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PROPERTIES OF MALANGA FLOURS AND THEIR USE IN PASTES AND GLUTEN- FREE BREADS

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Hace constar:

Que la presente Tesis Doctoral, titulada "Properties of malanga flours and their use in pastes and gluten-free breads" que presenta Jehannara Calle Domínguez para optar al grado de Doctor por la Universitat Politècnica de València, ha sido realizada en el Instituto de Agroquímica y Tecnología de Alimentos (IATA-CSIC) bajo su dirección y que reúne las condiciones para optar al grado de Doctor en Ciencia, Tecnología y Gestión Alimentaria.

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Prof. Cristina Molina Rosell

Efectivamente...Hay gente que, no es pobre por cómo vive, sino por cómo piensa

Platón

A Cristina por creer en mí, a Yaiza por soportarme y a los que dieron su aporte a mi tranquilidad emocional para alcanzar mi meta.

Resumen

El uso de *Colocasia esculenta* (L.) Schott y *Xanthosoma sagittifolium* (L.) Schott como materia prima en forma de almidón o harina es una alternativa sostenible y nutritiva al trigo y otros granos. Esta alternativa permite a los agricultores minimizar las pérdidas después de su cosecha y garantizar la seguridad alimentaria ya que sus propiedades nutricionales, digestivas y saludables son reconocidas por la comunidad científica. Sin embargo, la información existente sobre este rizoma dirigida a su aplicación es bastante limitada. Esta tesis expone la caracterización funcional y tecnológica de los almidones obtenidos a partir de cormos y cormelos de *Xanthosoma sagittifolium* (L.) Schott. Asimismo, se evaluó tecnológicamente el efecto de la combinación de enzimas, hidrocoloides, almidón de patata, harina pre-gelatinizada sobre la harina de los cormelos de la *Colocasia esculenta* (L.) Schott en el desarrollo de un pan sin gluten. Además, se evaluaron las propiedades tecnológicas y digestivas de una fórmula básica para puré desarrollada a partir de harina de cormelos de *Xanthosoma* spp. y *Colocasia* spp. Además, la revisión bibliográfica realizada permitió poner en contexto los efectos saludables demostrados clínicamente de esta materia prima y sus componentes.

Se demostró que existen diferencias significativas entre el almidón de cormos y cormelos de la misma especie. Se concluyó que la harina de *Colocasia esculenta* (L.) Schott es una buena opción para incrementar el valor nutricional de los panes sin gluten. Entre las estrategias probadas, el pan elaborado a partir de la mezcla con almidón de patata resultó la menos aconsejable. Además, todas las estrategias aplicadas originaron panes con menor índice glucémico que sus homólogos sin gluten reportados en otros estudios. Por primera vez, este trabajo recomienda el uso de harina de cormelos de *Xanthosoma sagittifolium* (L.) Schott y *Colocasia esculenta* (L.) Schott y para desarrollar purés con un valor nutricional agregado. La revisión bibliográfica realizada permitió recopilar los efectos demostrados clínicamente, concretamente antihiperglucémicos, antihepatotóxicos, antihipertensivos, hipoglucemiantes, anticancerosos, hipolipidémicos y prebióticos, entre otros, de los compuestos bioactivos presentes en esta planta.

Abstract

The use of *Colocasia esculenta* (L.) Schott and *Xanthosoma sagittifolium* (L.) Schott as a raw material in form of starch or flour is a nutritious and sustainable alternative to wheat and other grains. This alternative allows farmers to minimize losses after harvest and guarantee food safety since its nutritional, digestive and healthy properties are recognized by the scientific community. Nevertheless, there is still scarce information about these rhizomes that limit their application. This thesis illuminates the functional and technological characterization of the starches obtained from corms and cormels of *Xanthosoma sagittifolium* (L.) Schott. Likewise, the effect of the combination of enzymes, hydrocolloids, potato starch, pre-gelatinized flour on *Colocasia esculenta* (L.) Schott cormels flour toward the development of a gluten-free bread was technologically evaluated. Furthermore, the technological and digestive properties of a basic formula for pastes developed from cormels flour of *Xanthosoma sagittifolium* (L.) Schott and *Colocasia esculenta* (L.) Schott was evaluated. In addition, a review was conducted and the health effects clinically demonstrated are exposed.

It was shown that there are significant differences between the starch of corms and cormels of the same species. It was concluded that the flour from *Colocasia esculenta* (L.) Schott cormels is a good option to increase the nutritional value of gluten-free breads. Among the strategies tested, the bread made from mixtures with potato starch was the least desirable, but all strategies tested gave breads with lower glycemic index than gluten-free counterparts reported in other studies. For the first time, this works recommends the use of cormels flour from *Xanthosoma sagittifolium* (L.) Schott and *Colocasia esculenta* (L.) Schott was recommended to develop pastes to nutritional value to gluten-free products. In addition, the bibliographic review carried out allowed the compilation and analysis of the clinically demonstrated effects, especifically, antihyperglycemic, antihepatotoxic, antihypertensive, hypoglycemic, anticancer, hypolipidemic and prebiotic effects, among others, of the bioactive compounds present in these plants.

Resum

L'ús de *Colocasia esculenta* (L.) Schott i *Xanthosoma sagittifolium* (L.) Schott com a matèria primera en forma de midó o farina, és una alternativa per a minimitzar les perdues després de la seua collita i garantir la seguretat alimentària ja que les seues propietats nutricionals, digestives i saludables són reconegudes per la comunitat científica. Aquesta tesi exposa la caracterització funcional i tecnològica dels midons obtinguts a partir de corms i cormelos de *Xanthosoma sagittifolium* (L.) Schott. D'una banda és va avaluar tecnològicament l'efecte de la combinació d'enzims, hidrocol·loides, midó de creïlla, farina pre-gelatinitzada sobre la farina dels cormelos de la *Colocasia esculenta* (L.) Schott en el desenvolupament d'un pa sense gluten. D'altra banda, es van avaluar les propietats tecnològiques i digestives d'una fórmula bàsica per a puré desenvolupada a partir de farina de cormelos de *Xanthosoma spp*. i *Colocasia* spp. que es pot destinar a poblacions vulnerables amb afeccions gastrointestinals, diabètics, celíacs, entre altres. A més, es va realitzar una revisió on s'exposen els efectes saludables demostrats clíni-cament, dels seus components.

Es va demostrar que existeixen diferències significatives entre el midó de corms i cormelos de la mateixa espècie. Per tant, es va concloure que la farina dels cormelos de la *Colocasia esculenta* (L.) Schott és una bona opció per a incrementar el valor nutricional dels pans sense glútens i entre les estratègies provades, el pa elaborat a partir de la mescla amb midó de creïlla va resultar la menys aconsellable, però tots van mostrar menor índex glucèmic que els seus homòlegs sense glútens reportats en altres estudis. A més, per primera vegada es va recomanar l'ús de farina cormelos de *Xanthosoma sagittifolium* (L.) Schott i *Colocasia esculenta* (L.) Schott per a desenvolupar purés amb un valor nutricional agregat. La revisió bibilogràfica realitza va permetre recopilar el efectes demostrats clínicament, en concret antihiperglucémic, antihepatotóxic, antihipertensiu, hipoglucemiant, anticancerós, hipolipidémic i prebiòtic, entre altres, dels compostos bioactius presents en aquest rizoma.

I. Introduction

1. *Colocasia esculenta* (L.) Schott and *Xanthosoma sagittifolium* (L.) Schott production around the world

Colocasia esculenta (L.) Schott (*Colocasia* spp.) and *Xanthosoma sagittifolium* (L.) Schott (*Xanthosoma* spp.) are the most consumed species among Araceas family. They belong to the genus *Colocasia* and *Xanthosoma*, respectivily. These crops originated in ancient times with their corms or cormels used as the edible parts, serving as human foods in many developing countries (Garcia *et al.*, 2010). Their rizhomes are mainly consist of starch similar to patata, cassava (*Manihot esculenta*) and sweet potato (*Ipoemea batatas*), presenting superior nutritional value, protein digestibility and mineral composition (Wada *et al.*, 2019).

Xanthosoma spp. production is concentrated in the Americas, principally in tropical South American (Fig. 1A). It has been domesticated by people of the Caribbean (Owusu *et al.*, 2014), with Cuba being the largest producers in the world with 192,938 t followed by Venezuela with 83,572 t (FAOSTAT, 2018). *Colocasia* spp. is grown primarily in Africa and Asia with minor production in the Caribbean and Oceania countries (Fig. 1B). African countries generate the 74% of *Colocasia* spp. production, with Nigeria being the major producer (3,303118 t) (FAOSTAT, 2018).

These crops are widely consumed in Latin American and African countries but their consumption in Europe is still limited due to the scarce knowledge about their properties.

Spaniards from the Canary Island introduced the two genera to Cuba. Particularly, the central province of the country (Cienfuegos) is the region with the richest variability in *Colocasia* spp. varieties, followed by Pinar del Río (western region).

Fig. 1A. Production of *Xanthosoma* spp. around the world. Source: (FAOSTAT, 2018).

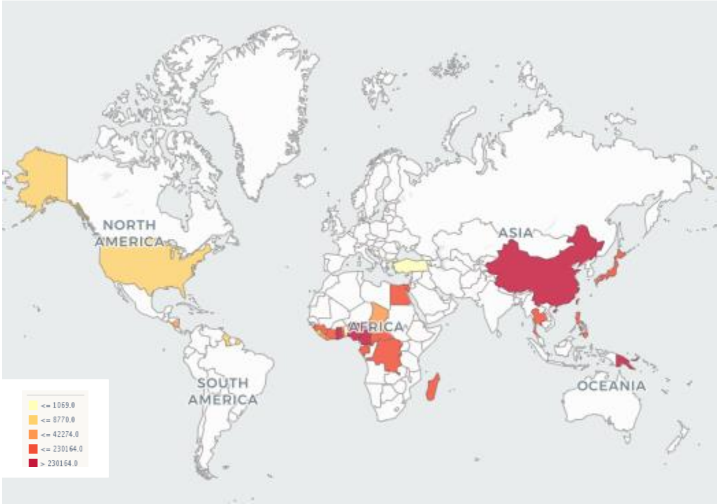

Fig. 1B. Production of *Colocasia* spp. around the world. Source: (FAOSTAT, 2018).

The harvest cycle of *Colocasia* spp. oscillates between 9 and 11 months and the total area sowed decreased from 69557 ha in 2015 to 4200 ha in 2018 (Gálvez *et al.*, 2018; Figueroa-Aguila *et al.*, 2019). In the case of *Xanthosoma* spp. the harvest cycle varies between 11 and 12 months. The total production of *Xanthosoma* spp. (100,000 t) doubled that of *Colocasia* spp. (50,000 t) in 2017 since it is preferred by consumers, presents a better yield and it is more resistant to drought (Gálvez *et al.*, 2018; Jiménez, 2018).

2. Nomenclature, edible part and consumption

Around the world, these plants are referred to by different names. In African countries, such as Nigeria and Cameroon (Markusse *et al.*, 2018) among others countries (Owusu *et al.*, 2014), cocoyam is the name use both species (*Xanthosoma spp.* and *Colocasia* spp.) (Alalor *et al.*, 2014).

Furthermore, in the literature different common names have been used to refer to the same species. The most common names are: taro, amadumbe (*Colocasia* spp.) in Durban (South Africa), yautía (*Xanthosoma* spp.) in Dominican Republic and Puerto Rico, or malanga (*Xanthosoma* spp. and *Colocasia* spp.) in Cuba, among others. Therefore, there is not a consensus among the scientific community to name these crops, which are driving to misunderstandings in the literature. For example, Ramos *et al.* (2020) refers to cocoyam and taro as independent tubers. Likewise, Wada *et al.* (2019) and Garcia *et al.* (2010) assigned taro to *Colocasia* spp. and cocoyam to *Xanthosoma* spp. Other authors, used tannia to name *Xanthosoma* spp. (Owusu *et al.*, 2014), while in Togo (West of Africa), tannia is recognized as new cocoyam, although that was used for the particular specie of *Xanthosoma*: *Xanthosoma mafaffa* (L.) Schott (Bammite *et al.*, 2018). In Ghana, *Xanthosoma* spp. is known as new tannia and *Colocasia* spp. it is recognized as old cocoyam (Alfred *et al.* 2016).

Besides to the previous controversy, there is much confusion about the rhizome part (corms or cormels) used in the research. There are some studies that characterize *Colocasia* spp. and *Xanthosma* spp., but without specifying the part of rizhome used for researches (Himeda *et al.*, 2014; Perez *et al.*, 2007). Following the author criteria, it would be recommended to name these crops with the scientific name (*Colocasia* spp. or *Xanthosma* spp.) and to identify correctly the part of tubers under study.

Corms and cormels obtained from *Colocasia* spp. and *Xanthosoma* spp. are used worldwide for human consumption (Njintang *et al.*, 2006). In

South Africa, corms from *Colocasia* spp. are usually consumed (Mawoyo *et al.*, 2017). In others countries like West Africa, corms of *Xanthosoma* spp. are boiled and mashed to produce weaning foods (Owusu *et al.*, 2014), while, in Ethiopia corms are peeled, dried and ground into flour but cormels are boiled or partly boiled, baked and fried previously to consumption (Coronell-Tovar *et al.*, 2019; Wada *et al.*, 2019). Usually, in Cuba corms and cormels from *Colocasia* spp. are consumed, but the central corm is preferred and cormels are used for sowing (Figueroa-Aguila *et al.*, 2019). Only the cormels of *Xanthosoma* spp. are used for human consumption and their corms are used to guarantee the production (Owusu *et al.*, 2014).

In Cuba, these rhizomes play a major role feeding the babies. They are the first food that health autorities recommends to mothers when introducing babies to chewing foods after the first six months of their life. Other common use is to include malanga as a basic healthy food, for example, in the diet of the hospitalized people, nursing homes, children's circles and when people has any stomach disorder (Jiménez, 2018). Usually, to keep the healthy properties and appropriate sensory texture, the rhizome is boiled in typical dishes like those called "*caldosa*" or "*ajiaco*", or alternatively fried or pounded into puree. In Asian countries, typically is consumed as a fermented food made with *Colocasia* spp. named *poi*. Some studies showed that babies who were fed with *poi* had lower incidence of health disorders such as diarrhea, pneumonia, enteritis and beriberi (Darkwa & Darkwa, 2013).

3. Studies in Cuba about malanga

Some studies have been carried out in Cuba in order to deepen the knowledge about malanga. Up to date, the focus has been put in agriculture practices to guarantee the cultivars sustainability. Those studies include research about flowering the germplasm of *Colocasia* spp. (Figueroa *et al.*, 2016), breeding, preservation and genetic diversity of *Colocasia* spp. (Figueroa-Aguila *et al.*, 2019). Other authors focused on the quality of the seed and application of biotechnological methods for obtaining new genotypes, as well as for the sanitation of pathogenic fungi and seed production with the objective of ensuring sustainability and increasing national average yields (Gálvez *et al.*, 2018).

Malanga production is limited, because the losses of these crops in the field represent more than 80% due to phytosanitary problems attributed to the rotting of corms and cormels during storage (Medero *et al.*, 2016). These values double what the FAO (2019) estimates to be acceptable annual losses in the case of global food crops. Because of that, initiatives like the production of flours or starch could enhance applications extending the shelf-life of those crops. Nevertheless, it is still underexplored and additional knowledge is necessary to ensure food security in developing countries and to decrease food waste.

4. Malanga use as food ingredient

Malanga plant reaches 1-3 meters' height. The central stem is known as corm or rhizome that develops lateral cormels covered with fibrous scales. The color of the pulp is usually white, but there are also purplish colored clones (Figueroa-Aguila *et al.*, 2019).

Corms and cormels from *Xanthosoma* spp. and *Colocasia* spp. are potential sources of starch and industrial flour that have not been exploited yet. In Cuba, the corms and cormels transformation into starch or flour may be useful, to decrease the losses after harvesting. Nonetheless, those applications are rather scarce due to the limited knowledge and efforts put into understanding the technological pro-perties of those rhizomes.

Recently, Cuban government funded a research project to develop gluten-free products in three different bakeries along the country. With that goal different baking mixes were imported to improve the quality of baked goods in order to satisfy the special requirement of celiac people. Overall, the development of gluten-free bakery business requires a huge investment and it is dependent on importation. In this context, the study of malanga flour or starch could be very beneficial because they could be effective ingredients for gluten-free products, reducing the level of importations.

A systematic search was carried out to analyze the use of this rhizome as non-conventional flours or starches, with potential applications in producing baked goods and pastes. For that purpose, different search engines like Web of science, Google scholar and Scopus, were used to collect the information. Key words like *Xanthosoma* spp., *Colocasia* spp.

flours, starch, baked goods, infant food, weaning food and pastes foods were used in that search. There were some articles about starch, flour, blends of wheat and malanga flour to be used in baked goods and *achu* (type of paste food usually made by cooking and pounding fresh corms). The most representative researches include the following studies: some researchers like Falade and Okafor (2013) evaluated the physicochemical properties of *Colocasia* spp. and *Xanthosoma* spp. starch. Other research evaluated the physical, functional and pasting properties of flours from the same crops (Falade & Okafor, 2014). Njintang and Mbofung (2006) studied the effect of precooking time and drying temperature on the physico-chemical characteristics and *in vitro* carbohydrate digestibility of *Colocasia* spp. flour. Then, different varieties of *Colocasia* spp. flour were used as food ingredients for the preparation of *achu*. In addition, Markusse *et al.* (2018) evaluated the physicochemical and sensory characterization of raw tubers from *Colocasia* spp. and *Xanthosoma* spp. varieties and their flour blends to produce *achu*. Likewise, Abera *et al.* (2017) studied the rheological, physical and sensory properties of wheat–taro flour composite bread. Some authors employed *Colocasia* spp. flour blended with soya, rice, maize and wheat flour to prepare baby food products, cake and chips with good sensory acceptability (Darkwa & Darkwa, 2013). All those findings extended the knowledge about functional and technological characteristics of starch and flours from malanga, enhancing its food applicability.

Thus, there are a few papers about the starch from *Xanthosoma* spp. but without stating possible differences between corms and cormels starches from the same species. There are no previous studies about the use of *Colocasia* spp. cormels flour in making gluten-free bread, and neither the knowledge about the behavior of *Colocasia* spp. and *Xanthosoma* spp. cormels flour in paste making, and all those studies could extend the application of those tubers, apart from the knowledge advance that will be provided.

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II. Objectives

The main objective of this research was to characterize functional and nutritionally the flour and starch from *Xanthosoma* spp. and *Colocasia* spp. to develop pastes food and gluten-free baked goods.

To achieve the main objective, the following specifics goals were proposed:

1. To establish the state of the art about this type of tubers, for better definition of the methodology beyond previous studies.

2. To identify possible differences between corms and cormels in this type of tubers.

3. To explore the potential of these tubers to be used as commodity in gluten-free breadmaking.

4. To develop food pastes from those tubers based on their functional characteristics.

Working plan

To reach previously defined objectives, the doctoral thesis has been organized in different chapters that are associated with the specific objectives. Chapters have been already published in peer-reviewed scientific journals. Following, it has been included a short explanation (graphical and in text) of the tasks carried out in each independent chapter.

-**Chapter 1.** Calle J., Gasparre N., Benavent-Gil Y., Rosell C. M. (2021) Aroids as underexplored tubers with potential health benefits. In Advances in Food and Nutrition Research. Volume 97. Ed. Fidel Toldrá. Elsevier Inc.doi: 10.1016/bs.afnr.2021.02.018.

A bibliographic search was carried out to have a global overview about this type of tubers, going from agronomic information to reported health benefits, passing through the technological applications.

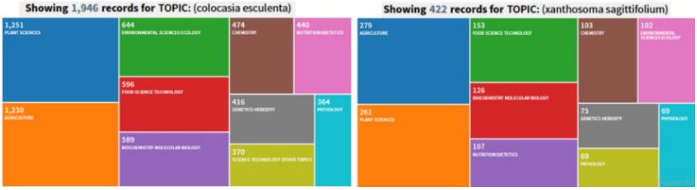


Fig. 2. Bibliographic searching from Web of Science core collection.

- **Chapter 2.** Calle, J., Benavent-Gil, Y., Garzón, R., & Rosell, C. M. (2019). Exploring the functionality of starches from corms and cormels of *Xanthosoma sagittifolium*. *International Journal of Food Science & Technology, 54*(7), 2494–2501. doi.org/10.1111/ijfs.14207.

To identify possible differences between corms and cormels, those from *Xanthosoma* spp. were selected. Focus was put on starch characterization because it is the main component in their composition. The starch characterization included structural and functional properties.

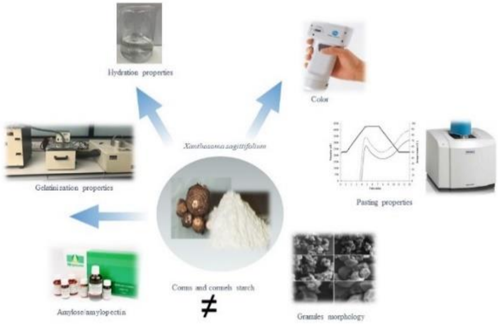
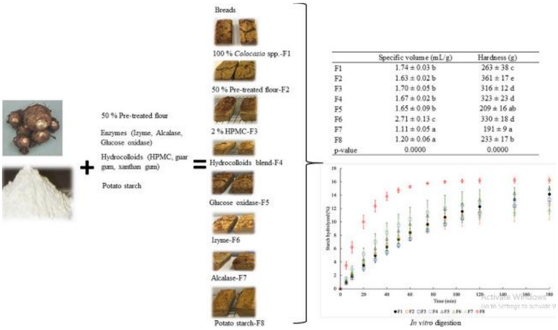


Fig. 3. Characterization of corms and cormels from *Xanthosoma* spp. starch.

