability of small yam producers thanks to their potential for the pharmaceutical industry and health sector. Furthermore, another study carried out by Chiang et al. (2018), evaluated the estrogenic activity of ground yam on a yeast strain in the proliferation of cancer cell lines, resulting in diosgenin as the main compound for the activity and inhibition of cancer cells. The use of biopolymers based on natural sources such as the derivative obtained from lactic acid called polylactic acid has been widely used because it helps reduce the use of petroleum-derived plastics (Rojas et al., 2015), in addition, the following review article aims to collect information on the uses of yams in agribusiness as a raw material for the production of biopolymers.

2. Chain of production

The most cultivated variety of yam is the Criollo with a percentage of 43 %, followed by the Espino variety with 42 %, however, these are not the only cultivated varieties since there are many producers who grow varieties such as Diamante 22 with a percentage of 15 % due to, which is not very common except when exporters require it, because it is considered a non-commercial variety in Colombia, for this reason, cultivation with that variety is not profitable (Escudero et al., 2010). For sowing this type of crop, the seeds are separated from the previous harvest, because there is no seed trade, so the producers themselves are in charge of selecting the seeds for the next harvest, of the total seeds only 22 % are fertilized and the re-

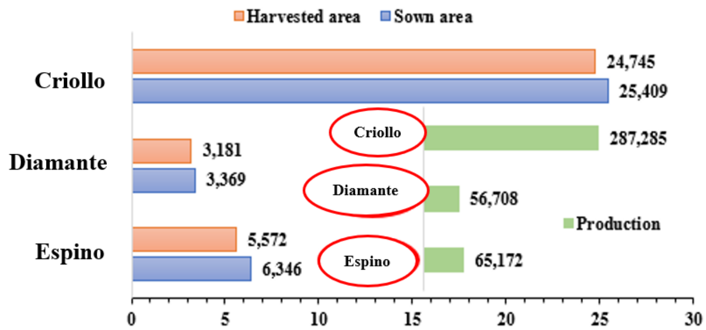

Figure 1. Productive indicators of Espino, Diamante, and Criollo yam varieties. Source: Municipal agricultural evaluations (MADR, 2021).

maining 35 % have fungicides added before planting (Escudero et al., 2010). From another point of view, yam cultivation lacks new agronomic practices, and establishment of monocultures, which generates high production costs in labor, this is due to the lack of research in previous years. On the other hand, a problem that exists in production is storage because it loses weight in different conditions. Furthermore, there are no storage structures, so there is a direct effect on the market price, therefore, it affects the economy. However, many of the producers have found a way to continue producing the yam with the help of research centers, managing to market it in Latin America and Europe (Vinicius et al., 2023).

2. National yam production

At the national level, yam has been grown mainly on the Caribbean coast, where it is practiced as family agriculture due to the low presence of large farmers, it is grown in the patios of houses or on small plots of land to obtain the necessary production for daily needs, the most common and easy to plant varieties are the Criollo, Espino, and Diamante yams. As a consequence of the above, the government has been allocating resources to conduct research on management practices, achieving significant increases in yam production to move from a micro to a macro level of production. Therefore, the research carried out by MADR (2021), in 2019 shows yam production exceeding 400.000 tons of common varieties grown for years, the information collected is detailed in **Figure 1**.
The greatest presence of these yam crops is found in the departments of Bolívar with 36 % of the production, Córdoba 33 %, Sucre 18 %, and the rest of the distribution is found in Antioquia. **Figure 2** shows the production in detail by tons that each department generates per planting area, it should be noted that the greatest production is contributed by Bolívar. It is also important to mention that other departments of the country also grow yams, but only in minimal quantities that are used to feed nearby areas (MADR, 2021). In 2015, yam crops on the Caribbean coast reached a production of more than 400.000 tons. Furthermore, the production indicators obtained in the departments of Bolívar and Atlántico stand out, which managed to double their yields thanks to the implementation of new agricultural practices.