- **Chapter 3.** Calle, J., Benavent, G. Y., & Rosell, C. M. (2020). Development of gluten-free breads from *Colocasia esculenta* flour blended with hydrocolloids and enzymes. *Food Hydrocolloids, 98*, 105–243. doi.org/10.1016/*j*.foodhyd.2019.105243.

For testing the breadmaking potential of these tubers, *Colocasia* spp. flour was selected as basic ingredient. Different strategies already tested in setting up other gluten-free breads were applied, including the addition of structuring agents (hydrocolloids, enzymes and starch), thermal pre-treatment of the flour or the use of flour blends. Gluten-free breads were evaluated from the technological and nutritional point of view.

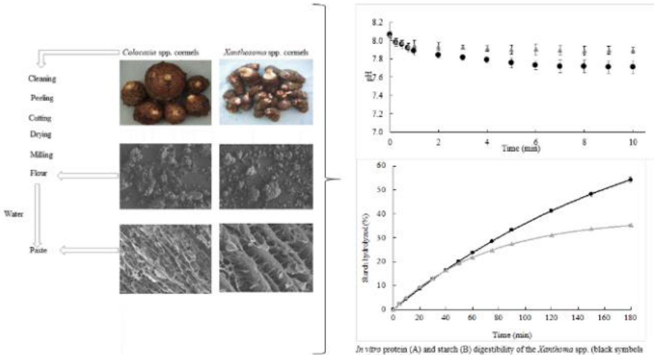


	Specific volume (mL/g)	Hardness (g)
F1	1.74 ± 0.03 b	263 ± 38 c
F2	1.63 ± 0.02 b	361 ± 17 e
F3	1.70 ± 0.05 b	316 ± 12 d
F4	1.67 ± 0.02 b	323 ± 23 d
F5	1.65 ± 0.09 b	209 ± 16 ab
F6	2.71 ± 0.13 c	330 ± 18 d
F7	1.11 ± 0.05 a	191 ± 9 a
F8	1.20 ± 0.06 a	233 ± 17 b
p-value	0.0000	0.0000

Fig. 4. Development of gluten-free breads.

- **Chapter 4.** Calle, J., Benavent-Gil, Y., & Rosell, C. M. (2020). Use of flour from cormels of *Xanthosoma sagittifolium* (L.) Schott and *Colocasia esculenta* (L.) Schott to develop pastes foods: Physico-chemical, functional and nutritional characterization. Food Chemistry, 344, 28666. 10.1016/*j*.foodchem.2020.128666.

Flours from cormels of *Xanthosoma* spp. and *Colocasia* spp. were characterize regarding their functional and morphological structure to develop food pastes. Possible health properties of the resulting pastes were evaluated assessing the *in vitro* starch and protein digestibility.



In vitro protein (A) and starch (B) digestibility of the *Xanthoma* spp. (black symbols or line) and *Colocasia* spp. (grey symbols or line) gels.

Fig. 5. Functional and morphological structure to develop food pastes.

III. Results and discussion

Chapter 1

Aroids as underexplored tubers with potential health benefits

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Author contributions

Jehannara Calle: Investigation, Writing-Original Draft. **Nicola Gasparre**: Writing-Original Draft. **Yaiza Benavent-Gil**: Writing- Review & Editing. **Cristina M. Rosell**: Conceptualization, Funding acquisition; Supervision, Writing- Review & Editing.

Abstract

Colocasia esculenta (L.) Schott and *Xanthosoma sagittifolium* (L.) Schott are the most popular tubers among the Araceas family. Their chemical composition related to their nutritional benefits could make these rhizomes a valid option for the nutritional and technological improvement of food products. This chapter provide a clarification about the correct nomenclature of both tubers giving an insight around the principle components and their health effects. The scientific literature review has primarily highlighted several *in vitro* and animal studies where the consumption (leaves and whole tuber) of *Colocasia esculenta* (L.) Schott and *Xanthosoma sagittifolium* (L.) Schott was related with certain antihyperglycemic, antihypertensive, hypoglycemic and pre-biotic effects. Owing to their functional properties, different component from these rhizomes, specially starch, mucilage and powders are being used by the food industry. Their ability to behave as thickener and gelling agent has allowed their incorporation in baked food, food paste and beverages. This chapter suggests the development of more research around these rhizomes since they could potentially play, with other crops, an important role in the future sustainable strategies to feed the planet.

Keywords: *Colocasia* spp., *Xanthosoma* spp., bioactive compounds, healthy effects, tubers, Araceas, aroid.

1. Introduction

Since the first stages of human evolution, starchy roots and tubers have represented an essential base for the diet of the early hominids. A remarkable number of roots and tubers, belonging to numerous species, creates a broad biodiversity even within the same geographical area (Chandrasekara & Kumar, 2016). From a nutritional standpoint, roots and tubers acquire great importance because they constitute an economical source of dietary energy, mainly in the form of carbohydrates. Moreover, in the developing countries they are used to feed livestock and to produce starch, alcohol, and fermented foods and beverages. Their annual global production, which is close to 836 million tons, points out the importance of these crops. The global production of roots and tubers is led by Asian and African regions that produced 43 and 33% respectively, followed by America and Europe (Chandra-sekara & Kumar, 2016). Among this huge number of tubers and roots, this chapter will be focused on *Colocasia esculenta* (L.) Schott (*Colocasia* spp. or taro) and *Xanthosoma sagittifolium* (L.) Schott (*Xanthosoma* spp. or tannia) belonging to the Araceae family. A section about the nutritional composition and a description of the main health benefits will introduce the use of these tubers in the food applications. Finally, the properties of the obtained powders will be discussed under a technological point of view. This chapter may provide a useful background for the food industry that could consider *Colocasia* spp. and *Xanthosoma* spp. for their technological quality, functional and healthy ingredients.

2. Aroids: world production and consumption

Aroid is the generic name for the plants belonging to the Araceae family, which has 118 genera and over 3800 species. They are one of the most important largest families of monocotyledons (Boyce & Croat, 2013). More than 95% of the species are present from the ever-wet or per-humid tropics to temperate forests and they can grow in the aquatic or arid habitats (Puebla *et al.*, 2019). They are dispersed world-wide, specifically in tropical America, mainland Southeast Asia, and the Malaysian region (Yuzammi, 2018). Furthermore, Henriquez *et al.* (2014) described eight subfamilies of Araceae: Gymnostachydoideae, Orotioideae, Lemnoideae, Pothoideae, Monsteroideae, Lasioideae, Zamioculcadoideae and Aroideae that are able to occupy a wide range of ecological habitats:

from sea level to above 3000 m, appearing from the form of submerged, emergent or free-floating aquatics to epiphytic, climbing and terrestrial plants. Garcia *et al.* (2010) informed that Aracea family is subdivided into nine subfamilies including Colocasioideae subfamily.

From an economic point of view, the Araceae family are employed as food, animal fodder, medicine, ornamental plants and cut flowers. Among the genera are: *Philodendron, Zantedeschia, Anthurium, Caladium, Zamioculcas, Peltandra, Arum, Spathiphyllum, Syngonium, Aglaonema, Colocasia, Dieffenbachia, Epipremnum, Monstera, and Xanthosoma* (Croat & Acebey, 2015).

Many aroids have been used as medicinal herb, for example, *Acorus calamus* L. has been used as a carminative, antidiarrheal, and appetite stimulant in Egypt, China, and India. In 210 B.C *Amorphophallus konjac* K. Koch was recorded in Chinese for treatment of wounds, tumors and skin diseases (Chen *et al.*, 2007). Therefore, this family includes some species with edible aroids, such as *Alocasia* (Schott) G. Don, *Cyrtosperma* Griff, *Amorphophallus* (Blume) Decne, *Colocasia* spp. and *Xanthosoma* spp. among others (Croat & Acebey, 2015). The genus *Colocasia* and *Xanthosoma* have about 25 and 40 species, respectively, grown as ornamentals and as food crops (Garcia *et al.*, 2010). *Colocasia* spp. and *Xanthosoma* spp. belong to the Colocasioideae and Caladieae sub-family, the most important and extensively cultivated specie that forms part of about half a billion people’s diet.

Colocasia spp. is one of the world's oldest crops and seems to have been cultivated 28,000 years ago in the Solomon Islands, while wheat and rice were domesticated 16,000 years later (Yin *et al.*, 2020). Usually, *Colocasia* spp. is cultivated at low or mid elevations (<1000 m over sea level) (Markwei *et al.*, 2010), in humid conditions at 21-27°C, rainfall of 250 mm to 1750 mm (Lim, 2015) and their height ranges between 30 and 180 cm depending on the cultivar (Andrade *et al.*, 2015). In Cuba, *Colocasia* genus has a strong African, Japanese Southeast Asia and the Philippines influence (Manzano *et al.*, 2010).

The cultivars of the genus *Xanthosoma* are the most important in Cuba, in fact, consumers prefer them due to their flavor and texture.

The most common species are *Xanthosoma cúbense* (Schott) and *Xanthosoma* spp. (Jiménez, 2018). Lately, the production of Cuban variant has increased due to its less water requirement, its high field yield (10-12 t ha^{-1}) and its low susceptibility to pests and diseases in relation to the other edible Araceae of the genus *Colocasia* (Jiménez, 2018). This plant grows under a particular environment conditions, between 500 and 2000 m over sea level, at 16-25 °C and rain regimes above 1200 mm per year (Serna-Loaiza *et al.*, 2018). Plant growth cycle lasts between nine and eleven months (Jiménez, 2018).

The world production of both species (*Colocasia* and *Xanthosoma*) has increased in the last decades (Zhu, 2016). Currently, the average world production is estimated to be ~11 million tones, of which 70% are produced in Africa alone, while ~21% and ~5% are produced in Asia and America, respectively (FAOSTAT, 2019). *Xanthosoma* spp. production has increased and Cuba has become the first world producer (FAOSTAT, 2019). Some superficial similarities often breed confusion between both species. *Xanthosoma* spp. appearance is rather similar to a large coarse *Colocasia* spp. As a result, *Colocasia* spp. and *Xanthosoma* spp. are commonly referred as "malanga" in Cuba, "yautía" in the Dominican Republic and Puerto Rico, "taioba" in Brazil, "taro" or "old cocoyam" in most communities of West Africa and "tannia" or "new cocoyam" in other regions (Boakye *et al.*, 2018). There are some articles that have attempted to elucidate the correct nomenclature, but the confusion, in this regard, still persists. Boakye *et al.* (2018) referred that cocoyam is the generic name of both species, taro is used for *Colocasia* spp. and tannia concerns *Xanthosoma* spp. On the other hand, Kaushal *et al.* (2015) described *Xanthosoma* spp. as a variety of taro. Cocoyam and malanga are the generic name depending on the country. To avoid this confusion, each species has been named by its scientific name, including the part of rhizome that have been addressed in this chapter: corms or cormels. Most research works do not make any distinction. Regarding this, the term "malanga" will be used in the present chapter to refer to both *Colocasia* spp. and *Xanthosoma* spp.

3. Botanical and morphological information

Malanga consists of subterranean stems, corms and cormels enclosed by dry scale-like leaves. Their vegetative parts are extremely varied; for instance, present a fleshy underground edible part of the plant, cormose, tuberous, rhizomatous stems that are modified into a starchy rhizome (Lim, 2015). *Colocasia* spp. and *Xanthosoma* spp. have similar phenotypic characteristics and can be distinguished by their leaf shape (Lebot, 2009). *Colocasia* spp. has large dark green peltate leaves with velvety textures and peltate petiole insertion near to the center, while *Xanthosoma* spp. has sagittate leaves with sub-coriaceous (Fig. 6A) textures, that are used as spinach and they present a basal insertion of the petiole (Sepúlveda *et al.*, 2017).

Fig. 6A. Morphological *Colocasia* spp. cultivar.

Regarding the underground parts, malanga is formed by a central corm and a considerable number of lateral cormels (Fig. 6B) and they constitute the most consumed parts of the plant. In contrast to conventional root and tuber crops such as potato, cassava or yam, *Colocasia* spp. and *Xanthosoma* spp. are unexplored crops in many parts of the world.

Fig. 6B. Morphological *Xanthosoma* spp. cultivar.

The morphological diversity of Araceae includes the smallest known angiosperms and one of the largest inflorescences in the world. *Colocasia* spp. is considered a very polymorphic specie with at least two botanical varieties well differentiated by the shape and size of corm and cormels: *Colocasia esculenta* var. *esculenta* which has a large central corm surrounded of several cormels and *Colocasia. esculenta* var. *antiquorum* which has a small central corm surrounded by lots of smaller side cormels (Banjaw, 2017). The first crop is considering non-acrid because of its low amount of calcium oxalate, the second is rarely eaten due to its high degree of acridity. The differences among them is given by length of the sterile appendix of the spadix and the number of chromosome 28 and 42, respectively (Ubalua, 2016). Based on the shape, size of the cormels and the color of the pulp, *Xanthosoma* spp. varieties have been characterized in Cuba. For this reason, there are the following *Xanthosoma*: *Xanthosoma violaceum* Schott (pink or purple pulp), *Xanthosoma atrovirens* K. Koch & Bouché (yellow pulp), *Xanthosoma caracu* K. Koch & Bouché (cream pulp), and the most important *Xanthosoma* spp. (white pulp) (Milián *et al.*, 2001). Their genetic diversity could result from sexual reproduction events through open pollination. Morphologically, it is a perennial monocotyledonous herb that grows to a height of 1-2 m with an underground central corm and cormels. Their leaves grow upwards from the corm and roots grow below underground (Ubalua, 2016) and they are consumed as a vegetable (Lewu *et al.*, 2010a). *Xanthosoma* spp. presents significantly higher length, width and weight than *Colocasia* spp. (Falade & Okafor, 2015) and their corm is usually acrid; due to this, they are mainly used for vegetative propagation, while cormels are destined to human consumption (Owusu *et al.*, 2014).

Following the author's criteria, *Colocasia* spp. is more studied than *Xanthosoma* spp., the reason could be the origin of the crop. In fact, *Colocasia* spp. is native to Asian countries, while *Xanthosoma* spp. is better known in American and African countries. In consequence, more studies have been carried out about *Colocasia* spp. Furthermore, there are many studies that did not specify the part of the rhizome (corm or cormels) that were used. This chapter will try to elucidate some of these issues.

4. Chemical composition

These roots are characterized by an interesting nutritional profile that allows them to be an important food component of the diets of many countries. As shown in Table 1, carbohydrates are the principal component in malanga followed by protein and fiber. The protein content constitutes about ~11% on dry matter basis (Temesgen & Retta, 2015), while fiber is present at levels of ~19.74 % of total dry weight. According to Wada *et al.* (2019) protein content differs depending on the type of malanga. Indeed, they reported the crude protein content of green (8.48%) and purple (10.10%) *Xanthosoma* spp., concluding that protein content in *Xanthosoma* spp. was slightly higher than *Colocasia* spp. In addition, other components that are also naturally found in malanga, such as minerals, vitamins, phenolic compounds and mucilage, have gained growing attention for their nutritional benefits (Mwenye *et al.*, 2011; Ndabikunze *et al.*, 2011). Looking at the results about the fat content (Table 1), it is possible to consider malanga as a low-fat food.

The dissimilarities between the nutritional profiles of *Colocasia* spp. and *Xanthosoma* spp. displayed in Table 1, have been attributed to variety, growing conditions, maturity at harvest, post-harvest management and storage (Temesgen & Retta, 2015).

For instance, a study conducted by Mwenye *et al.* (2011) concluded that genotypes from Malawi of *Colocasia* spp. are nutritionally superior to those of *Xanthosoma* spp. Conversely, *Xanthosoma* spp. variety grown in Tanzania and Uganda exhibited higher nutritional profile than the *Colocasia* spp. variety (Ndabikunze *et al.*, 2011). Furthermore, it should be noted that the chemical components are not homogeneously distributed over the corms and cormels structure.

Corm and cormels are complex biological materials, which can be roughly divided into three parts: skin, cortex and core (Lebot, 2009). Broadly, the skin is smooth, fibrous and covered with scales. The cortex comprises the region between the skin and the initial roots. Both, the cortex and the core mainly consist of parenchymatic tissues, however, the core is also made up of fiber (Chandrasekara & Kumar, 2016). In this respect, Sefa-Dedeh and Agyir-Sackey (2004) reported that the apical section has a high protein content, while high levels of fiber and minerals can be found in the distal section. Although its nutritional importance has been recognized, the attention towards malanga is still low but with great potential.

5. Technological functionality properties of malanga starch and powder

In order to understand the best way to obtain powders and isolate starch depending on their further uses, some technological functionalities are highlighted. Particular attention should be paid to hydration properties which include water absorption capacity (WAC), water binding capacity (WBC), swelling volume (SV), oil absorption capacity (OAC), and emulsifying capacity composed by foaming capacity (FC) and foam stability (FS). Pasting properties or the ability to form pastes under thermal treatment anticipate the performance of those powders or starches when subjected to a heating-cooling cycle, and those properties include: pasting temperature, onset temperature (OT), apparent peak viscosity (PV), trough viscosity (TV), breakdown viscosity (BV) and setback viscosity (SVy).

Table 1. Composition of *Colocasia* spp. and *Xanthosoma* spp. flour

Flour composition	***Colocasia* spp.**	***Xanthosoma* spp.**	**Method**	**Reference**
Amylose content (%)		Cormels: 27.65 Corms:19.06	amylose/amylopectin assay kit	(Calle *et al.*, 2019)
	12.9	11.3	amylose/amylopectin assay kit	(Hoyos-Leyva *et al.*, 2017)
	36	35.3	Iodine binding-colorimetry-based	
	10.7 to 49.3		Iodine binding-colorimetry-based in combination with near-infrared reflectance spectroscopy	(Naidoo, 2015; Zhu, 2016)
		35.34	Colorimetric method	(Perez, 2005)
	11.55 to 17.97	16.01 to 33.77	Colorimetric method	(Falade & Okafor, 2013)
Protein (%)	Cormels: 8.28 Corm: 2.4 to 5.9			(Amon *et al.*, 2014; Calle *et al.*, 2020a; Himeda *et al.*, 2014)
Total ash (%)	Corm: 0.6 to 4.9 Cormels: 5.04			
Fat (%)	Cormels: 0.53 Corm: 0.3 to 1.9			
Crude fiber (%)	Cormels: 4.38			

These properties are dependent on varieties, zone of the cultivar, state of ripeness and duration of drying and cooking methods (Amon *et al.*, 2014).

Hydration properties of flours provide guidance on their behaviour during the handling that determine their functionality. Higher values help to maintain the freshness of the products during storage (Falade & Okafor, 2015). These properties can vary depending on the starch structure, amylose-amylopectin content and their arrangement within the starch granule (Akonor *et al.*, 2017). WBC parameter has been employed as a good indicator to know the optimum quantity of water required to developed gluten-free doughs (Calle *et al.*, 2020a; Espinosa *et al.*, 2018) and it represents the water strongly retained by the powder.

WAC also plays an important role in dough properties giving information about the water molecules more loosely absorbed by powder constituents. In fact, Abera *et al.* (2017) showed that the WAC of *Colocasia* spp. powder was influenced by the drying method and blending ratio between wheat and cocoyam. They demonstrated that WAC of *Colocasia* spp. increased as its proportion in the blend. Some other authors (Amon *et al.*, 2014) compared the WAC of raw and boiled *Colocasia* spp. corms. They showed that the boiled ones had higher WAC than the raw powders. The authors added that the reported differences may be due to the presence of higher quantity of hydrophilic constituents (polysaccharides) in the boiled *Colocasia* spp. corms (Amon *et al.*, 2014).

Markusse *et al.* (2018) developed different blends of precooking powders from *Xanthosma* spp. and *Colocasia* spp. boiled rhizomes. The authors reported that their hydration properties varied as the *Colocasia* spp. ratio increased in the mixture; in fact, they found that *Xanthosoma* spp. absorbed less water than *Colocasia* spp. (Markusse *et al.*, 2018). Kumar *et al.* (2017) evaluated the quality of *Colocasia* spp. powders in terms of physicochemical, functional and anti-nutritional factors after different precooking methods such as in the presence of water and lemon solution, steam, or drying. They affirmed that the WAC of the steamed powders presented the highest values, probably owing to the protein structure changes and the presence of more gelatinized and damaged starch.

In this context, Calle *et al.* (2020a) reported that *Colocasia* spp. powder had higher WBC compared to gluten-free flours like conventional rice flour typically used in the gluten-free baked goods manufacture. Given its high WAC and PV, some authors employed *Colocasia* spp. powder as a thickener or gelling agent (Kaushal *et al.*, 2015) in setting up some food products, where a good viscosity is required, for example in soups and gravies (Amon *et al.*, 2014). Kaur *et al.* (2013) attributed these high values to the presence of high amount of carbohydrates and mucilage or gum (Kaushal *et al.*, 2015). Coronell-Tovar *et al.* (2019) explained that WAC was associated with the rise of the amylose leaching and changes in starch microstructure (loss of crystalline structure). For all these reasons, Kaushal *et al.* (2012) suggested the use of *Colocasia* spp. powder in the formulations of sausages, cheeses and bakery products. Himeda, *et al.* (2014a) observed that physicochemical and thermal properties of *Colocasia* spp. powders were significantly affected by the ripened stage, while drying processes showed no changes except for the color parameters. They reported high positive correlations among the grade of maturity, ash content, available sugars, protein and carbohydrate content.

Regarding the pasting properties, OT indicate the temperature at which the increase in viscosity begins due to the starch gelatinization phenomena, PV refers to the maximum apparent viscosity value at 95 °C, while trough viscosity is the minimum viscosity obtained at the same temperature (Calle *et al.*, 2020). The difference between these last two parameters is called breakdown (BV), and SVy represents the difference between the maximum and minimum viscosities during the cooling stage, which is related to the amylose recrystallization.

In order to understand the advantages of the *Colocasia* spp. powder in terms of nutritional and technological values, Perez *et al.* (2007) compared its powder with flours obtained from others cereals and tubers. The outcomes showed that chemical, physical, and physico-chemical properties of malanga powder were similar to those found for the conventional flours of cereal and tubers. The authors argued that *Xanthosoma* spp. powder showed higher values of gelatinization temperature, viscosity, setback and consistency than *Colocasia* spp. powder. Markusse *et al.* (2018) described that because of its higher amylose content, the temperature required for *Xanthosoma* spp. (95.08°C) powder to form a viscous paste was higher than *Colocasia* spp. (83.44°C).

Moreover, Falade and Okafor (2015) evaluated the physical, functional, and pasting properties of flours from corms of two different malanga cultivars. Following OAC (oil retained by the sample without being subjected to any stress), SP and PV properties, the authors observed that flours significantly varied among them. *Xanthosoma* spp. showed better potential as a thickener agent than *Colocasia* spp. because the parameters mentioned before, were higher. Moorthy (2002) concluded that the functional and physicochemical properties of the malanga were aligned with the ones found in the other roots and tubers like cassava and sweet potato. In these sense, Kaur *et al.* (2013) studied the physicochemical and pasting properties of *Colocasia* spp. powder and compared it with cereal, tuber and legume flours and powders. They confirmed that *Colocasia* spp. exhibited lower FC and SV (volume occupied by the swollen granules after 24 h in excess of water at room temperature). Whereas PV of *Colocasia* spp. powder was lower than potato powder but higher than soya and corn flours. Regarding these properties, the authors recommended the use of these powders in products where the replacement of conventional flours is required.

On the other hand, Saikia and Konwar (2012) evaluated the technological properties of starch from aroids cultivated in India reporting differences in composition and the physicochemical properties of the starches. The authors explained that the observed variations were caused by the granule size, crystallinity, and phosphorus content. They concluded that the starches with the small granule sizes could be used in baby foods preparation with slight modifications. Falade and Okafor (2013) described the physicochemical properties of *Colocasia* spp. and *Xanthosoma* spp. starches pointing out that *Xanthosoma* spp. showed higher amylose content and better pasting properties than *Colocasia* spp. Moreover, according to the authors the pasting properties of both powders could predict the cooking behaviour and other food uses.

Functional properties of starches from corms and cormels of the *Xanthosoma* spp. were explored by Calle *et al.* (2019), who showed that starch granules were morphologically different from each other. Authors found some positive correlations between the physical and hydration parameters of their starches, specifically, between granule size and WBC ($r = 0.994$; $P < 0.01$), OAC ($r = 0.999$, $P < 0.05$), and with WHC ($r = 0.974$, $P < 0.05$) too. According to some others authors, an increase in granule size reduced the absorptive capacities (de la Hera *et al.*, 2013). Overall, these differences have been attributed to the functional intrinsic characteristics of starches: granule size and amylose content, source and variety, method of extraction, method of analysis and processing conditions (Calle *et al.*, 2019).

6. Malanga as food ingredient

6.1. Malanga powder and starch production methods

The processing methods to produce powder and starch from malanga need to be considered since the resulting physicochemical and functional properties may be affected. Processing of malanga rhizomes into powder requires several steps such as washing, peeling, cutting, drying and milling to decrease the particles size.

Different methods have been proposed. Markusse *et al.* (2018) cooked the tubers before peeling, cutting them afterwards to obtain thick slices (0.5 cm) ready to be dried during 48 h at 45±2°C in a dehydrator, and then ground them passing through an 800 µm mesh. Conversely, Calle *et al.* (2019) washed and peeled the rhizomes, then slices of 1 cm were immersed in a solution of sodium metabisulfite (20 mg kg^{-1}) for 30 min, dried at 45°C for 24 h and milled to produce powder. To isolate starch, same authors proposed to mix powder with distilled water (1:10) and filter it through cotton filter cloth. The sediments were washed several times to wash off any starchy residue. The achieved solutions were pooled and centrifuged for 10 min at 3000 *g*. On the other hand, Kumar *et al.* (2017) precooked *Colocasia* spp. in boiling water with lemon juice, applying steam for 5, 10 and 15 min; then slices were dried at 60°C with air velocity of 1.3 $m \cdot s^{-1}$, milled into powder and passed through a 100 µm mesh sieve. The outcomes showed that the precooking process (10 min) significantly increases the drying rate and decreases drying time of *Colocasia* spp. slices.

6.2. Food and beverages produced with malanga

Malanga is produced primarily for food and it can be consumed fresh in several forms. When it is boiled, malanga can act as a thickener in soups (Perez *et al.*, 2007), it can be consumed boiled with garlic sauce on the top (Fig. 7A). A typical Cuban dish consists of frying a dough (prepared by grating the rhizome, seasoned with garlic) in order to obtain malanga fries (Fig. 7B). Corms and cormels of malanga can be mashed (Fig.7C), fried as malanga flakes (Fig. 7D) cooked and pounded or mixed with other tubers. Moreover, malanga can be baked, roasted, pounded or fermented to prepare poi (a sour paste made from boiled pounded malanga), typically consumed in Hawaii (Ubalua, 2016).

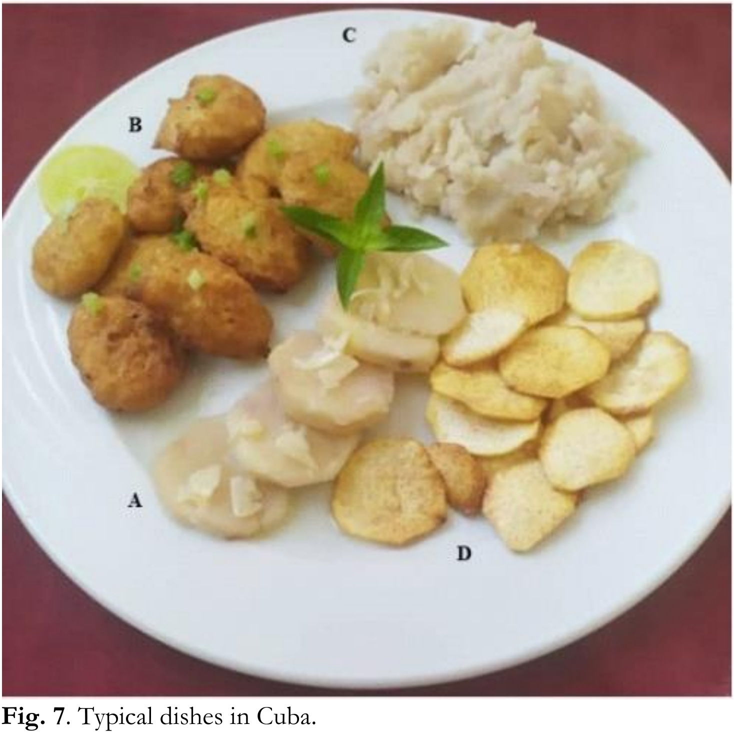

Fig. 7. Typical dishes in Cuba.

Due to its high moisture content and active metabolism, up to 30% of world production is lost in the post-harvest stage, precisely during the storage (FAO, 1993). To avoid these important losses, the fresh malanga can be processed into powder or starch, to extend its use as raw ingredient in syrups, gums, cereal base food products, powdered beverages, chips, sun-dried slices, flakes, grits and drum-dried and flakes (Ubalua, 2016).

Because of their nutritional content, malanga powders have been selected to develop several foodstuffs. Pensamiento *et al.* (2018) used malanga powder (*Colocasia* spp.) as raw material blended with mango pulp powder (up to 10 $g \cdot 100\ g^{-1}$) to obtain extruded snacks with high β-carotene content and acceptable quality properties. In addition, fresh tubers of *Xanthosoma* spp. were dried and ground to produce noodles using a twin-screw extruder and after the optimization of the feed moisture content, screw speed and barrel temperature noodles with a good overall acceptance were obtained (Sobowale *et al.*, 2018). Hendek *et al.* (2019) evaluated and compared the physicochemical properties of different pudding mixes made with malanga powder (25, 50, 75, and 100%), corn starch and rice flour. Results showed that the higher incorporation of malanga powder, the higher ash, protein, fiber, fat, mineral content and viscosity of the pudding. Therefore, authors concluded that these powders were very suitable for pudding making due to their high-water binding capacity, although milling must guarantee a small particle size to avoid the feeling of malanga particles in the mouth. Other type of products like energy bars have been developed with 100% of *Xanthosoma* spp. powder blended with cashew nuts, dates fruits and chocolate without affecting sensory attributes (Kabuo *et al.*, 2017). Malanga powder at 20% (w/w) has been even blended with maize to produce tortillas with good sensory and technological quality (Chel *et al.*, 2014).

Rapelo *et al.* (2014) reported the effect of malanga starch as filler and thickener in the production of Frankfurter sausages. Indeed, when 100% of wheat starch was replaced by malanga starch, no sensory acceptability changes and no cooking losses alterations were observed. Likewise, Hudi *et al.* (2018) developed French fries using *Xanthosoma* spp. soaked in $CaCl_2$, which showed better crispness and reduced oil absorption.

Only few studies describe the use of malanga in beverages manufacturing. Starch from *Colocasia* spp. acted as a stabilizer on the physicochemical and microbial characteristics of yoghurt (Krisnaningsih *et al.*, 2019), while its presence with sesame and beans allowed to obtain a kefir vegetable drink (da Costa *et al.*, 2018).

7. Healthy effect related to malanga consumption

Besides its nutritional profile, malanga has been used in traditional medicine, particularly in the tropical and subtropical regions (Park *et al.*, 2013). Historically, malanga has been used in China as therapeutic relief (Yu *et al.*, 2015), because of its antioxidant and anti-inflammatory properties probably related with its content of polyphenols, tannins, flavonoids, alkaloids and saponins (Ribeiro *et al.*, 2018). In ethnomedicine, malanga is used to manage different disturbs such as diabetes mellitus, treatment of ringworm, cough, sore throat and wounds (Mwenye *et al.*, 2010; Eleazu *et al.*, 2014; Eleazu *et al.*, 2018). The decoction of different parts like the peel is administered to cure diarrhea, while *Colocasia* spp. corm juice is used to treat alopecia, body ache and baldness (Prajapati *et al.*, 2011). de Oliveira *et al.* (2012) reported that *Xanthosoma* spp. was traditionally used in the prevention and treatment of osteoporosis.

7.1. Use of malanga leaves with nutritional and medicinal purposes

With respect to other edible parts of malanga, leaves are generally consumed after cooking in sauces, soups or stews. With nutritional enrichment purpose, some strategies have been employed to blanch the green leaves for using them as ingredient in the formulation of new food products (Maharaj & Sankat, 1996). Manisha *et al.* (2013) highlighted that blanching the leaves during 10 min in water at 98°C with 0.1% of sodium bicarbonate, inactivated the peroxidase enzymatic activity responsible for the oxidation and browning process of the cut tissues. malanga leaves are characterized by a high nutritional profile: protein 29.4%, fat 10.6%, ash 8.24%, total dietary fiber 35.2% of which 6.82% is soluble while carbohydrates are around 49% with glucose, fructose, xylose and mannose that represent the largest fraction (de Almeida, *et al.*, 2013a). The leaves are very rich in calcium (19.25 mg kg^{-1}), iron (12.20 mg kg^{-1}), magnesium (170-752 mg 100 g^{-1}), potassium (0.4-2.4 g 100 g^{-1}), zinc (0.6-4.2 mg 100 g^{-1}), vitamin C (26.35-82.6 mg 100 g^{-1}) and carotenoids (268.2 mg 100 g^{-1}) (Azubuike *et al.*, 2018; Gupta *et al.*, 2019). Other minor compounds in these leaves include lignin and amino acids (aspartic acid, glutamic acid, proline, arginine, leucine, and lysine). According to Manisha *et al.* (2013), the phenol content ranges between 28.33-30.53 μg 100 g^{-1}, while de Almeida *et al.* (2013) reported that malanga leaves contain 19.5-22.7 mg 100 g^{-1} of ascorbic acid. Secondary metabolites include six carotenoids, 35 flavones/flavonols, six flavanones, two flavanols and one indol (Muñoz-Cuervo *et al.*, 2016). The antinutrients content represents a limiting factor for the human consumption but, Lewu *et al.* (2010) reported that boiling *Colocasia* spp. leaves during 5 min decreased the levels of oxalate (16-78%), tannin (28-61%) and phytate contents (17-41%).

Animal studies have demonstrated that the intake of malanga leaves may be associated with antihyperglycemic (Kumawat *et al.*, 2010), antihepatotoxic (Bhagyashree & Hussein, 2011), antihypertensive (Otari *et al.*, 2012) hypolipidemic and hypoglycemic effects, anticancer and prebiotic activity (de Almeida *et al.*, 2013a).

Through the observation of the blood glucose level and the body weight, Kumawat *et al.* (2010) studied the antihyperglycemic activity of ethanolic extract from *Colocasia* spp. leaves in induced diabetic rats. According to the authors, the administration of ethanolic extract of *Colocasia* spp. (400 mg kg^{-1}) provoked the reduction of blood glucose onset after four h ingestion and their antihyperglycemic effect after 24 h, while the highest reduction took place after 14 days (174.34 mg dl^{-1}). Presumably, the presence of bioactive antidiabetic compounds, principally alkaloids, flavonoids, saponins and tannins might be responsible of those effects. The ethanolic extract also prevented weight loss due to its ability to reduce hyperglycemia, moreover, no lethality or toxic reactions occurred during the period of the assays. With regard to antihepatotoxic action of *Colocasia* spp. leaves, juice was tested in rats. Bhagyashree and Hussein (2011) hypothesized that the anthocyanins or flavonoids content could promote the antihepatotoxic and hepatoprotective activity, reducing the leakage of the biomarker enzymes for the liver injury (AST, ALT and ALP). The observed effects were attributed to the glutathione synthesis enhancement, which counteracted the action of the free radicals, without observing any toxic effect.

Otari *et al.* (2012) evaluated the antihypertensive and diuretic effects of the aqueous extract of *Colocasia* spp. leaves, which was associated to the presence of certain phytoconstituents (vitexin, isovitexin, orientin, and isoorientin flavonoids) acted as vasodilation, β-blocking, or Ca^{2+} channel blocking activities. They tested the acute oral toxicity of 2000 mg kg^{-1} of extract in mice during 14 days of administration and no signs of toxicity and mortality occurred. The administration of 400 mg kg^{-1} of aqueous extract showed positive weak diuretic activity at only 5 h. Following their hypothesis, the vasodilation may be ascribed to the inhibition of the phosphodiesterase (vascular α-receptors antagonist) or to the direct action on the vascular endothelium that increased the release of endothelium-derived relaxing factor.

Furthermore, Rifakat *et al.* (2018) evaluated the oral glucose tolerance and the antihyperglycemic effect of combined methanol extracts of *Colocasia* spp. stems and *Eichhornia crassipes* in mice. Dosage of 400 mg per kg of *Colocasia* spp. or *Eichhornia crassipes* reduced the blood glucose levels by 41.1% and 21.5%, respectively. No synergistic effects were observed with their combination.

de Almeida *et al.* (2013) lyophilized *Xanthosoma* spp. leaves to evaluate the protective effects on colon and cecum in model rats fed during four weeks. Rats fed with these leaves showed lower weight gain and an increase of fecal mass, likely associated to the high amount of insoluble fiber in the leaves that caused less energy intake and increased energy loss via the feces. Concerning to the total cholesterol lowering properties, increased fat excretion might have been caused by the enhanced fat binding capacity of the bile acids. Otherwise, in the intestine the leaves were fermented promoting the excretion of acetic acid in the feces of all the rats, increasing butyrate and propionate acids associated with growth inhibition and apoptosis of colon tumor cells. These findings pointed out the health benefits of *Xanthosoma* spp. leaves consumption since they may lower the risk of colon cancer and cardiovascular diseases (de Almeida *et al.*, 2013).

7.2. Health and nutritional effects related to consumption of malanga tubers

Malanga (*Xanthosoma* spp.*)* consumption significantly decreases blood glucose and increases glycogen levels in diabetes mellitus induced rats (Handajani *et al.*, 2018). Therefore, tubers from *Xanthosoma* spp. could represent a potential functional food source for the patients suffering diabetes mellitus type II (Simsek & El, 2015). Regarding the malanga hypoglycemic activity, Eleazu *et al.* (2018) reported that aqueous extracts of raw and cooked malanga tubers showed *in vitro* α-amylase inhibitory activity, which could be linked to a reduction of postprandial levels of blood glucose. In order to understand the biochemical basis of the antidiabetic action, Eleazu *et al.* (2014) studied *Colocasia* spp. action on pancreatic amylase and lipase, and their influence on liver, kidney function parameters, and relative pancreas weight in streptozotocin induced diabetes in rats. *Colocasia* spp. ameliorates liver damage and protects against nephrotoxicity as indicated by the increase in the serum protein and the decrease in the serum creatinine and urea of the diabetic rats. It must be stressed that some toxicological effects have been also described due to the consumption of *Colocasia* spp. Lewu *et al.* (2010a) clinically assayed the toxicological effects of *Colocasia* spp. on Wistar rats and after 4 weeks, their serum protein levels and kidney functional indices (albumin, bilirubin, and total and conjugated bilirubin) adversely varied, affecting the normal hepatic and renal function of the animals. Nevertheless, those effects have been associated to some varieties of *Colocasia* spp. from South Africa.

The *Xanthosoma* spp. action hindering starch degradation has been also related to the inhibition of the enzyme α-glucosidase by some isolated lactic acid bacteria (Nurhayati *et al.*, 2017). The pasting or viscosity increase promoted by *Colocasia* spp. powder has been associated with its beneficial effect on the non-insulin dependent diabetes mellitus (Adefegha, 2018). That action has been connected with both the inhibition of α-amylase and α-glucosidase and the increase in the phenolic content and antioxidant activity after pasting (Adefegha & Oboh, 2012).

In terms of microbiome, 20% of *Xanthosoma* spp. consumption significantly improved the overall diversity of the gut microbiome in mice by mitigating intestinal dysbiosis and promoting the growth of bacterial groups associated with health benefits (Handajani *et al.*, 2018). These rhizomes increased *Clostridium* cluster IV, *Ruminococcus 2* and *Acetatifactor* and decreased *Clostridium* cluster XIVa microbial communities (Handajani *et al.*, 2018). Furthermore, aqueous plant extracts from *Colocasia* spp. have shown activity against *Helicobacter pylori*, probably due to their anti-biofilm property (Prasad *et al.*, 2019).

An *in vitro* study revealed that *Colocasia* spp. consumption might have an hypocholesterolemic effect due to the inhibition of lanosterol synthase. Authors identified the monogalactosyldiacyl-glycerols and digalactosyldiacyl-glycerol as the compounds responsible of that inhibition (Sakano *et al.*, 2005).

The lower incidence of colorectal cancer on the Hawaiian population has been attributed to the ethnic differences in diet, and the consumption of poi made from *Colocasia* spp. tubers might contribute to that lower prevalence *(*Brown *et al.*, 2005). Different hypotheses have been proposed to explain that effect: first, poi consumption may induce apoptosis within colon cancer cells, and secondly, the lyse of cancerous cells can be occurred by non-specifically activating lymphocytes. Brown *et al.* (2005) reported an anti-proliferative activity of soluble extracts from poi against the rat YYT colon cancer cell line. The authors also observed that these soluble extracts activated the lymphocytes from splenocytes. Later, a potentially therapeutic polysaccharide compound derived from *Colocasia* spp. was identified (*Colocasia*-4-I) and purified by Park *et al.* (2013). This compound acts as immune-stimulant and the anti-metastatic preventive activity of 50 μg *Colocasia*-4-I was confirmed in mouse, concluding that the administration of~162.5 mg day^{-1} of *Colocasia*-4-I could produce anti-metastastic effect in humans (65 kg body weight). A similar study conducted by Kundu *et al.* (2012) demonstrated in a murine model the anti-metastatic activity of a water- soluble extract of *Colocasia* spp. corm. Chan *et al.* (2010) identified a cytokine-inducing hemagglutinin (Araceae lectin) from *Colocasia* spp. and evaluated its mitogenic and anti-tumour activity in mice, observing that its molecular size and N-terminal sequence was similar to *Xanthosoma* spp. and banana lectins. In *Colocasia* spp., 40% of the total soluble proteins have been identified as lectins, named tarin, which exhibited *in vitro* bioactive properties (Pereira *et al.*, 2018). Lectins like tarin, linked to complex and high mannose N-glycans have remarkable antitumor and antiviral properties (Akkouh *et al.*, 2015). Tarin stimulates splenocyte proliferation *in vitro*, one of the different white blood cell types, which have different immune functions such as promoting stimulation, suppression or modulation (Pereira *et al.*, 2014). Lately, an *in vivo* study showed that the intraperitoneal administration of 200 µg of this lectin significantly minimized leukopenia induced by cyclo-phosphamide at 300 mg kg^{-1} in immunosuppressed mice (Pereira *et al.*, 2018). Furthermore, an *in vitro* study reported the antiviral activity of lectins against the severe acute respiratory syndrome coronavirus (SARS-CoV) and against the virus of infectious peritonitis (Keyaerts *et al.*, 2007). After analysing different glycan binding structures, it was suggested that the strongest anti-coronavirus activity among the mannose-binding lectins was carried out by sugars attached to *N*-glycosylation in the SARS-CoV spike protein sites.