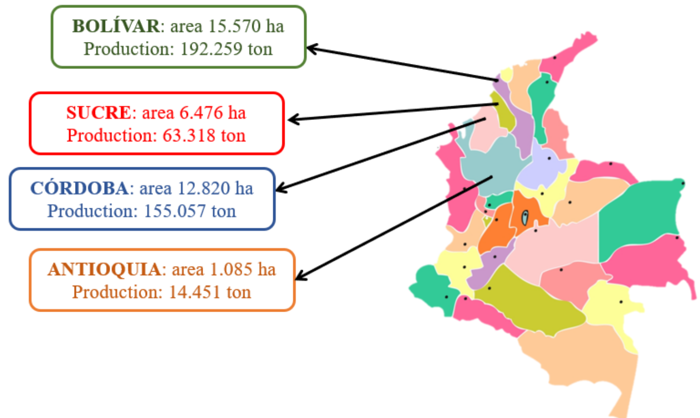

Figure 2. Yam production by planting area in departments of Colombia Fountain: Own elaboration based on MADR data (MADR, 2021).

2.3. Production costs

In Colombia, planting a hectare of yams has significant costs and depends on the variety to be grown. To learn a little more about production costs, is highlighted that the cost for planting one hectare of Criollo yam costs approximately 3.000.000 pesos (before 2000's), while the production cost of Hawthorn yam is four times higher, so it must be taken into account that prices may vary depending on the conditions of the land. Due to the high production costs throughout the different years, the main economic source of producers is credits, which according to FINAGRO, in the last 7 years more than 1.464 credits have been granted for the maintenance of yam cultivation, each year above 10.000.000 pesos. In 2020, according to AGRONET figures, an approximate production of 423.000 tons of yams was recorded, which were mainly sold in the markets of the cities of Cartagena, Barranquilla, and Montería (FINAGRO, 2021). In addition to this, MADR (2021), indicates that only 2 % of production is sold in wholesale stores focused on the Caribbean coast, which is why it has been considered a fundamental part of traditional food with the potential to exploit it.

3. Industrial applications of yam by-products

3.1. Starch

Starch is an inexpensive biobased polysaccharide with excellent biocompatibility and biodegradability, and is mainly available in vegetables. Starch is highly appreciated and used because it improves the functionality, consistency, and reliability of food processes, in the same way it provides moisture and texture in foods, it also gives resistance to high temperatures, and in the same way, it protects the processes of refrigeration and freezing (Cornejo et al., 2017). On the other hand, the most common sources used to develop

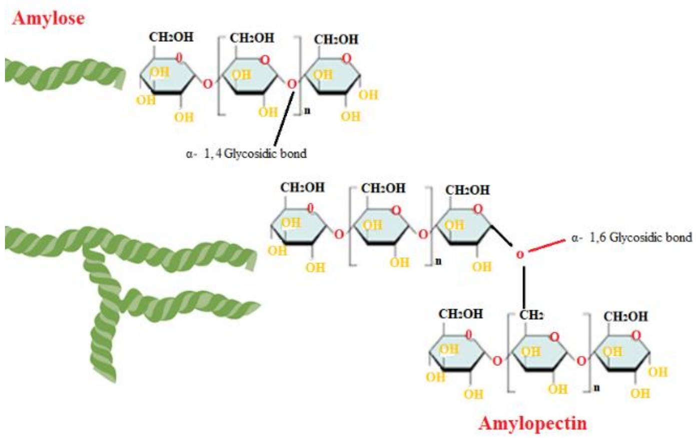

Figure 3. Structure of Amylose composed of D-Glucose with the union of α-(1-4) bonds being a linear polymer; B. Structure of Amylopectin composed of D-Glucose with the union of bonds in α-(1-4) and α-(1-6) converting it into a branched polymer. Adapted from (Navarro et al., 2019).

bioplastics are those of plant origin due to their low cost, renewal, abundance, and availability (Acquavia et al., 2021), they are sources that have a large composition of amylose and amylopectin, their chemical structure can be seen in **Figure 3**.

Starch in its structure has many hydroxyl groups (O-H), where the O-H found on carbons C-2, C-3, and an O-H of C-6 are not interconnected; allowing the starch to be hydrophilic. In addition, the structure of Amylose presents linear molecules of glucose elements connected by α-(1-4) bonds, and with some ramifications with α (1-6) bonds. Therefore, the structure of Amylopectin unites because it has bifurcated molecules with α-(1-6) bonds that allow branched structures to be attached to the linear glucose chain with α (1-4) bonds (Navarro et al., 2019).

The amylose content in yam is around 30 %, according to Salcedo et al. (2016), the amylose content for the Espino and Criollo varieties is between 23.37 – 25.01 % respectively. Therefore, it is favorable for the formation of films that allow the structure to be more stable in environmental conditions (Caetano et al., 2018), although it has a disadvantage due to its brittle behavior (Nguyen and Lumdubwong, 2016). Due to these deficiencies, many researchers have reported the integration of a plasticizer, such as glycerol, to make films softer, thus improving their flexibility.