The consumption of *Colocasia* spp. powder has been clinically assayed to evaluate its effect on hormones (testosterone) levels and gametogenic epithelium in Wistar rats, resulting in a significant relationship with higher testicular mass and hormonal parameters, because of that further studies were advised to confirm the fertility increase (Ribeiro *et al.*, 2018). Previous studies associated testis weight to sperm production (Hikim *et al.*, 1989). According to Ribeiro *et al.* (2018) polyphenols, flavonoids, alkaloids and saponins present in *Colocasia* spp. powder improve the serum levels of testosterone, increasing the body mass and length of the rats (Gauthaman & Ganesan, 2008). In the study lead by Lewu *et al.* (2011), it was shown that the intake of *Colocasia* spp. enhanced the total body weight, liver–body weight ratio, and kidney–body weight ratio in rats fed during 28 days with this crop, because of its high nutritional quality.

Concerning the estrogenic activity and the effect to prevent menopause symptoms in women, flavonoid glycoside-rich fraction from *Colocasia* spp. and other bioactive compounds of different plants have been studied (Rodrigues *et al.*, 2018). Results showed that the rats fed with 80 $mg·kg^{-1}$ of *Colocasia* spp. for 21 days, exhibited estrogenic activity in each phase of the oestrous cycle and on the opening of the vaginal canal and vaginal epithelium in prepubescent rats. Uterotrophic assays and cytological evaluation of the optical microscopy images showed that the convoluted tubule cells were unaffected. The authors suggested that, owing to the capacity of flavonoid glycoside-rich fraction from *Colocasia* spp. to bind selective estrogenic receptors present in each organ, its consumption may prevent some of the metabolic disorders related to estrogenic deficiency like menopause.

8. Malanga constituents related with its health benefits

The consumption of malanga implies some nutritional but also physiological benefits and different hypotheses have been formulated to explain such benefits. Overall, these hypotheses can be grouped into categories related with the beneficial effects caused by the different chemical compounds of the malanga. The combined incidence of these nutritional components governs the overall health benefits of malanga.

8.1. Starch

Among the polysaccharides, starch is undoubtedly the most investigated component of malanga. On the other hand, the main monosaccharides identified in malanga are galactose, mannose and arabinose (Njintang *et al.*, 2014), although glucose, fructose, fucose, rhamnose, maltose, raffinose and xylose have been also reported (Andrade *et al.*, 2015).

Numerous studies described the nutritional, physical and technological properties of malanga starch. Starch constitutes up to 80% of the malanga composition on dry matter basis (Temesgen & Retta, 2015), although some authors reported even higher values (94.33%) for *Colocasia* spp. (Lovera *et al.*, 2017), making malanga a good ingredient for energy supply. Scanning electron micrographs of starches from *Colocasia* spp. and *Xanthosoma* spp. indicate great variations in size and shape. Starch granules from *Colocasia* spp. have polygonal irregular shape with small rounded or ellipsoidal-truncated granules (from 0.5 to 13.6 μm in diameter) (Odeku, 2013; Zhu, 2016). Granules from *Xanthosoma* spp. corms showed two different populations, the large A-type with truncated shapes and several grooves on the surface and with average area of 24.56 μm^2 and the small B-type granules with polygonal shape and area of 7.18 μm^2. Whereas, starch from cormels presented many truncated granules with similar shapes to the corms A-type granules with larger size (Calle *et al.*, 2019).

The structure of starch consists of linear and helical amylose and the branched amylopectin. Several authors have quantified (Table 2) the amylose content in malanga starch concluding that their values were different because of the different experimental conditions and instrumentations (Zhu, 2016). Calle *et al.* (2019) reported that amylose content (Table 2) was greatly dependent on the part of the plant from which the starch was isolated, since significant differences in amylose contents were found between starches from corm and cormels from the same species of *Xanthosoma* spp.

Estimated glycemic index (*e*GI) has been used as an indicator of the food effect in postprandial rise blood glucose (Foster-Powell *et al.*, 2002) caused by the action of enzymes such as α-glucosidase and α-amylase involved in the carbohydrate digestion (Adefegha & Oboh, 2012). As result of this digestion, the glucose is released and then absorbed by the gut with a consequent postprandial hyperglycemia.

Considering the glucose as reference, food glycemic index has been classified in high (*e*GI > 70), medium (56 < *e*GI < 69), and low (*e*GI < 55), resulting in a good predictor for nutrition purposes (Foster-Powell *et al.*, 2002). The starch characteristics have led to classify malanga as an intermediate glycemic index food (Simsek & El, 2015). Some factors, such as nutritional composition and processing, affect the change in blood glucose after eating a meal. In the case of the starch, different types have been described based on their rate and extent of digestion: rapidly digestible starch (RDS), slowly digestible starch (SDS) and resistant starch (RS) (Jenkins, 2007). Table 2 compiles the *e*GI results of different studies on *Colocasia* spp. and *Xanthosoma* spp. Ramdath *et al.* (2007) evaluated glycemic index of *Xanthosoma* spp. commonly eaten in the Caribbean, classifying it as an intermediate-*e*GI foods. Eleazu *et al.* (2018) assessed the starch digestibility of cooked *Colocasia* spp. and *Xanthosoma* spp. pointing out that processing increased digestibility of theses rhizomes (Table 2). They reported that both (raw and cooked) had low starch digestibility compared with the starch digestibility of other tubers like *Solenostemon rotundifolius*, *Plectranthus esculentus* and potato.

Table 2. Healthy effects of *Colocasia* spp. and *Xanthosoma* spp.

Parameters	***Colocasia* spp.**	***Xanthosoma* spp.**	**Effect**	**Reference**
*e*GI (%)	Boiled: 57.59 ± 0.40 Raw: 35.89 ± 0.13	Boiled: 71.38 ± 1.37 Raw: 54.15 ± 0.25	Influence postprandial rise blood glucose	(Eleazu *et al.*, 2018)
		Intermediate-*e*GI		(Dan Ramdath *et al.*, 2007)
	Corm: 63.1± 2.5	*54		(Simsek & El, 2015);* (Graf *et al.*, 2018);* (Handajani *et al.*, 2018)
RDS (%)	19.7	57.3	Influence the digestion rate	(Hoyos-Leyva *et al.*, 2017)
SDS (%)	13.7	72.9		(Naidoo *et al.*, 2015)
RS (%)	15.0	73.8		
	Boiled corm: 13.0 ± 0.2; 16.3 ± 0.2 Raw corm: 11.2 ± 0.4; 23.1 ±0.3 Bake corm: 13.0 ± 0.2; 17.2±0.2			(Eleazu *et al.*, 2018)
	Raw: 20.90 ± 0.14 Boiled: 15.10 ± 0.14	Raw: 11.60 ± 0.00 Boiled: 9.70 ± 0.71		
In vitro α-amylase inhibitory actions (%)	Raw: 32.47 ± 7.86 Boiled: 41.91 ± 3.63	Raw: 44.54 ± 2.75 Boiled: 46.62 ± 6.05	Inhibition of the carbohydrate metabolizing enzymes	(Eleazu *et al.*, 2018)
In vitro cellular proliferation in mice (µg/mL)	Crude extract: 3.12 Purified Tarin: 2.5			(Pereira *et al.*, 2014)

This result could be attributed to the higher fraction of RS found in malanga which was responsible for the potential hypoglycemic action (Eleazu *et al.*, 2014).

Graf *et al.* (2018) reported that starch was rapidly digested and presented high bioavailability of sugars in mice feed with *Xanthosoma* spp., particularly bio accessible free sugars (glucose, maltose, and sucrose) were found after 90, 120, and 150 min of digestion (280.9 ± 229.3 mg, 201.2 ± 73.1 mg and 194.4 ± 83.9 mg, respectively). In consequence, *Xanthosoma* spp. was recommended to young infants with digestive system in development and adult suffering of gastritis but not to adults with diabetes. However, when Adefegha (2018) evaluated the *e*GI of a puree from malanga (malanga powder was boiled in water at 100°C and stirred manually with a wooden spoon under reduced temperature of about 50-60°C for about 40 min) observed a reduced *e*GI and sugar content compared with untreated malanga powder. Presumably, the interaction of the starch constituents with some phytochemical compounds might reduce the content of the available monosaccharides, since they are involved in the formation of brown pigments (melanoidins) typical of the Maillard reaction during heat treatment.

8.2. Protein

The protein content of malanga is around ~15% per dry matter basis (Table 1). It is mainly composed by four major protein families, two albumins, A1 (with molecular mass of 12–14 kDa) and A2 (with molecular mass of 55–66 kDa) and two globulins, G1 (with molecular mass of about 14 kDa) and G2 (with molecular mass of about 22 kDa) (Pereira *et al.*, 2015). The protein content reported for *Colocasia* spp. cormels powder was lower than the one found in teff and buckwheat flours but higher than that in maize, rice, cassava or sweet potato powders (Calle *et al.*, 2020a).

The main amino acids reported in malanga are lysine, tryptophan, cysteine, isoleucine, leucine, aspartic acid, asparagine, glutamine, glutamic acid, glycine, and serine (Andrade *et al.*, 2015; Njintang *et al.*, 2014). Since the crude extract of *Colocasia* spp. corm is a natural source of bioactive proteins able to stimulate haematopoietic cells, Pereira *et al.* (2015) evaluated the *in vitro* and *in vivo* (two murine models) immunomodulatory potential. They concluded that *Colocasia* spp. corms acted as an immune stimulator of the total bone marrow (associated with the active plant proteins classified as lectins) and spleen cells in distinct mice strains. The immunomodulatory potential was attributed to a significant production of antibodies after five days due to the proliferation of mice B220+ splenocytes. The authors explained the possible mechanism of action by the link established between the tarin and the CD34 + progenitor cells, favoring lymphopoiesis B.

8.3. Fiber

Malanga powder presents both dietary and non-dietary fiber that have been associated with some nutritional benefits and desirable health effects such as cancer prevention through absorbing carcinogens (Zeng *et al.*, 2020). Malanga powder is a good source of dietary fibre (Darkwa & Darkwa, 2013) and their content represent the second most abundant fractions in *Xanthosoma* spp. Dietary fiber content of malanga varies from 11 to 19.74%, with insoluble fiber ranging from 4.57 to 15.43% and soluble fiber from 0.62 to 4.1%, depending on the part of tuber utilized (Pérez *et al.*, 2005; Graf *et al.*, 2018). Nevertheless, Panyoo *et al.* (2013) evaluated the dietary fiber content of unpeeled and peeled *Colocasia* spp. reporting values from 22 to 32.6 g 100 g^{-1}. Dietary fiber content in aroids powder, particularly the insoluble fraction and the resistant oligosaccharides are higher than in potato powder, sweet potato and yuca (Vargas-Aguilar, 2016; Graf *et al.*, 2018).

Fiber is considered a health promoting compound, since its consumption is associated with a decrease in the incidence of several diseases (Dhingra *et al.*, 2012) related to glucose metabolism, and fecal bolus flowing (Seke, 2018). Apart from that, Ferguson *et al.* (1992) showed that malanga edible fiber could adsorb mutagens that are carcinogenic and might also contribute to the anticancer effects against colon and colorectal cancers. Even fiber may activate the action of intestinal bifidobacteria improving digestion and vitamin synthesis (Sefa-Dedeh & Agyir-Sackey, 2004). Darkwa and Darkwa (2013) recommended the use of *Colocasia* spp. powder to prepare infant formula since its dietary fiber favours bowel health and improve the glycemic index (Vargas-Aguilar, 2016).

8.4 Minerals

In terms of mineral content, malanga has been recognized to have higher content compared to other root and tuber crops (Wada *et al.*, 2019), particularly potassium, phosphorus and magnesium are the most abundant (Mwenye *et al.*, 2011; Ndabikunze *et al.*, 2011). However, other essential minerals such as calcium, iron or zinc are also present. Fluoride and calcium have been naturally found in *Colocasia* spp. (Ubalua, 2016). The mineral content depends on the different genotype of malanga, being the content of Mg, Mn, P, Na, K and Ca higher in green malanga than in the purple variety (Wada *et al.* 2019). Nevertheless, the mineral content depends on the crops, genotypes and growth location (Mawoyo *et al.*, 2017).

8.5 Vitamins

Malanga like other roots is a poor source of vitamins. Temesgen and Retta (2015) reported the presence of vitamin C, thiamine (Vitamin B_1), riboflavin (Vitamin B_2) and niacin in corms. Also, β-carotene, which has a provitamin activity, is contained in the tubers (Goncalves *et al.*, 2013; Amon *et al.*, 2014). Nevertheless, according to Argandoña *et al.* (2019) the amount of vitamin C in *Xanthosoma* spp. leaves (87 mg 100 g^{-1}) is higher than in some conventional vegetables such as lettuce (21.4 mg 100 g^{-1}), broccoli (34.3 mg 100 g^{-1}) and spinach (2.4 mg 100 g^{-1}), but poorer in vitamin E (Arruda *et al.*, 2004).

8.6 Mucilage

Mucilage is a water-soluble viscous material characterized by a light color, which is part of the fiber. It is formed by some specialized secretory cells of the plant endosperm and its function is to prevent excessive dehydration (Sandra *et al.*, 2011; Dhingra *et al.*, 2012; Andrade *et al.*, 2015). Sharma and Kaushal (2016) reported that the roots contained around 10% of mucilage, while Njintang *et al.*, (2014) reported that yield of mucilage fraction varied from 30 to 190 $g \cdot kg^{-1}$. Such divergences were explained based on the extraction methods, ripening state and variety of the rhizomes.

Mucilage is considered a type of hydrocolloid (Nagata *et al.*, 2015) containing arabinogalactan-proteins (93.2-98.2%), in which the protein fraction is linked to the carbohydrate chain (Andrade *et al.*, 2015). Its behaviour as emulsifier could be explained by the weak polar interaction with the amino acids as it has been described for Arabic gum (Andrade *et al.*, 2015), because of that it could be useful in beverages and jelly candy as a substitute of Arabic gum (Manhivi *et al.*, 2018). Owing to its properties, mucilage has used in the food industry as thickening, binding, emulsifying, stabilizing and gelling agent (Alalor *et al.*, 2014). It has been reported that viscosity of mucilage was 10 times higher than that for Arabic gum (Njintang *et al.*, 2008) due to their abundant hydroxyl groups content (Mijinyawa *et al.*, 2018). This mucilage has been used in bakery products like breads, blending 0.73 g of lyophilized mucilage from malanga and 1.58 g of fat led to breads with good sensory quality, specific volume, texture, nutritional qualities and lower fat levels (Sharma & Kaushal, 2016). Similarly, Bicalho *et al.* (2019) obtained an improved alveolar distribution in French rolls adding mucilage (7.3%) from *Colocasia* spp.

The viscous nature of the mucilage might contribute to the management of diabetes and obesity (Chukwuma *et al.*, 2018). In fact, it inhibits *in vitro* α-glucosidase, α-amylase and lipase activities, even *Colocasia* spp. dry mucilage extracts could potentiate antilipidemic effects (Chukwuma *et al.*, 2018). That effect was also stated by Dechakhamphu and Wongchum (2015), who found the suppression of fat digestion and absorption due to the stronger inhibitory activity towards pancreatic lipase, which might be related to the phenolic content. Chukwuma *et al.* (2018) suggested that dry mucilage extracts might be useful for the management of the weight gain and obesity, because the mucilage viscosity could entrap glucose reducing its intestinal absorption. In the same line, Eleazu *et al.* (2014) supported the use of *Colocasia* spp. in the management of diabetes, and related its effect with the reduction in the level of the serum pancreatic lipase in rats feed with these rhizomes. In that effect could also contribute the phenolics compounds present in the mucilage (Chukwuma *et al.*, 2018; Nguimbou *et al.*, 2014).

On the other hand, the pharmaceutical industry has taken advantage of the physicochemical properties of the mucilage (high-water swelling behaviour, non-toxicity, low cost and free availability) (Laguna *et al.*, 2017). In fact, pharmaceutical industry has used it as diluent, disintegrating agent in tablet, binder agent, emulsifier, gelling agent, material stabilizer, thickening agent in oral liquids, protective colloid in suspensions, excipient in suppository and matrix former in transdermal drug delivery systems (Prajapati *et al.*, 2013). In this sense, Sarkar *et al.* (2014) evaluated *Colocasia* spp. corms mucilage and hydroxypropyl-methylcellulose (HPMC) to develop a transdermal patch as a way to deliver diltiazem hydrochloride drug. The positive effect of diltiazem released from the polymer matrix was evaluated *in vitro* and in the skin of albino rats, obtaining a prolonged released of the drug, being more resistant to breakage.

8.7. Total phenolic and flavonoid content

According to Simsek and El (2015), the total phenolic and flavonoid contents of *Colocasia* spp. corm are 205 mg Catechin Acid Equivalent (CAE) 100 g^{-1} and 61 mg CAE 100 g^{-1}, respectively. While, Ukom *et al.* (2014) reported that in *Dioscorea* spp. and *Xanthosoma* spp. tubers, the total polyphenol content ranged from 7.02 to 163.37 mg of Gallic Acid Equivalent (GAE) 100 g^{-1} fresh weight (FW), while flavonoid amount was comprised between 3.14 and 155.38 mg CAE 100 g^{-1} (FW). The corresponding antioxidant activities for *Xanthosoma* spp. evaluated by 2,2-diphenyl-1-picrylhydrazyl (DPPH) assay ranged from 88.17 to 729.39 Trolox Equivalent 100 g^{-1} (FW), while 2,2´-azino-bis-(3-ethylbenzothiazoline-6-sulphonic acid diammonium salt values ranged from 32.49 to 756.0 Trolox Equivalent 100 g (FW) and ORAC assay gave activities from 459.29 to 669.45mg Trolox Equivalent/100g (FW). Likewise, the total antioxidant capacity reported for *Colocasia* spp. are 452 mM TEAC 100 g^{-1} (904 μmol TEAC 100 g^{-1}), and 244 mM TEAC 100 g^{-1} (488 μmol TEAC 100 g^{-1}) by ABTS and DPPH assays, respectively (Simsek & El, 2015). Nishanthini and Mohan (2012) indicated that the methanolic extract from *Xanthosoma* spp. corm had higher antioxidant potential than ascorbic acid, and it was mainly associated to the presence of flavonoids (0.26 g 100 g^{-1}) and phenolic compounds (0.32 g 100 g^{-1}).

8.8. Antinutritional factors

The amount of the so-called antinutrient compounds present in malanga tubers interferes with the bioavailability of some nutrients and it could affect the food products acceptance (Kumar *et al.*, 2017). The amount of oxalates (one of the factors implicated in acridity), phytates and tannins content varied in malanga depending on the varieties, climatic and irrigation conditions, location, type of soil, and growing season of the plant. The oxalate content is higher in the tuber peel, but negligible in the edible part. The calcium oxalate is present in fresh rhizome as raphides aggregates with spherical shape (Ramos *et al.*, 2020). However, processing methods required for the consumption, such as boiling, fermentation and roasting, reduce its level (Lewu *et al.*, 2010; Wada *et al.*, 2019). In the same line, Akpan and Umoh (2004) reported that heating in the presence of drug tetracycline, sodium bicarbonate (Temesgen & Retta, 2015) or lemon solution cooking for 10 min could reduce the acridity factors in *Xanthosoma* spp. and *Colocasia* spp. (Kumar *et al.*, 2017). The levels of reduction promoted by cooking effects could be higher than 85% for oxalate content in *Xanthosoma* spp. rhizomes (Ramos *et al.*, 2020) and more than 70% in *Colocasia* spp. powder (Kumar *et al.*, 2017). Nevertheless, Lewu *et al.* (2010) reported calcium oxalate values of 140.2-411.8 mg 100 g^{-1} and 265.2-552.5 mg 100 g^{-1} for cooked and uncooked tubers of *Colocasia* spp., respectively.

Similarly, the reduction of other antinutrients like phytates and tannins have been investigated. Wada *et al.* (2019) evaluated the antinutrient content of different varieties of *Xanthosoma* spp., showing that the content of phytates (187.57 mg 100 g^{-1}) and tannins (156.11 mg 100 g^{-1}) in purple *Xanthosoma* spp. were significantly higher than those (phytate 167.76 mg 100 g^{-1} and tannin 139.62 mg 100 g^{-1}) in green *Xanthosoma* spp. Cooking is also effective for the tannin and phytates reduction (Kumar *et al.*, 2017). Tannin content of uncooked against cooked tubers decreased from 495.0-1518.8 mg 100 g^{-1} to 239.6-841.7 mg 100 g^{-1}, and the phytates content from 36.8-70.7 to 23.5-47.8 mg 100 g^{-1}, respectively (Lewu *et al.*, 2010). The total acceptable tannic acid and phytate (vegetarian diets) daily intake is 560 and 2600 mg per day, respectively. In rural areas of developing countries, the content permitted is around 150–1400 mg for mixed diets (Akalu & Geleta, 2017).

9. Current applications

9.1. Baked products

Colocasia spp. and *Xanthosoma* spp. rhizomes have been used in baked goods formulations in the form of starches or powders because of their nutritional, functional, and technological properties. Blends of wheat and malanga have been employed in biscuits preparation (Amon *et al.*, 2014; Himeda *et al.*, 2014; Abera *et al.*, 2017). Biscuits showed good quality up to 30% wheat flour substitution with malanga powder, although a salty taste was detected when malanga powder was mixed with wheat in the proportion 15:75 (Abera *et al.*, 2017). In the case of doughnuts and bread, up to 20% of wheat replacement by malanga powder could be applied without any impact on sensory acceptability (Akonor *et al.*, 2017). In the case of cakes, optimal wheat substitution level was 10%, without affecting textural properties, volume, color and sensory attributes (Kumar *et al.*, 2014).

In order to improve the technological properties of malanga baked goods, several ingredients have been suggested. Alam *et al.* (2015) evaluated the effect of different *Colocasia* spp. starch-hydrocolloids-wheat flour mixtures on the physical and sensory characteristics of bread, concluding that guar and xanthan gums can be used to improve volume and sensory characteristics of the leavened bread.

In the production of gluten-free foods, usually powders from leguminous (soybean, lentils, dry beans, peas, chickpeas), pseudocereals (amaranth, quinoa and buckwheat), tubers (sorgo, potato, cassava, sweet potato), carob germ chestnut, tiger nut, teff or edible aroids (malanga) have been employed (Matos & Rosell, 2015; Liu *et al.*, 2018). Malanga protein is free from toxic prolamins for celiac patients (Pereira *et al.*, 2018), because of that some authors used malanga powder blended with hydrocolloids (HPMC, xanthan gum, guar gum), and enzymes (glucose oxidase, laccase and proteases) to develop gluten-free breads (Calle *et al.*, 2020a; Manhivi *et al.*, 2018a). Breads obtained from *Colocasia* spp. powder had acceptable protein, minerals and fiber contents and were poor in fats, but also presented low *e*GI due to its high amount in SDS and RS (Calle *et al.*, 2020a). Giri and Sajeev (2019) employed malanga powder (50%) blended with rice (25%), sorghum (15%) and cassava (10%)

flours to develop gluten-free cookies with enhanced physico-mechanical and nutritional properties. *Xanthosoma* spp. (70%) and tiger nut (30%) powders have been blended to produce cookies with improved nutritional composition and acceptable sensory properties (Akujobi, 2018).

9.2. Food pastes

Taking advantage of the nutritional benefits of malanga, some researchers have studied the effects of malanga powder inclusion in the development of baby foods and products destined to elderly and people with some nutritional special requirement. Babajide and Olatunde (2010) focused on the proximate composition, rheology and sensory qualities of purée made by blending corn and *Colocasia* spp. starches, indicating that the substitution of corn starch with malanga starch (up to 50%) could give a satisfactory product viscosity without any significant changes on the product sensory quality. According to Onuoha *et al.* (2014), the use of 10% of *Colocasia* spp. powder blended with rice and tiger nut was a good alternative to improve the technological properties of weaning food, because the *Colocasia* spp. small and medium polyhedral starch granules produce low viscosity facilitating their ingestion. Alternatively, 50.2% of *Colocasia* spp. blended with soya powder provide weaning food with low levels of antinutrients (Ikpeme-Emmanuel *et al.*, 2009). The use of pre-gelatinized *Colocasia* spp. powder mixed with corn and soya for the development of puree could be an alternative to modify the pastes density, functional properties, overall sensory acceptability and to decrease the anti-nutritional factors content (Melese *et al.*, 2016). In addition, some authors suggested the use of malanga as unique ingredient to prepare pastes. Markusse *et al.* (2018) blended *Xanthosoma* spp. and *Colocasia* spp. precooked powders in different proportions to develop reconstituted *achu* (smooth paste food), a traditional food in Cameroon. Likewise, Njintang *et al.* (2006) employed corm and cormels from *Colocasia* spp. to prepare *achu* in both a traditional and reconstituted method. They evaluated the differences in terms of rheology, functional properties, particle size distribution, organoleptic characteristics, and microstructure. The traditionally pre-pared *achu* boiling the whole corms received higher acceptance than reconstituted *achu* because of the softer texture of the gel. Recently, Calle *et al.* (2020) showed that cocoyam powders from cormels of *Xanthosoma* spp. and *Colocasia* spp. could be used to make paste foods with a medium glycemic index, despite the significant differences in their physico-chemical properties.

Future trends

Owing to its nutritional quality, malanga rhizomes powder could represent a valid alternative for the development of more nutritious food products. The incorporation of powder and starch from malanga improved the technological characteristics of the cereal based products. A correct knowledge of the processes able to reduce some antinutrients compounds and the application of good practices in handling and storing malanga products are necessary to ensure high-quality foods. Furthermore, due to its low water requirement and its easy cultivation, malanga could play a pivotal role in human feeding. However, more studies are needed to extend the application of malanga and malanga derived products to other kind of foodstuffs such as functional beverages.

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Chapter 2

Exploring the functionality of starches from corms and cormels of *Xanthosoma sagittifolium*

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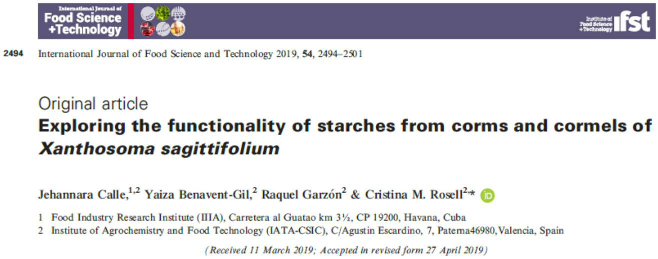

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Original article

Exploring the functionality of starches from corms and cormels of *Xanthosoma sagittifolium*

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Summary

Xanthosoma sagittifolium, belonging to the araceas family, represents an attractive alternative as a starch source. Nevertheless, as a rhizome plant two differentiated parts could be distinguished named corms and cormels." by "However, the rhizome of *Xanthosoma sagittifolium* has two differentiate parts named corms and cormels of *Xanthosoma*. Granules morphology, composition, hydration properties, pasting/thermal behaviour, as well as gelling performance were assessed. Scanning Electron Microscopy (SEM) revealed different morphology, granules were organized as aggregates in starch isolated from corms. Corms starch displayed lower hydration properties, lower apparent viscosity during heating and cooling and higher gelatinization temperatures than cormels starch. Gels from corms starch showed less syneresis than cormels starch, but no significant differences were observed regarding their hardness. Therefore, the part of the araceas plant from which the starch is extracted must be always defined, because significant differences in their functionality are ascribed to their morphological origin.

Keywords: Cormels, corms, functional properties, starch microstructure, *Xanthosoma sagittifolium*.

Introduction

Xanthosoma sagittifolium (L.) Schott and *Colocasia esculenta* (L.) Schott are the most common edible species of Araceas, originally from northern south America and Asia countries, respectively (Eleazu *et al.,* 2018). Lately, the increasing knowledge about araceas' properties has prompted their worldwide distribution (Hoyos-Leyva *et al.,* 2017). Nutritional benefits related to starch high digestibility are behind that growing trend, making araceas recommended for infants (Owusu-Darko *et al.,* 2014) and elderly foods (Ubalua 2016), as well as functional foods (Graf *et al.,* 2018). Main component of these crops is starch organized in very small granules (Sit *et al.,* 2015) of irregular shapes (Aboubakar *et al.,* 2008, Agama *et al.,* 2011) although variations within araceas have been described. Starch from *Xanthosoma sagittifolium* (*Xanthosoma* spp.) tends to display spherical-polyglonal shapes (Graf *et al.,* 2018), whereas starch from *Colocasia esculenta* (*Colocasia* spp.) is irregular and polygonal in shape (Aboubakar *et al.,* 2008). In spite of the recent interest, scientific literature is very confusing, mainly in the case of *Xanthosoma* spp. either due to the variety of common names used for referring to those species or the lack of information regarding the physiological part used for the studies. In fact, common names for *Xanthosoma* spp. largely varied in the different countries, including *taro* in Cameroon, *yautía* in Dominican Republic, *malanga* in Cuba or *cocoyam* in Ghana and other South Africa regions (Hoyos-Leyva *et al.,* 2017, Graf *et al.,* 2018). Henceforth, the name of *malanga* is going to be used owing to its growing location.

Morphologically, *malanga* is characterized by subterranean stems, termed corms, which form secondary stems named cormels (Owusu-Darko *et al.,* 2014). Cormels are usually boiled, fried or pounded after boiling and used for human consumption, in opposition corms guarantee vegetative propagation (Owusu-Darko *et al.,* 2014). Although they are used differently, no specific study has been focused on assessing their physico-chemical characteristics to explain their diverse applications, particularly concerning starch properties. Previous studies have been focused on comparing the starches isolated from different species, although without unraveling possible existing differences derived from their diverse morphological origin, namely among corms and cormels. In fact, Falade and Okafor (2013) confirmed differences between *Colocasia* spp. and *Xanthosoma* spp. starches isolated from corms, regarding physical, functional and pasting properties, which was also confirmed by Hoyos-Leyva *et al.,* (2017) when compared starches from those species grown in Mexico. Mepba *et al.,* (2009) concluded that cormels' starches from *Xanthosoma* spp. had higher apparent viscosity peak and enthalpy of gelatinization than starches from *Colocasia* spp. (Andrade, 2017).

Nevertheless, as far as the authors know, there are no studies of starch isolated from the corms and cormels of the same plant that allows to compare the properties of them. To extend the application of corms as starch source, the knowledge of the functional properties of starches from corms and cormels could help to predict their behavior in meals and thus to suggest the best end uses. As a result, the main objective of the present study was to characterize the structural and functional properties of starch isolated from corms and cormels of *Xanthosoma* spp.

Materials and methods

Starch isolation

Corms and cormels from *Xanthosoma* ssp. MX-2007 cultivars were harvested at 9-13 months of maturity by the National Institute of Tropical Food Research Farms (INIVIT) in Cuba. Starch isolation was obtained from washed and peeled rhizomes, which were cut into slices of 1 cm and immersed in a solution of sodium metabisulfite (20 $mg \cdot kg^{-1}$) during 30 min. Resulting pieces were dehydrated with a forced convection tray dryer (Keller, Ihne & Tesch KG No. 3709, Lampertheim, Germany) at 45 °C for 24 h. The powder obtained after grinding in a Fiztpatrick mill (Fitzmill model, Waterloo, ON, Canada) was mixed with distilled water (1:10) and filtered through cotton filter cloth. Sediments were washed several times with distilled water till they were free of starch. Starchy solutions were pooled and centrifuge for 10 min at 3000 *g*. The starch obtained was freeze-dried, passed through a 60-mesh sieve, and kept at 4 ºC for further analyses.

Scanning electron microscopy

Samples were coated with gold using a vacuum evaporator (JEE 400, JEOL, Tokyo, Japan). Observation was done using a SEM (S-4800, Hitachi, Ibaraki, Japan) at an accelerating voltage of 10 kV. The image analysis to assess size was carried out using the methodology described by Benavent-Gil and Rosell (2017).

Composition

A standard procedure (AOAC.968.06-1969) was applied to measure protein content. For amylose content, a commercial assay kit (Megazyme International Ireland Ltd., Bray, Co. Wicklow, Ireland) was used, which is based on the concanavalin A method (Gibson *et al.,* 1997).

CIE *L* a* b** color determination

Color were analyzed by using a Minolta colorimeter (Chromameter CR-400/410. Konica Minolta. Japan). Prior standardization with a white calibration plate (L^* = 96:9; a^* = -0.04; b^* = 1.84) was done. The color was recorded using CIE-$L^*a^*b^*$ uniform color space (CIE-Lab), recording lightness (L^*), hue on a green (-) to red (+) axis (a^*), and hue on a blue (-) to yellow (+) axis (b^*).

Starch hydration properties

The water binding capacity (WBC) was determined according to the micro method described by Cornejo and Rosell (2015). The water holding capacity (WHC) and oil absorption capacity (OAC) quantified the amount of either water or oil retained by the sample without being subjected to any stress. Those were determined by mixing 0.100 ± 0.001 g of starch with distilled water (1 mL) or vegetal oil (1 mL), respectively. After 24 h at room temperature, the supernatant was carefully removed with a pipette. Swelling volume (SV) was carried out according to the method reported by Cornejo and Rosell (2015), as the volume occupied by swollen granules after 24 h at room temperature. Solubility index (SI) of starch powder was measured according to the method described by Dura *et al.,* (2014), assessing the weight of dry solids recovered after evaporating the supernatant at 50 °C till constant weight. Equations used for calculating above described parameters were:

$$\text{WBC}\ (\text{g}\cdot\text{g}^{-1}) = \frac{\text{Weight of sediment after centrifugation -Sample weight}}{\text{Sample weight}}, \qquad (1)$$

$$\text{OAC}\ (\text{g}\cdot\text{g}^{-1}) = \frac{\text{Weight of sediment after drainig oil}}{\text{Sample weight}}, \qquad (2)$$

$$\text{WHC}\ (\text{g}\cdot\text{g}^{-1}) = \frac{\text{Weight of sediment after draining supernatant -Sample weight}}{\text{Sample weight}}, \qquad (3)$$

$$\text{SV}\ (\text{mL}\cdot\text{g}^{-1}) = \frac{\text{Total volume of swollen sample}}{\text{Sample weight}}, \qquad (4)$$

$$\text{SI}\ (\text{g}\cdot\text{g}^{-1}) = \frac{\text{Weight of dissolved solids in supernatant}}{\text{Sample weight}} \qquad (5)$$

Hydration properties were also evaluated on starchy gels following the method described by Cornejo and Rosell (2015).Water absorption index (WAI) and water solubility index (WSI) were assessed using the following equations:

$$\text{WAI}\ (\text{g}\cdot\text{g}^{-1}) = \frac{\text{Weight of sediment}}{\text{Sample weight}} \qquad (6)$$

$$\text{WSI}\ (\text{g}\cdot\text{g}^{-1}) = \frac{\text{Weight of dissolved solids in supernatant}}{\text{Sample weight}} \qquad (7)$$

Assessment of gelatinization parameters of starches

The gelatinization characteristics of starches were determined using a differential scanning calorimetry (DSC) from Perkin–Elmer (DSC 7, Perkin–Elmer Instruments, Norwalk, CT). Starch and water (1:3) were mixed and placed into stainless steel capsules that were then hermetically sealed. After that, samples were equilibrated at room temperature for one hour before analysis. Samples were scanned from 30 to 120 °C at a heating rate of 10 °C/min $^{-1}$ under nitrogen atmosphere, using an empty stainless steel capsule as reference. Onset temperature, peak temperature, conclusion temperature and enthalpy of gelatinization were recorded.

Determination of pasting properties of starches

The pasting properties of starches were measured using the standard method (AACC.61-02.01 2012) with a Rapid Visco Analyzer (RVA-4500, Perten Instruments, Hägersten, Sweden). Starch (2 g based on 14% moisture content) was added to 20 mL of water. Slurries underwent a controlled heating and cooling cycle, from 50 to 95 °C in 282 s, holding at 95 °C for 150 s and then cooling to 50 °C. The initial speed for mixing was 960 min^{-1} for 10 s, followed by 160 min^{-1} paddle speed that was maintained for the rest of assay. Pasting parameters such as onset temperature, peak viscosity, trough, breakdown (peak viscosity-trough), final viscosity, setback (cold paste viscosity-trough) were recorded using Thermocline software for Windows (Perten Instruments, Hägersten, Sweden).

Gel hardness

To evaluate the hardness of the gels, a TA.XT-Plus Texture Analyses (Stable Micro Systems Ltd., Godalming, UK) equipped with a 5 kg load cell and a 2-mm aluminum cylindrical probe was used. Briefly, the paste obtained from RVA was transferred into disposable sample cups with a diameter of 60 mm and height of 15 mm. These were allowed to cool down to room temperature and then stored at 4 ºC for 24 h. Gel penetration up to 50% was performed in the texturometer at a speed of 1×10^{-3} $\text{m}\cdot\text{s}^{-1}$. Three replicates were made for each sample.

Syneresis

Syneresis was evaluated by a spinning test (Ribotta *et al.*, 2007) by using an Eppendorf 5415 R centrifuge, (Eppendorf, Germany). Starch gels were stored up 7 days (168 h) at 4 °C. For syneresis measurements, gels were kept at 25 °C for 2 h and centrifuged at 5175 *g* for 10 min at 25 °C. After centrifugation the free water was separated, weighed, and calculated the percentage of water released from gels. Measurements were the mean of three repetitions for each duplicated gel.

Statistical analysis

The data reported in the tables are average values of two batches of samples and expressed as a mean ± standard deviation. They were subjected to analysis of variance. Multifactorial analysis was carried out with Fisher's least significant differences test with a significance level of 0.05. To indicate correlations and their significance, Pearson correlation coefficient (r) and *P*-value were determined by using Statgraphics Centurion XVII software (Bitstream, Cambridge, MA).

Results

Granular morphology of corms and cormels starches

Figure 1 shows selected SEM micrographs of starch granules isolated from corms and cormels of *Xanthosoma* spp. that were observed at three different magnifications 2,000x (a, b), 5,000x (c, d) and 10,000x (e, f). Although no clear evidence has been previously reported regarding differences in the granule size distribution of the corms and cormels from the same plant (Zhu, 2016), noticeable differences were observed on the granule size and shape of isolated starches. Granules from corms comprised two different populations, the large A-type granules exhibited truncated shapes and several grooves on the surface, while the small B-type granules had principally polygonal shape. Their average area was 24.56 and 7.18 μm^2 for A-type and B-type granules, respectively (Figure 1 a, c, e). Two different populations have been previously reported for tuber starches like potato starch (Benavent-Gil & Rosell, 2017). At lower magnifications, SEM micrographs also revealed that corms starch granules appeared to be grouped as aggregates, likely due to the smallest fraction. In fact, it has been described that small granules size starches have the ability to form aggregates (Gonzalez-Soto *et al.*, 2011), which are induced by the residual protein remaining in the starch powder (Beirão-da-Costa *et al.*, 2011). Conversely, starch granules isolated from cormels were composed of many truncated granules with an average area of 44.36 μm^2, presenting comparable shapes to the corms A-type granules with larger size (Fig. 1 b, d, f). Those morphological characteristics along with size distribution have been previously reported for cocoyam starches (Lawal, 2004), suggesting that cormels were the source used.

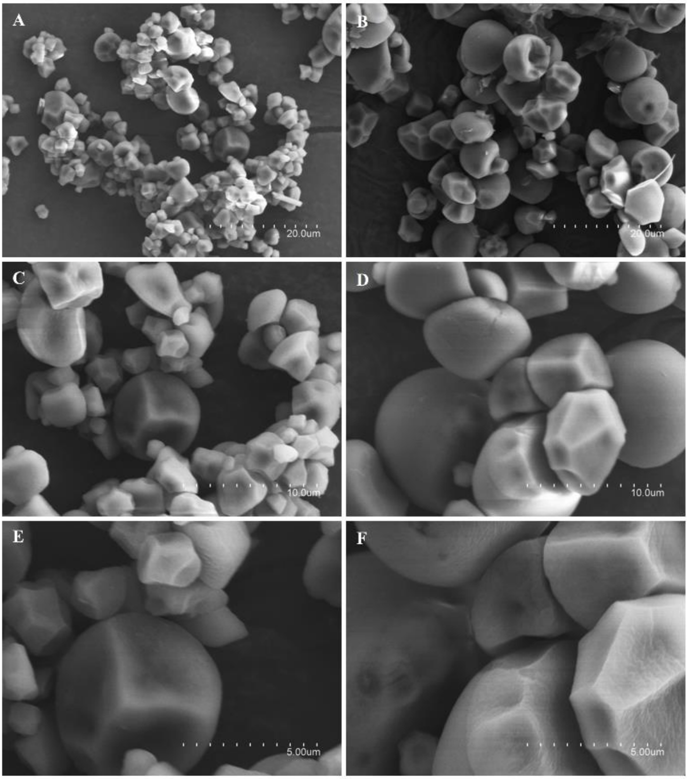

Fig. 1. Scanning electron micrograph of corms (a, c and e) and cormels (b, d and f) starch samples. Magnifications 2000x (a, b), 5000x (c, d) and 10 000x (e, f).

Color parameters of starches

Visibly, the color of corms and cormels starches was light, which was further confirmed by their higher *L** value ranging from 98.2 (corms) to 97.7 (cormels). Overall, the *L** (lightness) values were higher than those reported, likely due to the discoloration of the starch granules after extraction (Moorthy 2002).

Regarding *a**, both samples exhibited negative (green hue) values, varying significantly from -0.11 (corms) to -0.03 (cormels). Conversely, the *b** scale displayed positive values (yellow hue) for both samples, differing significantly from 1.1 (corms) to 1.9 (cormels). Difference in the color characteristics could be ascribed to inherent pigments, since yellow intensity is dependent on the beta carotene pigment (Falade & Okafor, 2015). According Aboubakar *et al.*, (2008) botanical origin of the plant and composition of the flour determine the pigments content. Results suggest that malanga composition is dependent on the part of the plant, allowing to isolate starches with diverse quality.

Composition of isolated starches

Amylose starch content was determined in starches isolated from both parts, corms and cormels. The statistical analysis indicated significant differences in amylose contents among the starches studied. Corms starch displayed an amylose content of 19.06%, while cormels starch showed a value of 27.65%. Reported results about the amylose content of starches from corms ranged from 15.04 to 33.77 (Lawal, 2004, Falade and Okafor, 2013). Mepba *et al.*, (2009) found 23% amylose in starch from cormels. Present results supported that amylose content was also greatly dependent on the part of the plant from which the starch was extracted. The content of protein in the starch samples from corms was 1.10%, confirming the presence of protein acting as gluing material, which would explain the aggregates formation. In the case of starch from cormels, the amount of protein was even higher (2.72%), but likely owing to larger size of the granules, protein content was not enough to induce extensive aggregation.