3.2. Properties of agroindustrial interest of yam starch

3.2.1. Amylose content

Amylose is one of the main compounds found in starch, which has transcendental importance in the main properties and its applications in the industry (Jiang et al., 2010), in addition, the contents may vary depending on the species. On average, the content of amylose in *D. alata* is 28.50 %, according to an investigation carried out by Karam et al. (2006), the yam *D. alata* has 28.50 % of amylose, values that contrast with those obtained by Freitas et al. (2004), with 36.4 %. It should be noted that the amylose content values for the same sample may vary depending on the analysis method used (Rolland et al., 2003). In addition, different environmental factors have been determined, such as practices of fertilization, water availability, disease management, and insects that can intervene in the production of amylose in yams (Huang et al., 2006).

3.2.2. Gelatinization

One of the most important properties of starch is gelatinization, which influences the proportion of amylose and amylopectin, and also depends on the size of the molecules, and intermolecular forces, among other properties (Rached et al., 2006). However, amylose has the ability to disperse the molecules to form a gel, while amylopectin loses the form of crystal organization (Singh et al., 2003). In the case of yam, recent studies have found gelatinization temperatures depending on the variety with values between 82.30 and 84.43 °C (Salgado et al., 2019). Therefore, research conducted by Singh et al. (2003), mentions that the most effective way to measure starch gelatinization is through differential scanning calorimetry (DCS), which consists of mixing a portion of starch with purified water in a container that resists temperatures and is closed, heated with programmed temperatures, the initial, maximum and final temperatures are recorded to obtain the enthalpy change. On the other hand, Sang et al. (2008) mention that another very common method is Kofer Hot Stage Microscopy (KHSM), in which gelatinization temperatures are obtained and at the same time the changes that occur in the granules can be observed microscopically.

3.2.3. Solubility

According to what was investigated by Daiuto (2005), when starch is subjected to high volumes of water and is subsequently subjected to high temperatures, its structure breaks hydrogen bonds and the structure becomes completely unstable; allowing the water molecule to join by hydrogen bonds through the free functional groups of amylose and amylopectin, which reflects an increase in the starch size and solubility. While Yamani (2010), establishes that the increases in size and solubility depend on the variety chosen (from where to extract the starch), morphology, and structure of the starch. As mentioned above, when the starch increases in size, amylose is released, therefore, the starch grains become more soluble. Therefore, it can be affirmed that as the size of the starch increases, its solubility will increase. In addition, it is important to emphasize that what allows solubility is the breaking of the chain of the amylose molecule, because it inhibits swelling and due to its properties decreases solubility (Salcedo et al., 2018).

Mercado L.L., et al., J. Sci. Technol. Appl. 19 (2025), art 112,1-10. DOI: 10.34294/j.jsta.25.19.112
ISSN: 0719-8647 | Available: www.jsta.cl

3.2.4. Viscosity

Viscosity is a fundamental property in starch compounds since it allows us to know the behavior of the materials when they are subjected to increases in temperature and at the same time observe any type of change that occurs in the paste that is being formed. According to Guerreiro (2002), this property is generally evaluated with significant increases in temperature as a function of time up to approximately 95 °C. In accordance with what was mentioned by the previous author, it is understood that viscosity depends mainly on two aspects, which are the increase in the size of the starch grains and the resistance to solubility in the face of increases in temperature, therefore, when it is subjected to a volume of water and the temperature is increased, we speak of an increase in the viscosity of the compounds. This occurs because the granules release a low molecular mass compound, such as amylose in this case. Because of this, this property reaches its maximum during bonding, but if there is a temperature change lower or higher than 95 °C and constant stirring is lost, this value can drop (Zortéa et al., 2011). Furthermore, according to Ribeiro (2011) indicates that the form in which the polysaccharides are found can have a direct impact on viscosity. When these compounds are subjected to a viscous solution, they can circulate without any impediment in a place called the effective volume. In the case of polysaccharide structures that are linear, when found in viscous solutions they have the capacity to occupy more space, so their molecules manage to collide with each other, causing an increase in temperature that is observed with the increase in temperature and viscosity. However, these molecules that have branched structures, with the same molecular weight, can take up less space, making it difficult for one molecule to collide with another, resulting in lower viscosity.