Starch and starch gel hydration properties

The hydration properties of corms and cormels starch granules and starch gels are summarized in Table 1. Statistical differences among starch samples were observed in all parameters studied. Unexpectedly, despite their smaller size, corms starch granules led to substantially lower WBC, OAC and WHC compared to cormels starch. A correlation analysis indicated a positive significant relationship between granule size and WBC (r = 0.994; $P < 0.01$), OAC (r = 0.999, $P < 0.05$), and also with WHC (r = 0.974, $P < 0.05$). Conversely, some researchers have reported that an increase in granule size results in reduced absorptive capacities, de la Hera *et al.* (2013) owing to the reduction in the surface area. Presumably, the formation of aggregates in the case of starch from corms could have affected these capacities (Gani *et al.*, 2013).

Granules aggregation reduces the surface area that might be in contact with water molecules, inducing lower intake of water. In addition, it has been described that amylose content promotes a reduction in these capacities. However, the amylose content showed a positive correlation with WBC ($r = 0.959$, $P < 0.05$), OAC ($r = 0.956$, $P < 0.05$) and WHC ($r = 0.995$, $P < 0.01$). Therefore, it seems that differences observed in the amylose content were not large enough to compensate the modifications derived from the agglomerates structure, which was responsible for the hydration properties.

Starch sample isolated from corms also had lower value of SV. Again, granule size ($r = 0.979$, $P < 0.05$) as well as amylose content ($r = 0.989$, $P < 0.05$) significantly influenced this parameter. Correlations also indicated that SI was affected by granule size ($r = -0.997$, $P < 0.01$), which agrees with previous results (Lin *et al.*, 2015).

The water uptake during thermal treatment was measured by determining the WAI and WSI (Table 1). Both parameters were significantly dependent on the starch source. Corms starch showed higher WAI values than those obtained by cormels sample. In line with other report (Kadan *et al.*, 2008), no correlation was obtained between granule size and WAI. Nevertheless, a negative correlation between amylose content and WAI ($r = -0.9726$; $P < 0.05$) was found. Cornejo and Rosell (2015) suggested that in flours with high WBC, water become less available to hydrate the amorphous region of the starch, during the hydration and gelatinization of the flour, leading to WAI decrease. WSI showed significant lower value in corms starch than in cormels starch. A positive relationship between granule size and WSI ($r = 0.9734$; $P < 0.05$) and between amylose content and WSI ($r = 0.9926$; $P < 0.01$) were observed, likely due to the amylose leached out during heating (de la Hera *et al.*, 2013).

Table 1. Color and hydration properties of starch granules and gels isolated from corms and cormels

Starch Properties	Corms	Cormels	*P*-value
Color			
L^*	98.2 ± 1.39	97.7 ± 0.10	0.5418
a^*	-0.11 ± 0.03a	-0.03 ± 0.02b	0.0189
b^*	1.10 ± 0.14a	1.90 ± 0.16b	0.0042
Hydration			
WBC ($g \cdot g^{-1}$)	1.02 ± 0.02a	1.30 ± 0.05b	0.0203
OAC ($g \cdot g^{-1}$)	0.96 ± 0.00a	1.39 ± 0.08b	0.0162
WHC ($g \cdot g^{-1}$)	0.62 ± 0.01a	0.96 ± 0.00b	0.0008
SV ($mL \cdot g^{-1}$)	2.00 ± 0.01a	3.00 ± 0.00b	0.0001
SI ($g \cdot g^{-1}$)	3.00 ± 0.11b	1.98 ± 0.20a	0.0241
Gels hydration			
WAI ($g \cdot g^{-1}$)	8.80 ± 0.30b	6.47 ± 0.38a	0.0211
WSI ($g \cdot g^{-1}$)	1.40 ± 0.00a	7.30 ± 0.14b	0.0003
Gels syneresis			
120 h (%)	6.00 ± 1.00b	2.67 ± 0.58a	0.0075
168 h (%)	12.33 ± 1.53a	20.67 ± 0.58b	0.0009

Values with different letters in the same row are significantly different ($P < 0.05$) (n = 3). WBC: Water binding capacity; OAC: Oil absorption capacity; WHC: Water holding capacity; SV: Swelling volume; SI: Solubility index; WAI: Water absorption index; WSI: Water solubility index.

Thermal properties

The values for the thermal parameters of the isolated starches were determined by DSC to detect possible changes in physical states of the starch structures. The transition temperatures (To) significantly ($P < 0.05$) differed among samples.

Corms starch exhibited higher To and peak temperature (Tp) than cormels starch. No statistically significant differences were observed in Tc. Wang & Copeland (2012), indicated that DSC thermal transition represents water absorption and swelling of starch granules. Considering the described impact of granule size and amylose content on the hydration properties, those might have relevant influence in To and Tp parameters. In fact, To was negatively correlated with granule size ($r = -0.988$, $P < 0.05$), amylose content ($r = -0.979$, $P < 0.05$) and WBC ($r =$

-0.997, $P < 0.05$). Moreover, amylose content showed also significant relationship with Tp ($r = -0.999$, $P < 0.01$). These correlations suggest that the lower WBC of corms starch caused a delay in the onset of swelling behavior, which leads to higher To. On the other hand, Liu *et al.* (2015) indicated that smaller starch granule tend to absorb water faster, which reinforces the hypothesis that the formation of aggregates in corms starch plays a crucial role on the functional properties of this starch.

Similar enthalpy was recorded for both starches, suggesting similar structural order in both starches (Ribotta *et al.*, 2007).

Pasting properties

The overall shape of the RVA pasting curves of both starches displayed typical behaviour when starchy suspensions were subjected to a heating and cooling cycle (Fig. 2). As expected, clear dissimilarities were observed taking into account the great microstructure divergences earlier mentioned. Regarding starch source, starch from corms showed a delayed pasting formation, suggesting retarded gelatinization. Cormels sample reached higher viscosity after heating and it was also observed along the cooling stage.

Parameters recorded from the pasting curves are summarized in Table 2. The statistical analysis revealed significant differences in all their pasting parameters. The onset temperature, where viscosity begins to increase, was significantly ($P < 0.05$) higher in corms starch. Therefore, higher temperature would be required for its gelatinization, likely due to its lower water absorption ($r = -0.979$, $P < 0.05$). Corms starch exhibited the lowest pasting viscosities. The peak, trough, breakdown, final and setback viscosities of corms sample were lower than those recorded for the cormels sample. The pasting viscosities of corms starches were similar to the results of Falade and Okafor (2013). Again, different behavior on pasting performance, might be attributed to different granule size and amylose content.

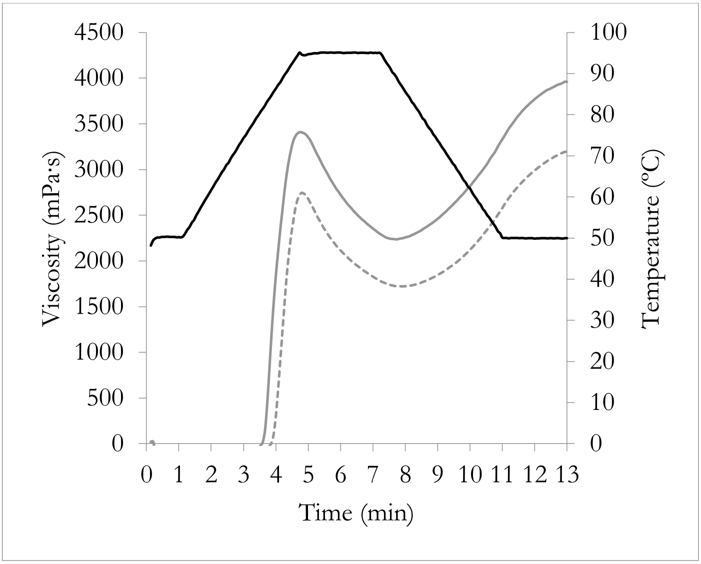

Fig. 2. Apparent viscosity profiles corms (—) and cormels (---) starches obtained with a rapid viscosity analyzer. Thick solid line indicated the temperature settings during the heating-cooling cycle.

In fact, positive significant correlations between granule size and pasting parameters were found (not shown), except for the breakdown. Similarly, amylose content had relevant influence in pasting properties as demonstrated its positive correlation with all the pasting parameters. Similar correlations have been previously described in the literature for other type of starches (Schirmer *et al.*, 2013).

Table 2. Properties of starches isolated from corms and cormels measured with the RVA for assessing pasting behavior, DSC for thermal properties and texturometer for gel hardness

Properties	**Corms**	**Cormels**	***P*- value**
Pasting			
T_o (ºC)	84.80 ± 0.00b	81.50 ± 0.00a	0.0000
PV (×10^3 Pa·s)	2762 ± 24^a	3410 ± 34b	0.0020
Trough (×10^3 Pa·s)	1709 ± 19^a	2236 ± 57b	0.0067
Breakdown (×10^3 Pa·s)	1053 ± 43^a	1174 ± 23b	0.0480
FV (×10^3 Pa·s)	3191 ± 4^a	3961 ± 54b	0.0025
Setback (×10^3 Pa·s)	1482 ± 16^a	1725 ± 2b	0.0019
Thermal			
To (ºC)	74.17 ± 0.25b	71.65 ± 0.28a	0.0109
Tp (ºC)	79.45 ± 0.35b	76.28 ± 0.35a	0.0122
Tc (ºC)	86.69 ± 0.48	85.51 ± 0.04	0.0748
Gelatinisation enthalpy (J g^{-1})	18.82 ± 1.37	16.80 ± 0.19	0.1759
Textural			
Gel hardness (N)	0.207 ± 0.1	0.197 ± 1.5	0.1705

Means in the same row with different letters are significantly different ($P < 0.05$) (n = 3). FV, Final viscosity; PV, Peak viscosity; Tc, Conclusion temperature; To, Onset temperature; To, Onset; Tp, Peak temperature.

Texture profile analysis (TPA) and syneresis during storage

The hardness of corms and cormels gels was measured after storage at 4 °C for 24 h. Results obtained did not reveal significant differences. The behavior of those gels over a period of up to 168 h at 4 ºC was assessed evaluating their syneresis or water released from the polymer network after cooling. It was virtually zero during the first days of storage, and only after 120 h at 4 ºC could be detected (Table 1). The gels obtained from cormels starch exhibited lower syneresis values than the corms starch after 120 h, holding the water molecules in its structure, which has been related to its tendency to retrograde (Tetchi *et al.*, 2007).

Nevertheless, inverse behavior was observed after longer storage, when syneresis of gels from cormels exhibited significantly higher values. As expected, storage time promoted a significant increase of the syneresis in both samples, which agrees with previous results obtained by Tetchi *et al.* (2007) when evaluated the physicochemical characteristics of starches from diverse araceas, although authors did not specify if they were isolated from corms or cormels.

Conclusions

Corms and cormels from *Xanthosoma sagittifolium* contained morphologically different starch granules. Starch isolated from corms exhibited smaller granules with an aggregate disposition which, besides the lower amylose content, might be responsible of their hydration properties (lower WBC, OAC WHC, SV and higher SI), lower apparent viscosity during heating and cooling, higher To and Tp, as well as lower syneresis after seven days storage. In fact, correlation analysis confirmed that granule size and amylose content play a determinant role in the functional behavior of starch granules. Differences noticed between starches isolated from corms and cormels of *Xanthosoma* spp. stressed the importance of identifying the starch source within the botanical parts of araceas to allow understanding and comparing research studies.

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Conflict of interest

The authors have declared no conflict of interest.

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Chapter 3

Development of gluten-free breads from *Colocasia esculenta* flour blended with hydrocolloids and enzymes

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Development of gluten free breads from *Colocasia esculenta* flour blended with hydrocolloids and enzymes

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Abstract

Colocasia esculenta, belonging to the Araceae family, represents an attractive alternative as gluten-free (GF) main ingredient owing its healthy pattern. The aim was to explore the GF breadmaking potential of *Colocasia* spp. cormels flour, thermally treated or blended with hydrocolloids (HPMC, xanthan gum, guar gum), enzymes (glucose oxidase or proteases) or potato starch. A total of eight formulations were used to obtain GF bread-like products. Resulting breads were characterized based on their technological quality, but also on their functional quality by *in vitro* starch digestion. *Colocasia* spp. cormels flour-based breads displayed similar quality parameters observed in previous reported GF formulations. The addition of an endoprotease allowed developing breads with higher specific volume, but the alcalase type protease increased crumb softness. In general, resulting GF breads contained higher SDS and RS fraction than RDS fractions. A better starch digestibility pattern than those previously reported in GF breads was also observed, which confirm the potential of *Colocasia* spp. cormels flour as novel nutritive source of GF flours.

Keyword: bread; *Colocasia esculenta*; digestibility; gluten-free; glycemic index.

1. Introduction

Over the last decades, the popular belief that gluten-free (GF) diet is a healthier option along with gluten-related disorders are driving an increasing number of consumers to opt for a GF diet as a lifestyle choice. Consequently, numerous researches have been conducted on GF products to improve their technological and nutritional properties (Capriles & Arêas, 2014; Capriles *et al.*, 2016). Nevertheless, diverse studies stated that consumers remain unsatisfied with the quality of GF products (do Nascimento *et al.*, 2014), while others highlighted their lack of nutritional values compared to their gluten-containing counterparts (Pellegrini & Agostoni, 2015). Therefore, a balance between technological properties and nutritional value is necessary to match the consumer's requests.

Currently, refined flours or starches are the main ingredients used to produce commercial GF products, specifically GF breads. As a result, breads have poor technological quality including dry crumbling crumb, poor mouthfeel and poor flavor (Gallagher *et al.*, 2003). These GF breads also show deficient nutritional values including low protein content and higher carbohydrate than the recommended intake (Segura & Rosell, 2011). The inclusion of alternative GF flours into GF breads recipes is one of the main approaches to improve their claimed poor technological and nutritional quality (Alvarez-Jubete *et al.*, 2010). Alternative flours from pseudocereals, roots, tubers and legumes sources have been applied successfully to improve the nutrient profiles of the GF products (Capriles & Arêas, 2014). Nevertheless, their minimal structure-building potential requires the use of additives or ingredients. Thus far, hydrocolloids, proteins, enzymes have been mixed with blends of GF flours and starches to improve the technological quality of end-products (Masure *et al.*, 2016). Apart from mentioned inferior technological properties, the inclusion of all these alternative flours into GF breads is limited owing its detrimental effect on the sensory properties of end-products (Capriles *et al.*, 2016). Therefore, further searches on other nutritive GF flours are needed.

Colocasia esculenta (L.) Schott (*Colocasia* spp.) rhizome is grown largely in Cuba for their edible corms and cormels (Calle *et al.*, 2019). Its nutritional components make this material very attractive to improve the nutritional value of foods (Kaushal *et al.*, 2015). *Colocasia* spp. has been stated as a good source of protein (11–16%), crude fiber (5–9%) and potassium (2271–4276.06 mg·100 g^{-1}), but also other minerals including iron, calcium, sodium, magnesium, phosphorus, zinc and copper (Arıcı *et al.*, 2016). Furthermore, *Colocasia* spp. flour also contains vitamins and has antioxidant activity (Chandrasekara & Kumar, 2016).

Despite the evidence of positive nutritional value of *Colocasia* spp. flour and its promising economic value, as far as authors knowledge, there are no studies about the utilization of this flour in GF bread-making. Ammar *et al.*, (2009) incorporated 5, 10, 15 and 20% *Colocasia* spp. flour into a wheat flour-based dough and concluded that the adding of 10% *Colocasia* spp. flour results in bread with similar rheological and organoleptic properties than those observed in wheat flour bread (Emmanuel *et al.*, 2010). Sanful (2011) also replaced wheat flour with different percentages of *Colocasia* spp. flour, increasing the amounts of ash, total carbohydrates and fiber as increasing the taro flour level in the breads.

The main objective of the present study was to explore the GF breadmaking potential of *Colocasia* spp. flour. Furthermore, based on the aforementioned complex GF systems found in the literature, the effect of different additives including hydrocolloids, enzymes and starch was also evaluated to overcome the technological challenge involved in the gluten removal. The suitability of *Colocasia* spp. flour individually, thermally pretreated or blended with different additives for application in a GF systems was investigated and their effects on the technological and nutritional properties of the GF bread products were evaluated.

2. Materials and methods

2.1. Materials

Cormels from freshly *Colocasia* spp. MC-2012, harvested at nine months of maturity, were collected from National Institute of Tropical Food Research Farms in Cuba. The rhizomes were cleaned to remove all foreign matter, peeled and cut into slices of 1 cm. After mixing with water and a solution of sodium metabisulfite (20 mg·kg^{-1}) during 30 min to avoid oxidation reaction, the slices were dehydrated with a forced convection tray dryer (Keller, Ihne & Tesch KG No. 3709, Lampertheim, Germany) at 45 °C during 24 h. Then, the dry slices were milled and the obtained flour kept at 4 °C for subsequent analyses. Hydroxypropylmethylcellulose (HPMC, Methocel™ K4M) was generously donated by Dow Pharma & Food Solutions (La Plaine Saint Denis, France). Guar gum – 3500 and xanthan gum food grade were obtained from EPSA (Valencia, Spain) and Jungbunzlauer (Wulzeshofen, Austria), respectively. Gluzyme Mono 10000 BG (EC 1.1.3.4) containing 10,000 glucose oxidase U/g, iZyme BA (EC 3.4.21.1) containing 0.15 AU/g endo-protease activity, and Alcalase 1.5 MG Type FG (EC 3.4.21.62) containing 1.5 AU/g alcalase activity (Subtilisin type) were provided by Novozymes (Bagsværd, Denmark). Potato starch was purchased from Tereos Syral (Marckolsheim, France). All other ingredients were acquired in the local market. All reagents were of analytical grade and used without further purification.

2.2. Flour characteristics

Standard methods were used to determine the flour characteristics (AACC, 1999; AOAC, 1990). Moisture was measured by oven drying at 130 °C for 90 min (AACCI Method 44–15.02). Total nitrogen content was analyzed according to the Kjeldahl method (AACCI methods 46–12.01) using a nitrogen-to-protein conversion factor of 6.25. Fat content was quantified following the Soxhlet method (AACC Method 30–25.01). Ash content was determined by incinerating samples in a muffle at 900 °C for 2 h (AACC Method 08–01.01). The crude fiber content of the samples was analyzed in accordance with the AOAC Method 973.18. Carbohydrate content was estimated by difference. Water binding capacity (WBC) was analyzed according to the method described by Cornejo and Rosell (2015). Results were expressed as grams of water retained per gram of solid.

2.3. Baking process

A total of eight reported GF bread formulations were selected (Calle *et al.*, 2014; Gujral & Rosell, 2004; Marco & Rosell, 2008; Morreale *et al.*, 2018; Renzetti & Arendt, 2009a) and adapted to *Colocasia* spp. cormels flour characteristics. All of them were prepared relying on a simple GF formulation based on *Colocasia* spp. cormels flour, present individually, pretreated or blended with different ingredients (starches, enzymes and other hydrocolloids) widely used in the design of GF bread. To obtain pretreated *Colocasia* spp. cormels flour, 50 g of resulting *Colocasia* spp. cormels flour were mixed during 5 min with 113.5 mL of boiled water, which corresponded to the water binding capacity required for hydrating 50 g of flour. This partially pre-gelatinized flour was directly used in the recipe and it was referred as pretreated flour. The formulations used are summarized in Table 1, which were based on flour as follows: 100% of rhizome flour (F1); 50% of flour blended with 50% of pre-gelatinized flour (F2); 100% of flour blended with hydrocolloids (F3 and F4); 100% of flour blended with enzymes (F5, F6 and F7); and 80% of flour blended with 20% of potato starch (F8).

GF doughs were prepared by mixing the dry ingredients and then by adding the oil and water with the compressed yeast previously dissolved at 20 °C. Mixing was carried out in a Robot Coupe RM8 (Barcelona, Spain) at speed 3 for 8 min. 50 g-Dough pieces were put into pans and placed into a proofer (Lezo, Spain) for 50 min at 30 °C and a relative humidity of 85%. The breads were baked in an electric oven (F106, FM Industrial, Córdoba, Spain) at 185 °C, 80% of humidity for 20 min. After baking, bread loaves were removed from the pans and cooled at room temperature for 45 min. Loaves packed in polyethylene bags o prevent drying were stored at 24 °C for 24 h and then used for further analysis. Baking was performed on two independent trials and five loaves were pre-pared for each bread type at each baking trial.

2.4. Quality assessment of the GF breads

Resulting GF breads were evaluated in terms of quality parameters as previously described by Matos and Rosell (2013). Bread moisture content was determined in two steps following the AACC (1999). Bread volume was measured by the rapeseed displacement method. Specific volume ($cm^3 \cdot g^{-1}$) was calculated as the ratio between the volume of the bread and its weight. Weight loss during baking was assessed by weighing the pans before and after baking. These measurements were carried out in three breads of each batch.

Table 1. Gluten-free bread recipes

Ingredients	F1	F2*	F3	F4	F5	F6	F7	F8
Flour (g)	100	100	100	100	100	100	100	80
Water (g)	227	227	227	227	227	227	227	227
Salt (g)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Compressed Yeast (g)	3	3	3	3	3	3	3	3
Sugar (g)	2	2	2	2	2	2	2	2
Oil (g)	2	2	2	2	2	2	2	2
HPMC (g)			2	0.29				
Xanthan gum (g)				0.21				
Guar gum (g)				0.50				
Gluzyme Mono 10000 BG (g)					0.01			
izyme BA (g)						0.1		
Alcalase 1.5 MG Type FG (g)							0.01	
Potato starch (g)								20

Ingredients: 100% of rhizome flour (F1); 50% of *Colocasia* spp. cormels flour blended with 50% of pre-treated *Colocasia* spp. cormels flour (F2); 100% of flour blended with hydrocolloids (F3 and F4); 100% of flour blended with enzymes (F5, F6 and F7); and 80% of flour blended with 20% of potato starch (F8).

The texture parameters including hardness (g), cohesiveness, chewiness (g) resilience and springiness were evaluated using a Texture Analyzer TA-XT2i (Stable Micro Systems, Surrey, UK) equipped with a 5 kg load cell, which compresses the bread crumb with a 25mm aluminum cylindrical probe. Bread samples were sliced into 10mm slices and analyzed with a texture profile analysis (TPA) double compression test. During the test, samples were compressed twice up to 50% strain (penetration of its original height) at a cross head speed of 1 mm·s^{-1} and 30 s gap between compressions with a trigger force of 5 g. Data was acquired using Texture expert software and showed as the average value taking three breads from each batch.

Crumb color was recorded using a Minolta colorimeter (Chromameter CR-400/410 Konica Minolta Japan) after standardiza-tion with a white calibration plate (L^*=96:9; a^*=−0.04; b^*=1.84). The data collected from three slices of each bread measured at three different locations of the slices were averaged and expressed using CIE-L^* a^*b^* scale where L^* indicates lightness, a^* indicates hue on a green (−) to red (+) axis, and b^* indicates hue on a blue (−) to yellow (+) axis.

2.5. *In vitro* digestion

Digestibility of GF breads was assayed following the method described by (Benavent-Gil & Rosell, 2017b). The amount of starch fractions based on the hydrolysis rate of starch was calculated and expressed in amount of glucose released (mg·100 mg^{-1}) by using the method of Englyst, Veenstra, and Hudson (1996). Rapidly digestible starch (RDS) was defined as the starch fraction that was hydrolyzed within 20 min of incubation, SDS was the starch fraction hydrolyzed within 20 and 120 min, and resistant starch (RS) was defined as the starch fraction that remaining unhydrolyzed after 16 h of incubation.

Glucose measure was determined in supernatant samples using a glucose oxidase–peroxidase (GOPOD) kit (Megazyme, Dublin, Ireland). Starch was calculated as glucose (mg)×0.9.

Experimental data were fitted to first order equation to study the kinetics of *in vitro* digestion (Goñi *et al.*, 1997): $C = C_\infty (1-e^{-kt})$. C was the concentration at t time, C_∞ was the equilibrium concentration or maximum hydrolysis extent, k was the kinetic constant and t was the time chosen. The hydrolysis index (HI) was calculated as the ratio area under the hydrolysis curve (0–180 min) of the sample and area of a standard material (white bread) over the same period of time. The expected glycemic index (*e*GI) was obtained using the equation $eGI=8.198+0.862HI$ (Granfeldt *et al.*, 1992).

2.6. Statistical analysis

The data reported in the tables and figures are average values of duplicates and expressed as a mean ± standard deviation. Data was subjected to analysis of variance (ANOVA) to separate the effect of different additives. Fisher's least significant test was used for assessment of significant differences among experimental mean values with a significance level of 0.05. Pearson correlation coefficient (r) and p-value were used to indicate correlations and their significance using Stat-graphics Centurion XVII software (Bitstream, Cambridge, N).

3. Results and discussion

3.1. Proximate composition of raw *Colocasia esculenta* cormels flour

The composition of *Colocasia* spp. flour used in the present study expressed in percentage (based on dry basis) was as follows: moisture: 6.33 ± 0.02%, protein: 8.28 ± 0.07%, ash: 5.04 ± 0.00%, fat: 0.53 ± 0.00%, crude fiber: 4.38 ± 0.23% and carbohydrates: 75.44 ± 0.35. Data obtained are in agreement with literature (Temesgen & Retta, 2015a). As expected, *Colocasia* spp. cormels flour displayed high carbohydrate content, but it also proved to be a good source of minerals and fiber. The protein content was lower than that found in teff (12.84 ± 0.51) and buckwheat (12.39 ± 0.38) flours (Hager & Arendt, 2013). However, it was higher than that found in the most commonly used GF flours such as maize (5.50%), rice (7.33%), cassava (1.4%) or sweet potato (6.3%) flours (Hager & Arendt, 2013; Pasqualone *et al.*, 2010; Yadav *et al.*, 2006).

3.2. Characterization of *Colocasia* spp. cormels flour-based breads

The suitability of *Colocasia* spp. cormels flour (F1) for GF breadmaking was evaluated testing the different alternatives that the literature offers for building up inner structures. Nevertheless, the amount of water used for making GF breads was based on the water binding capacity of the flour (2.27 g·g flour^{-1}), since that parameter has been previously confirmed as a good indicator of the optimum amount of water to be used in gluten-free systems (Espinosa-Ramírez *et al.*, 2018). Resulting GF breads were characterized regarding their moisture content, weight loss, specific volume and crumb color (Table 2). The observed moisture content (44.29–50.64%), specific volume and weight lost in F1 breads were comparable to GF rice based breads such as oat, quinoa and so on (Hager *et al.*, 2012). Likely, the higher water binding capacity of *Colocasia* spp. flour (Calle *et al.*, 2019) compared to other common GF flours and starches (Martínez & Gómez, 2017), might be responsible for those high values of moisture content.

The color of bread is one of the first characteristics observed by consumers, determining choice and preference. Results from the crumb color parameters are summarized in Table 2. As expected, the color of F1 breads was visually dark, which was further confirmed by their lower *L** value. This value could be attributed to the natural color of raw *Colocasia* spp. flour, which displayed 81.05 ± 0.36, 1.17 ± 0.07 and 14.63 ± 0.45 for *L**, *a** and *b**, respectively. Kumar *et al.* (2014) highlighted that *Colocasia* spp. flour can contain naturally colored pigments and those affected the color characteristics of end products.

To describe the texture of *Colocasia* spp. -based breads (F1), crumb hardness, cohesiveness, chewiness, resilience and springiness are depicted in Table 3. Resulting breads revealed much lower crumb texture values than those reported for commercial GF bread (Matos & Rosell, 2012), probably due to the higher moisture contents (de la Hera, Rosell, & Gomez, 2014).

3.3. Effect of additives in *Colocasia* spp. cormels flour-based breads

Different strategies previously reported to build up inner structures in gluten-free breads or improve flour functionality were applied to increase the technological quality of *Colocasia* spp. breads. The effect of thermally treated *Colocasia* spp flour blended with the raw flour (F2), hydrocolloids (F3, F4), enzymes (F5–F7) or potato starch (F8) in the quality of *Colocasia* spp. based breads were evaluated (Table 2).

Those formulations have been selected from literature to show the different alternatives applied to improve GF breads quality. Among them, hydrocolloids of different nature -HPMC (Marco & Rosell, 2008), mixture of HPMC, xanthan gum and guar gum (Calle *et al.*, 2014), enzymes with strengthening (glucose oxidase) or weakening action (proteases), and potato starch. The statistical analysis revealed significant differences ($p < 0.05$) regarding moisture content, weight loss and specific volume. In general, the effect of treated *Colocasia* spp. flour (F2) as well as hydrocolloids (F3, F4) and enzymes addition (F5–F7) resulted in higher moisture content than those observed in F1 breads. Overall, F2 and F7 samples displayed the highest moisture content. F2 bread was obtained replacing *Colocasia* spp. cormels flour by pretreated *Colocasia* spp. cormels flour. The pretreatment involved the heating of the flour in excess of water to cause a partial or complete gelatinization of the starch granules, which increase its ability to bind water (Njintang & Mbofung, 2006). On the other hand, F7 breads that incorporates a protease (Alcalase 1.5 MG Type FG) in its recipe, might bind more water due to the hydrophobicity reduction of the flour. Some authors explained the effect of the protease on gluten-free flours due to its hydrolytic action on the proteins, that led to a decrease in the hydrophobicity of the system in specific flours (Renzetti & Arendt, 2009b). Nevertheless, no general trend could be defined regarding proteases, since that effect was not observed in F6 that also contained a protease type enzyme. Conversely, F8 breads displayed lower moisture content, likely due to the low capacity of potato starch to bind water (Benavent- Gil & Rosell, 2017a).

Table 2. Different quality characteristics of gluten-free breads based on raw *Colocasia* spp. cormels flour, pretreated or blended with different ingredients, additives or processing aids

	Moisture ($g \cdot 100\ g^{-1}$)	**Weight loss (%)**	**Specific volume ($mL \cdot g^{-1}$)**	***L****	***a****	***b****
F1	57.63 ± 0.26 b	15.49 ± 0.69 bc	1.74 ± 0.03 b	57.01 ± 0.37 c	6.88 ± 0.38 e	22.29 ± 0.63 c
F2	60.23 ± 0.18 ef	12.78 ± 0.60 a	1.63 ± 0.02 b	57.48 ± 0.49 c	5.18 ± 0.10 b	20.34 ± 0.25 b
F3	58.74 ± 0.61 c	14.93 ± 0.97 bc	1.70 ± 0.05 b	56.87 ± 0.66 bc	7.09 ± 0.82 e	23.97 ± 0.66 d
F4	58.80 ± 0.41 cd	13.80 ± 0.81 ab	1.67 ± 0.02 b	56.09 ± 0.49 bc	6.13 ± 0.13 d	21.04 ± 0.53 b
F5	59.69 ± 0.29 de	13.98 ± 1.57 ab	1.65 ± 0.09 b	55.02 ± 1.98 ab	5.85 ± 0.30 cd	21.75 ± 0.96 b
F6	59.30 ± 0.68 cd	13.07 ± 1.78 a	2.71 ± 0.13 c	57.21 ± 0.80 c	5.92 ± 0.49 cd	20.70 ± 0.52 b
F7	60.96 ± 0.17 f	13.89 ± 1.03 ab	1.11 ± 0.05 a	57.41 ± 2.27 c	5.63 ± 0.16 bc	20.74 ± 0.40 b
F8	55.56 ± 0.20 a	16.30 ± 1.53 c	1.20 ± 0.06 a	57.21 ± 0.80 a	5.92 ± 0.49 a	20.70 ± 0.52 a
p-value	0.0000	0.0031	0.0000	0.0029	0.0000	0.0000

Values followed by different letters within a column denote significant differences. Ingredients: 100% of rhizome flour (F1); 50% of *Colocasia* spp. cormels flour blended with 50% of pre-treated *Colocasia* spp. cormels flour (F2); 100% of flour blended with hydrocolloids (F3 and F4); 100% of flour blended with enzymes (F5, F6 and F7); and 80% of flour blended with 20% of potato starch (F8).

In line with previous findings (Cornejo & Rosell, 2015; Matos & Rosell, 2013; Renzetti & Arendt, 2009a; Shin *et al.*, 2010), the specific volume values ranged from 1.11 ± 0.05 to 2.71 ± 0.13 $mL·g^{-1}$, values were significant dependent on the recipe applied. Compared to F1 breads, differences were only observed in the case of F6, F7 and F8 breads. Among them, F6 breads displayed the highest specific volume, likely due to the enzyme ability to modify protein functionality

Nevertheless, proteases effect on GF breads are really dependent on the type of flour (Renzetti & Rosell, 2016). In fact, it seems that iZyme improves breadmaking performance of cormels' flour. In opposition, the other protease tested (alcalase) led to the smallest specific volume (F7). Small statistical differences were also observed in the case of weight loss, particularly the lower weight loss of F2 and F6 breads compared to F1 breads. However, in the case of F2 the water ability retention of starch would be responsible of that effect, conversely in F6, it might be ascribed to the more hydrophilic structure resulting from proteins hydrolysis.

The L^*, a^* and b^* values for crumb color showed significant ($p < 0.05$) differences among the different formulations used to obtain the GF breads. The lowest value of L^* (lightness) was obtained for F8, which could be expected due to the opacity that confers the potato starch. Regarding a^* and b^* values, all samples exhibited positive values, indicating hue on red and yellow axis for all bread samples. However, significant variation was observed among the different formulations. HPMC present in F3 was the unique additive that did not modify the a^* value, compared to the control. The rest of recipes showed a decrease in the a^* values. Regarding the b^* parameter, again could be distinguished the effect of HPMC, leading to brownish crumb in F3; in contract, more pale crumbs were obtained when adding potato starch. Therefore, crumbs color was not only dependent on the flour color, but on the interaction of ingredients and additives.

Table 3. Analysis of crumb texture of gluten-free breads based on *Colocasia* spp. cormels flour alone, pretreated or blended with different ingredients, additives or processing aids

	Hardness (g)	**Cohesiveness**	**Chewiness (g)**	**Resilience**	**Springiness**
F1	263 ± 38 c	0.337 ± 0.044 a	24 ± 3 a	0.104 ± 0.019 c	0.419 ± 0.075 a
F2	361 ± 17 e	0.384 ± 0.041 b	69 ± 17 e	0.126 ± 0.013 d	0.484 ± 0.107 ab
F3	316 ± 12 d	0.348 ± 0.028 ab	50 ± 4 cd	0.095 ± 0.010 a-c	0.441 ± 0.087 ab
F4	323 ± 23 d	0.313 ± 0.044 a	45 ± 6 cd	0.091 ± 0.009 ab	0.434 ± 0.135 a
F5	209 ± 16 ab	0.373 ± 0.020 b	39 ± 14 bc	0.103 ± 0.009 c	0.546 ± 0.193 b
F6	330 ± 18 d	0.331 ± 0.037 a	54 ± 3 de	0.101 ± 0.012 bc	0.473 ± 0.116 ab
F7	191 ± 9 a	0.334 ± 0.030 a	27 ± 4 ab	0.086 ± 0.008 a	0.473 ± 0.111 ab
F8	233 ± 17 b	0.500 ± 0.031 c	65 ± 6 e	0.143 ± 0.019 e	0.697 ± 0.090 c
p-value	0.0000	0.0000	0.0000	0.0000	0.0001

Values followed by different letters within a column denote significant differences. Ingredients: 100% of rhizome flour (F1); 50% of *Colocasia* spp. cormels flour blended with 50% of pre-treated *Colocasia* spp. cormels flour (F2); 100% of flour blended with hydrocolloids (F3 and F4); 100% of flour blended with enzymes (F5, F6 and F7); and 80% of flour blended with 20% of potato starch (F8).

As expected, crumb texture was significantly ($p < 0.05$) influenced by the recipe applied (Table 3). Hardness values ranged from 191 ± 9 to 361 ± 17 g. Overall, F2 and F7 breads displayed the highest and lowest values, respectively. The hardness of F3 and F4 increased, despite the hydrocolloid addition usually tends to decrease hardness (Liu *et al.*, 2018). Nonetheless, their effect seems to be also dependent on the flour used (Sasaki, 2018).

Again, enzymes effect on crumb hardness was really erratic, particularly in the case of proteases that increase (F6) or decrease (F7) it, depending on the type of protease (Kawamura-Konishi *et al.*, 2013). It should be emphasized that although general consensus exits about the inverse relationship between specific volume and crumb hardness, recipes tested in this study confirmed that additives/enzymes modify constituents network and in consequence the crumb structure, breaking down that general rule.

Noticeable differences were also showed in chewiness. In general, the ingredients addition increased this parameter, except in the case of F7 breads, which did not modify it. In the case of cohesiveness, all breads exhibited similar behavior, except in the case of F2, F5 and especially F8 bread that increased this parameter, suggesting a more integrated matrix. Among them, F8 breads showed the highest value. Consumer's acceptance is greatly influenced by the cohesiveness, which quantifies the internal resistance of material. Therefore, starch addition led to more compact structure, since it decreased the crumbling. Starch addition (F8) also affected significantly the resilience and springiness of the breads. Springiness has been commonly related with resilience values, which reduction indicates the loss of crumb elasticity (Onyango *et al.*, 2011). Considering the overall texture results, it seems that starch addition it is advisable to improve the texture properties of *Colocasia* spp. based breads.

3.4. Digestibility of GF breads

Relevant starch fractions including RDS, SDS and RS were evaluated and categorized depending on its rate of digestion (Table 4) (Englyst *et al.*, 1996). *Colocasia* spp. cormels flour-based breads (F1) exhibited high

SDS and RS fractions and low RDS fraction. Considering the great impact of RDS on the glycemic response (Englyst *et al.*, 1996), the production of GF breads with higher amounts of SDS and RS fractions are interesting from a nutritional point of view. It has been already known the healthy profile of *Colocasia* spp. starch due to their small size (Temesgen & Retta, 2015), but what this study shows, is that the healthy profile is even present in *Colocasia* spp. based breads.

In general, the starch fraction pattern observed in F1 breads was also found in the rest of the breads, except in the case of potato starch addition (F8). Nevertheless, the different recipes caused changes in α-amylase susceptibility, resulting in significantly ($p < 0.05$) differences within RDS contents without significantly affecting the SDS and RS content (Table 4). The largest increase of RDS fraction was found in F8 samples, which is consistent with the pattern previously reported for starchy foods (Poutanen *et al.*, 2009). Furthermore, studies conducted by Segura & Rosell (2011) highlighted that RDS is the most pre-dominant fraction in available commercial GF breads mainly based on corn starch. This effect could be attributed to the starch gelatinization (Shumoy *et al.*, 2018), which results in a rapid degradation of starch (Poutanen *et al.*, 2009).

3.5. *In vitro* and expected glycemic index of GF breads

The different gluten-free breads were subjected to *in vitro* enzymatic hydrolysis in order to simulate starch digestibility. At specific intervals of *in vitro* reaction, starch hydrolysis was measured as glucose released and Fig. 1 shows the resulting plots. Furthermore, primary and secondary parameters derived from the *in vitro* digestion were also analyzed. Results obtained including the kinetic constant (k), equilibrium concentration of hydrolyzed starch (C_∞), area under the hydrolysis curve after 180 min (Liu *et al.*, 2018), hydrolysis index (HI) and estimated glycemic index (*e*GI) are summarized in Table 4. Starch hydrolysis draws plots characterized by a linear increase of glucose released during the early stage of digestion, which can be maintained over time or reach the plateau (Blazek & Gilbert, 2010). In this regard, a typical digestion pattern was observed for F1 breads, which at the early stage of hydrolysis exhibited a linear increase in the amount of glucose released. Nevertheless, k for the amylolysis evidenced slower hydrolysis kinetics than those observed by Segura & Rosell, 2011 when evaluated different commercial GF breads. After 90 min of *in vitro* digestion, F1 breads reached the plateau, showing the maximum hydrolysis (C_∞) to a lower extent than those previously reported (de la Hera *et al.*, 2014). Following this trend, lower *e*GI was found compared with reported GF breads (de la Hera *et al.*, 2014; Liu *et al.*, 2018; Segura & Rosell, 2011; Wolter *et al.*, 2013). Some authors reported that GF breads display significantly higher *e*GI compared to traditional breads (Segura & Rosell, 2011). These results suggest that *Colocasia* spp. flour might provide end products with higher nutritional properties.

Concerning the influence of the different recipes, varying susceptibilities to enzyme hydrolysis were observed (Fig. 1). Starch hydrolysis exhibited different rate and extent for *Colocasia* spp. based breads obtained from the diverse recipes (Table 4). The kinetic constant (k) of amylolysis ranged from 0.0249 ± 0.0028 to 0.0116 ± 0.0053, displaying similar hydrolysis kinetics than F1 breads. Nevertheless, F8 samples evidenced faster hydrolysis kinetics than those observed for the other samples, which agrees with the increase of RDS above described. The maximum hydrolysis (C_∞) was not significantly affected, thus all studied GF breads displayed similar extent of starch hydrolysis than F1 breads.

Nevertheless, ingredients addition had a significant effect ($p < 0.05$) on the HI, AUC and *e*GI parameters, which showed similar trend. Results obtained revealed that only the addition of potato starch increased the HI, AUC and *e*GI parameters, while the addition of pretreated flour, gums or enzymes did not change these parameters. Considering that *in vitro* glycemic index has been previously correlated with RDS content (Liu *et al.*, 2018), the greatest *e*GI presented by F8 breads could be explained by their large RDS content. In fact, a strong positive correlation was observed between RDS content and *e*GI (r=0.9498, $p < 0.0100$) in the present study. Nevertheless, it is worth noting that the observed *e*GI was lower than those previously reported, even using potato starch in the formulation (de la Hera *et al.*, 2014; Liu *et al.*, 2018; Segura & Rosell, 2011; Wolter *et al.*, 2013). These results suggest that *Colocasia* spp. flour could maintained its nutritional pro-perties in complex food matrix.