3.3. Uses of yam starch as an innovative technology

According to Nascimento et al. (2005), the use of edible or biodegradable films and coatings for food protection has been used empirically through generations, which has generated an increase over the years. In the 12th and 13th centuries, it was very common in China to use a layer of wax from oranges and lemons to reduce water loss. Later, around the 16th century in England, it was common practice to cover foods to reduce the rate of dehydration of these products. Taking into account that over the years new needs for innovation and production are created; taking advantage of the resources that are available in nature, for this reason, the need is created to use native starch in different activities, according to its chemical, physical, and functional properties of amylose in the formation of gels and its ability to form films. For this reason, the parallel organization that amylose molecules tend to take when they are in solution can reduce the compatibility of the polymer in contact with water, which favors the formation of hydrogels and films with greater resistance (Xiao et al., 2012).

3.4. Biodegradability

Currently, the term biodegradability plays an important role, taking into account the damage caused by polymers such as plastic that resist degradation due to biological effects and subsequently accumulate, generating pollution in the environment (Vroman and Tighzer, 2009); for this reason, the biodegradability properties of the new compounds that are created day by day, to select a polymer as a biodegradable material, both the mechanical properties and the degradation time necessary for a particular application must be taken into account. The factors that influence the degradation rate, according to Moncmanová (2007), are:

- Natural conditions: humidity, solar radiation, movement, air pressure, precipitation.
- Chemical conditions: effects of interaction between particles or incidence of some molecules.
- Biological conditions: attacks by micro or macroorganisms.

One of those that is very relevant is the incidence of microorganisms, be they bacteria, fungi, or algae, which mainly act through biochemical processes where enzymes intervene (Tejada et al., 2020). In addition, an interaction occurs between the effects of the conditions mentioned above, where water intervenes first, which allows the polymers to be completely fragmented through chemical bonds, and then the metabolic processes that end with the reduction of the polymeric mass that is biodegrading.

3.4.1 Biodegradable Polymers

Biodegradable polymers have been working for many years, the first ones were developed in the 80's with a mixture of a compound called polyophelines and starch, managing to break down into different fragments, although this first generation was not accepted and had to be completely withdrawn (Tejada et al., 2020). At present, different biodegradable polymers have continued to be developed, however, their main problem is production costs and therefore, the market price, for which, the polymers produced have been:

- starch-based
- based on Poly(lactic) acid
- based on Polyhydroxyalkanoates
- based on Polycaprolactones

Many of the investigations have shown that starch-based polymers present good biodegradability results, due to their easy processing and their mechanical properties when mixed with synthetic poly-

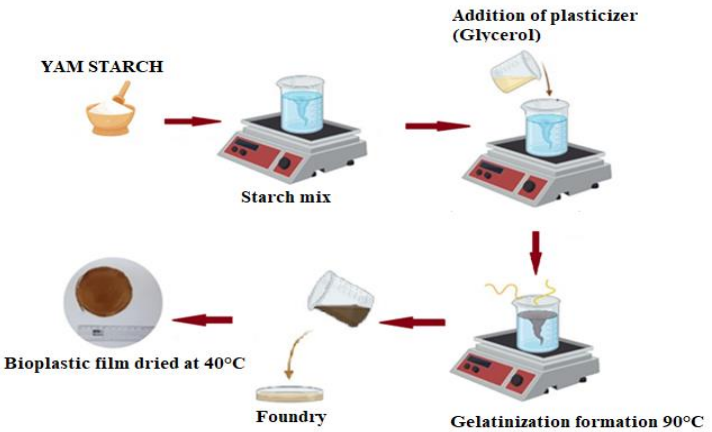

Figure 4. Schematic of the development of a bioplastic film from yam starch. Source. Adapted from Behera et al. (2021).

mers according to Tejada et al. (2020). On the other hand, the results obtained with polylactic acid show that it has desirable properties and its processing is relatively easy; however, its main problem is production costs. In addition, polylactic acid (PLA) has good mechanical properties, and transparency in addition to its processability, but its greatest disadvantage for many applications is its fragility and its high cost decreases the possibilities of commercialization. Starch blends with non-biodegradable polymers such as polyethylene (PE), polyvinyl chloride (PVC), ethylene-vinyl alcohol copolymers, and ethylene-acrylic acid copolymers, starch blends with other biodegradable polymers such as aliphatic polyesters (Ruiz, 2005).

4. Development of biodegradable bioplastic films for applications in agribusiness

Recently Behera et al. (2021), showed he developed a new bioplastic film using yam starch, glycerol (as a plasticizing agent), and bentonite (reinforcing filler). Therefore, for the development of this film, *in-vitro* tests were carried out with the objective of obtaining bioplastic films that can supplant the use of plastic in the food industry, additionally, an attempt was made to improve the biodegradability properties (Behera et al., 2021). The procedure for the development of this research is schematically represented in **Figure 4**. This study complements the research carried out by Reis et al. (2013), where drying temperatures and glycerol concentration in film-forming were studied for the subsequent development of yam starch-based hydrogels. In said investigation, it was determined that the glycerol concentration did not influence any of the parameters evaluated.

4.1. Related research

According to Durango et al. (2009), research was carried out to extract and characterize yam starch in order to develop antimicrobial edible films and determine its permeability to water vapor. This study demonstrated, due to its physicochemical properties and viscosity, that yam starch has potential in the food industry with the production of films highly biodegradable films. However, another application of yam starch in agroindustry is that it has the ability to coat seeds to be a bridge between the passage of water and oxygen, which are essential for the germination stage, depending on its affinity for water (hydrophobic or hydrophilic property), it can also act as a carrier of nutrients or chemical and biological substances that can help in the development of plants (Lobato et al., 2019). On the other hand, the use of yam starch-based coatings has been shown to preserve the bright color of minimally processed carrots after 15 days of storage (Durango et al., 2011).
Starch offers advantages in the food industry, since it can be used to thicken foods such as soups and liquids (Alvis et al., 2008), the same occurs in the pharmaceutical industry. Its use is favorable, due to the influence on the creation of syrups through the use of the α-amylase enzyme in 36 and 46 % yam starch solutions (Vidal, 2010). Studies carried out on the microencapsulation of Thyme essential oil in polymeric matrices using yam starch (*D. rotundata*), subjecting it to hydrolysis and lipophilization processes, using dodecenylsuccinic anhydride (DDSA) can significantly increase the oily and emulsifying (surfactant) capacities of native starch, whose main function is to encapsulate the essential oil of thyme, which has already been shown to have powerful antibacterial activity on the strains involved in the development of acne. Microencapsulation was carried out using solid lipid microparticles, followed by emulsification, obtaining favorable results that contribute to the development of stable and functional pharmaceutical, cosmetic, and food formulations of essential oils (Matiz et al., 2015). **Figure 5**, shows the absorption capacity of starches.

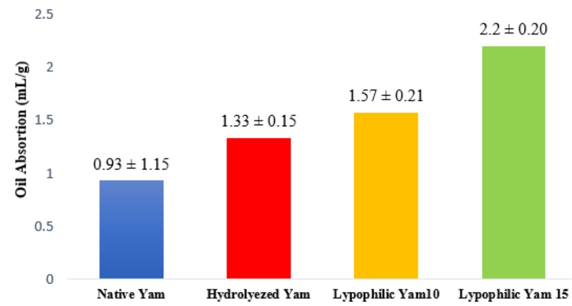

Figure 5. Oil absorption capacity of native starches. The values correspond to the measurements of three replicates ± the standard deviations of the native starches (Matiz et al., 2015).

5. Conclusions

The use of yam starch in the elaboration of biodegradable materials attributes an added value to this crop due to its energy potential due to its composition, because it is a crop that is highly adaptable to environmental conditions and sustainable, in addition, it can provide information in the technological development of agroindustry. The physical and chemical properties of yam starch allow it to be applied in different industrial fields, which can be clarified with the reported research, affirming that this crop is a reliable path for sustainable innovation. In addition, the implementation of self-sustaining techniques in agro-industry, provides great advantages, in terms of reducing plastic materials and increasing the economy in rural areas that are involved with cultivation. However, it is important to acknowledge that further research and development are necessary to fully realize the potential of yams in the production of biodegradable materials. Studies focused on optimizing the extraction and purification processes of yam starch, as well as exploring its compatibility with different industrial applications, are essential for scaling up its usage. Additionally, collaboration between researchers, policymakers, and industry stakeholders is crucial to ensure the successful implementation and adoption of these sustainable technologies.

Conflict interest. The authors declare that there is no conflict of interest.

Acknowledgements. The authors thank to Universidad de Córdoba, Universidad del Valle, Universidad de Sucre, and National Planning Department of Colombia, specifically, the general royalty system (Sistema General de Regalías, SGR) for project BPIN 2020000100027.

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