Table 4. *In vitro* starch digestibility and its kinetic parameters of gluten-free breads based on *Colocasia* spp. cormels flour alone, pretreated or blended with different ingredients, additives or processing aids

	RDS (mg·100 mg^{-1})	**SDS (mg·100 mg^{-1})**	**RS (mg·100 mg^{-1})**	**k**	C_∞	**AUC**	**HI**	***e*GI**
F1	4.98 ± 0.51 ab	7.316 ± 0.035	6.032 ± 0.344	0.0127 ± 0.0020 ab	15.82 ± 0.48	1715 ± 81 ab	19.01 ± 0.89 ab	24.58 ± 0.77 ab
F2	5.32 ± 0.48 a-c	6.232 ± 1.391	5.959 ± 0.370	0.0173 ± 0.0028 ab	13.32 ± 2.77	1643 ± 245 ab	18.21 ± 2.71 ab	23.90 ± 2.34 ab
F3	4.38 ± 0.40 a	6.895 ± 1.309	6.730 ± 0.393	0.0116 ± 0.0053 a	16.10 ± 4.90	1565 ± 92 a	17.35 ± 1.02 a	23.15 ± 0.88 a
F4	7.01 ± 0.40 bc	5.809 ± 0.094	6.492 ± 0.362	0.0243 ± 0.0016 ab	13.56 ± 0.17	1885 ± 57 ab	20.89 ± 0.64 ab	26.20 ± 0.55 ab
F5	6.05 ± 2.17 a-c	7.298 ± 0.692	7.228 ± 1.085	0.0161 ± 0.0091 ab	16.66 ± 1.75	1897 ± 286 b	21.02 ± 3.17 b	26.32 ± 2.74 b
F6	5.25 ± 0.49 a-c	5.632 ± 0.652	7.178 ± 1.184	0.0189 ± 0.0043 ab	12.25 ± 0.92	1560 ± 7 a	17.29 ± 0.08 a	23.10 ± 0.07 a
F7	7.29 ± 0.56 c	5.864 ± 0.313	5.153 ± 0.387	0.0249 ± 0.0028 b	13.87 ± 0.01	1939 ± 59 b	21.49 ± 0.66 b	26.72 ± 0.57 b
F8	12.36 ± 0.84 d	3.815 ± 1.174	7.207 ± 0.329	0.0486 ± 0.0100 c	16.24 ± 0.40	2576 ± 7 c	28.55 ± 0.08 c	32.81 ± 0.07 c
p-value	0.0005	0.0514	0.1006	0.0031	0.3868	0.0017	0.0017	0.0017

Ingredients: 100% of rhizome flour (F1); 50% of *Colocasia* spp. cormels flour blended with 50% of pre-treated *Colocasia* spp. cormels flour (F2); 100% of flour blended with hydrocolloids (F3 and F4); 100% of flour blended with enzymes (F5, F6 and F7); and 80% of flour blended with 20% of potato starch (F8). Values followed by different letters within a column denote significant differences. C_∞ and k were quantified following the equation, $C = C_\infty(1-e^{-kt})$. *e*GI was estimated as reported Goñi *et al.* (1997).

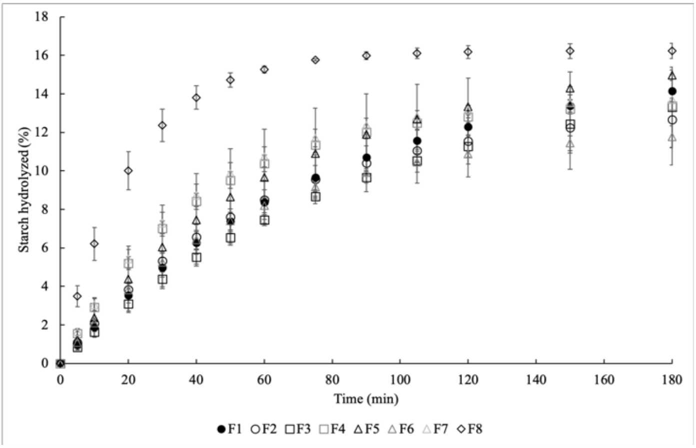

Fig. 1. Starch hydrolyzed during *in vitro* starch digestibility of gluten-free breads based on *Colocasia* spp. cormels flour, pretreated or blended with different additives.

4. Conclusions

The positive nutritional value of *Colocasia* spp. flour including high protein, minerals and fiber content, as well as low fat content makes this ingredient attractive to enhance the nutritional value of GF breads. However, to build up a light bread crumb structure from *Colocasia* spp. flour requires the development of specific strategies. For doing so, different recipes have been tested in this study. By compiling results, it can be concluded that proteases had a significant effect on the specific volume of breads, but their effect was dependent on the type of proteases. Izyme increased the specific volume, whereas alcalase type protease decreased it, but lead to softer crumbs. All GF breads showed very appropriate pattern regarding starch digestibility, with high amount of SDS and RS, which were not significantly affected with the recipes tested, and neither the *in vitro* glycemic index. Within the tested recipes, the addition of potato starch was the least advisable. Overall, *Colocasia* spp. flour can be used to produce GF breads with similar technological quality parameters than those previously reported with common GF flours, but with significantly better estimated glycemic index.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodhyd.2019.105243.

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Chapter 4

Use of flour from cormels of *Xanthosoma sagittifolium* (L.) Schott and *Colocasia esculenta* (L.) Schott to develop pastes foods: physico-chemical, functional and nutritional characterization

Jehannara Calle, Yaiza Benavent-Gil, Cristina M. Rosell

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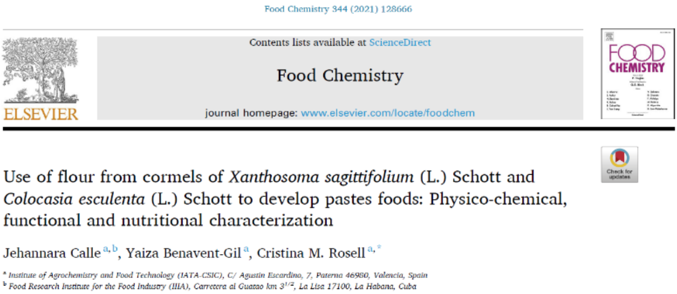

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Use of flour from cormels of *Xanthosoma sagittifolium* (L.) Schott and *Colocasia esculenta* (L.) Schott to develop pastes foods: Physico-chemical, functional and nutritional characterization

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Authorship contribution

Jehannara Calle: Investigation, Methodology, Data curation, Formal analysis, Writing - original draft. **Yaiza Benavent-Gil:** Supervision, Data curation, Formal analysis. **Cristina M. Rosell:** Conceptualization, Funding acquisition, Methodology, Supervision.

Abstract

The corms of cocoyams, specifically *Colocasia esculenta* (L.) Schott and *Xanthosoma sagittifolium* (L.) Schott are usually consumed as pastes. Nevertheless, the secondary corms, also named cormels, are not fully exploited. In this study, the chemical composition and functional properties of cormels from different botanical sources were evaluated, and the digestibility of the resulting pastes investigated. *Colocasia* spp. flour contained significantly higher protein (10.32% *vs.* 9.65%), ash (5.65% *vs.* 5.05%) and oxalates (0.32% *vs.* 0.22%) content, and exhibited lower Amylab gel strength (773 g *vs.* 1040 g) than *Xanthosoma* spp. flour. In the resulting pastes, micrographs revealed that starch gelatinization depended on cocoyam variety. Indeed, the very tight and closed microstructure of pastes containing *Colocasia* spp. flour led them to better stability during storage with lower syneresis. Lower protein digestibility was obtained in *Colocasia* spp. gels (67.56% *vs.* 70.91%), but they showed faster (higher *k*) *in vitro* starch hydrolysis (0.0140 *vs.* 0.0050) with lower *e*GI (61.29 *vs.* 65.84) than *Xanthosoma* spp. gels. The present findings offer ways to develop cocoyam based foods by using cormels, enhancing the applicability of cocoyams.

Keywords*:* cocoyam cormels, physico-chemical properties, starch, paste, digestibility.

1. Introduction

The consumption of foods containing root crops like edible aroids is quite common in many tropical and sub-tropical countries. Till the last decade, scarce scientific information was available about them, but lately, the increasing knowledge about their nutritional benefits has attracted much expectation. Cocoyams, particularly, *Colocasia esculenta* (L.) Schott (*Colocasia* spp. or taro) and *Xanthosoma sagittifolium* (L.) Schott (*Xanthosoma* spp. or tannia) are subsistence crops in South Pacific Island countries and in the Caribbean and West Africa, respectively (Owusu-Darko *et al.*, 2014). The underground tubers so-called corms and cormels (secondary corms) can be used as such, although in *Colocasia* spp., corms are the part commonly utilized for human consumption (Njintang *et al.*, 2006), while *Xanthosoma* spp. cormels are eaten after boiling or roasting and its corms are used for vegetative propagation (Owusu-Darko *et al.*, 2014).

Cocoyam tubers contain naturally occurring compounds such as fiber, minerals, vitamins, phenolic compounds, and mucilage (Mwenye *et al.*, 2011; Ndabikunze *et al.*, 2011). Nutritional benefits, like highly digestible starch with intermediate glycemic index (Simsek & El, 2015) and the reduction of postprandial levels of blood glucose (Handajani *et al.*, 2018) have been reported. Despite the importance of these aroids as emergency crops, their high moisture content (>70%) is responsible for a rapid deterioration after harvest, with the consequent losses (Falade & Okafor, 2015). Because of that, the production of flours from those tubers becomes an attractive alternative for extending storage stability and enhancing applicability ends (Kaushal *et al.*, 2015).

Among flour applications reported in the scientific literature, taro flour has been used as a texturizing agent (added up to 4% total weight) in a milk pudding, owing to its thickening properties and nutritional content (Hendek *et al.*, 2019). Flours from *Colocasia* spp. corms have also been utilized to partially replace (up to 30%) wheat flour in bread doughs, but only 10% replacement could be accomplished without affecting the functionality and viscoelastic properties of the bread dough (Aboubakar *et al.*, 2008). Cocoyam flours, being of tuber origin, can be employed for producing gluten-free fermented breads, in fact, flour from *Colocasia* spp. cormels have been used for that purpose obtaining gluten-free breads with improved digestibility patterns (Calle *et al.*, 2020). Precooked flours of *Colocasia* spp. corms are used for preparing paste food by reconstitution, although the optimization of the cooking conditions is advisable (Aboubakar *et al.*, 2009). This type of precooked flours of *Colocasia* spp. corms has been also useful for preparing weaning foods by blending up to 10% taro flour with variable amounts of *Digitaria exilis* and *Cyperus esculentus* flours (Onuoha *et al.*, 2014).

Therefore, scientific literature has mainly focused on *Colocasia* genera and the use of corms as edible parts (Kaushal *et al.*, 2015), despite other genera such a *Xanthosoma* might offer alternative flours. In fact, Falade and Okafor (2013) characterized the flours obtained from the corms of five cocoyams (*Xanthosoma* spp. and *Colocasia* spp.) showing the cultivars variability regarding the physico-chemical properties of the flours. Nevertheless, the authors stated that despite morphological differences in the corms between those species, their flour properties resembled those of other roots or tubers crops. Likewise, precooked flours of *Xanthosoma* spp. and *Colocasia* spp. have been studied for producing a traditional food paste in Cameroon (*achu*), confirming the use of *Xanthosoma* spp. for partial replacement of *Colocasia* spp. (Kaushal *et al.*, 2015; Markusse *et al.*, 2018). In addition, although most studies have been carried out with cocoyam corms, the use of secondary corms or cormels could be an extra commodity for human consumption. Nevertheless, Calle *et al.* (2019) reported significant differences between *Xanthosoma* spp. starches isolated from corms and cormels in terms of granule morphology, hydration properties, and pasting performance. Because of that, some additional knowledge about cormels flours from both cocoyam species it is necessary to extend their application.

Cormels flours from *Xanthosoma* spp. could have the same use as those from *Colocasia* spp., which are the most extended ones, despite differences in corms and cormels already reported.

For this purpose, flours from cormels of *Xanthosoma* spp. and *Colocasia* spp. were characterized regarding their functional and morphological structure. Also, their use in paste food was evaluated assessing the *in vitro* starch and protein digestibility.

2. Materials and methods

2.1. Materials

Fresh cormels from *Xanthosoma* spp. MX-2007 and *Colocasia* spp. MC-2012 were collected in the National Institute of Tropical Food Research Farms in Cuba. Flours were obtained as described by Calle *et al.* (2020) and then sieved, collecting the fraction under the 0.300 mm sieve to get homogeneous fractions with similar particle size distributions. Two different batches were performed to obtain flours. All reagents were of analytical grade and used without further purification.

2.2. Chemical composition of flours

Standard methods (AACC, 1999; AOAC, 1990) were applied to determine the compositional analysis of cocoyam flours referred to as moisture (AACCI Method 44–15.02), protein content (AOAC method 992.23), fat content (AACC Method 30–25.01), ash content (AACC Method 08–01.01) and crude fiber content (AOAC Method 973.18). The calcium oxalate content of samples was analyzed following the method described by Kumoro *et al.* (2014) with slight modifications. Briefly, a mixture of flour (2 g), water (195 mL), and 12 M HCl (5 mL) was heated and digested at 100 °C for 1 h under constant stirring. After cooling, the solution was trimmed up to 250 mL and then filtered (Whatman No.4 filter paper). The pH of sample portions (125 mL) was increased to 4–4.5. with a concentrated NH_4OH solution and then heated at 90 °C, cooled down, and filtered to remove the precipitate containing ferrous ion. The filtrate was heated again at 90 °C and 10 mL of 5% $CaCl_2$ solution was added while stirring. Samples were kept overnight at 4 °C and then centrifuges for 6 min at 3000 *g*. The precipitate was dissolved with 10 mL water/H_2SO_4 (80/20). The solution was kept at 80–90 °C during its titration with 0.05 M standardized $KMnO_4$. The oxalate content was quantified considering that 1 mL of 0.05 M $KMnO_4$ solution = 0.00225 g oxalate. The sample was analyzed in duplicate and data expressed as a percentage of oxalate.

2.3. Particle size distribution and hydration properties

The particle size distribution of the flours was assessed with a Malvern Mastersizer equipment (Model 2000; Malvern Instruments Limited, Worcestershire, U.K.). The refractive and absorption indexes were 1.36. Particle size distribution parameters included volume-weighted mean particle diameter (D [4,3]) and d (0.9), d (0.5) and d (0.1), which represent 90%, 50%, and 10% of sample volume with particle size below the size indicated, respectively. The polydispersity index (PDI) was also calculated as:

$$PDI = (d(0.9) - d(0.1))/d(0.5) \qquad (1)$$

The measurement was carried out in three replicates. Water binding capacity (WBC) and water holding capacity (WHC) were analyzed according to the method described by Calle *et al.* (2019). Results were expressed as grams of water retained per gram of solid.

2.4. Differential scanning calorimetry (DSC)

The thermal properties of *Xanthosoma* spp. and *Colocasia* spp. flours were examined by differential scanning calorimetry using a DSC 7 (Perkin–Elmer Instruments, Norwalk, CT, USA) instrument. Flours were accurately weighed (10 mg) in triplicate into stainless steel pans. Starch gelatinization was studied at 1:3 (w/w) (flour d.m.: water) ratio. Hermetically sealed pans were equilibrated at room temperature before heating from 30 to 120 °C at 10 °C min^{-1} under the nitrogen atmosphere. An empty capsule was used as a reference. Thermal transition temperatures and enthalpy were determined.

2.5. Viscosity force of the flours

The viscosity of the gels was measured using the Amylab FN device (Villeneuve-la-Garenne, France). Amylab was used in its testogram mode to record the apparent viscosity of flours (Garzon & Rosell, 2020). Cocoyam flour (7.0 g ± 0.1 g, corrected according to the specific moisture content) and distilled water (25 mL) were agitated for 90 s while heating up to 100 °C. The force required for a stirrer to pass through the gel was recorded, following the 90 s Testogram protocol and the parameters evaluated were: Onset_{90} (time at which the force begins to increase, s) and A1_{90} (peak force, g).

2.6. Paste production and characterization

Preliminary tests were carried out to define the best flour suspension to resemble the common consumption texture of the paste food. The paste was prepared with 87.7% water and 12.3% flour. Formulas were prepared by heating the suspension for 15 min at 100 °C. The resulting pastes were placed in a glass petri plate then cooled at room temperature before analysis. Three replicates were performed for each sample. Paste color was measured with a Minolta colorimeter (Chromameter CR-400/410 Konica Minolta. Japan) using a CIE-*L** *a** *b** scale, after standardization with a white calibration plate (*L**= 96.9, *a**= - 0.04, *b**= 1.84). Parameters indicated: *L** lightness, *a** hue on a green (-) to red (+) axis, and *b** hue on a blue (-) to yellow (+) axis. AACC methods 02–31.01 and 02–52.01 were used to analyze the pH and total titratable acidity (TTA) of the gels, respectively.

The viscosity profile was analyzed in duplicate with a Rapid Visco Analyzer (RVA) 4-SA (Newport Scientific, Warriewood, Australia). To this end, flour (3.5 g ± 0.1 g, corrected according to the specific moisture content) and distilled water (25 mL) suspensions were equilibrated at 50 °C for 1 min under continuous stirring (160 min^{-1}) and then heated to 95 °C. After an isothermal step at 95 °C for 10 min, samples were cooled to 50 °C and held at this temperature for 2 min. Parameters identified from the plots included: peak viscosity (maximum viscosity during heating), final viscosity (after cooling), breakdown viscosity (the difference between peak viscosity and minimum viscosity of hot paste), setback (the difference between cold and minimum hot paste viscosities).

Syneresis of pastes was recorded during 9 days of storage at 4 °C following the method described by Ribotta *et al.* (2007), with minor modifications. Briefly, pastes (prepared as described previously) (~1.0 g) were placed into Eppendorf tubes while they were hot and stored. Samples were tempered at 25 °C for 2 h, and centrifuge at 3000 *g* for 10 min at 25 °C. The free water was separated, weighed, and expressed as percentage of the total water present in the gel. Measurements were the mean of four repetitions for each duplicated gel prepared in different days.

2.7. Scanning electron microscopy (SEM)

Morphology of the flours and freeze-dried pastes were observed using a SEM (S-4800, Hitachi, Ibaraki, Japan). Samples were mounted on specimen holders followed by coating with gold in a vacuum evaporator (JEE 400, JEOL, Tokyo, Japan). All micrographs were recorded at an accelerating voltage of 10 kV. The image analysis to assess the granule size and the microstructure analysis of the pastes was carried out using the methodologies described by Benavent-Gil and Rosell (2017a) and Benavent-Gil *et al.* (2019), respectively.

2.8. *In vitro* starch digestibility and estimated glycemic index

Digestibility of pastes was evaluated following the method described by Benavent-Gil and Rosell (2017b). Briefly, 100 mg of sample was suspended in 4 mL of 0.1 M sodium maleate buffer (pH 6.9) containing porcine pancreatic α-amylase (0.2 U/mL) (Type VI-B, ≥10 units·mg^{-1} solid, Sigma Chemical, St. Louis, USA). Incubation was performed in a shaking water bath at 37 °C for three hours. Aliquots of 200 µL were taken and 200 µL ethanol (96%) were added to stop the enzymatic hydrolysis. Then, the sample was centrifuged for 5 min at 10 000 *g* and 4 °C. The pellet was washed with 50% ethanol (200 µL) and supernatants were pooled together and kept at 4 °C for further glucose determination. The results were expressed in the amount of glucose released (mg·100 mg^{-1}). Glucose was quantified in samples using a glucose oxidase–peroxidase kit (GOPOD, Megazyme, Dublin, Ireland). The absorbance was measured using an Epoch microplate reader (Biotek Instruments, Winooski, USA) at 510 nm. Starch was calculated as glucose (mg) × 0.9. Experimental data were fitted to the equation reported by Goñi *et al.* (1997) equation:

$$C = C_{\infty} (1 - e^{-kt}) \tag{2}$$

where C represents the concentration at t time, C_{∞} the equilibrium concentration or maximum hydrolysis extent, k the kinetic constant, and t

the time chosen. The *e*GI was calculated using the following equation (Goñi *et al.*, 1997):

$$eGI = 39.21 + 0.803HI90 \quad (3)$$

where HI90 was the percentage of starch hydrolyzed at 90 min.

2.9. *In vitro* protein digestibility (IVPD)

In vitro protein digestibility in pastes was determined according to the method described by Espinosa-Ramírez *et al.* (2018). The percentage of protein digestibility was quantified by using the equation:

$$IVPD\ (\%) = 210.464 - 18.1x \quad (4)$$

where × is the change in pH after 10 min (Hsu *et al.*, 1977).

2.10. Statistical analysis

All experiments were performed at least in triplicate and values were expressed as a mean ± standard deviation. All statistical analyses were conducted using an analysis of variance to separate the responses of different flours. Fisher's test was used for the assessment of significant differences among experimental mean values with 95% confidence. Data were computed with Statgraphics Centurion XV software (2020 Statgraphics Technologies, Inc., The Plains, Virginia, US).

3. Results and discussion

3.1. Chemical composition of cocoyam flours

Flours from *Xanthosoma* spp. and *Colocasia* spp. cormels were characterized regarding the chemical composition and functional properties. Moisture content of the flours was 6.78% and 6.56% for *Xanthosoma* spp. and *Colocasia* spp., respectively. There were significant differences in the proximate composition of both flours, specifically *Colocasia* spp. flour had a higher content of proteins and ash (Table 1). This was contrary to the findings of Ndabikunze *et al.* (2011), but in line with observations made by Falade and Okafor (2015).

Table 1. Proximate composition (g 100 g^{-1} dry matter bases) and functional properties of *Xanthosoma* spp. and *Colocasia* spp. flours

Flour properties	***Xanthosoma* spp.**	***Colocasia* spp.**	***P*-value**
Chemical composition			
Starch (%)	51.31 ± 1.56	53.07 ± 2.41	0.5000
Protein (%)	9.65 ± 0.12 b	10.32 ± 0.06 a	0.0194
Ash (%)	5.05 ± 0.07 b	5.65 ± 0.13 a	0.0092
Fat (%)	0.88 ± 0.06	1.03 ± 0.03	0.0815
Crude fiber (%)	3.29 ± 0.01b	4.38 ± 0.23a	0.0004
Oxalate (%)	0.22 ± 0.00 b	0.32 ± 0.03 a	0.0298
Particle size distribution* (μm*)			
d (0.1)	4.91 ± 0.03	4.86 ± 0.50	0.8711
d (0.5)	30.53 ± 1.41b	117.24 ± 8.62a	0.0001
d (0.9)	439.52 ± 30.53a	359.47 ± 30.69b	0.0328
D [4,3]	147.16 ± 22.90	191.03 ± 33.22	0.1328
PDI	14.23 ± 0.34a	2.90 ± 0.21b	0.0000
Hydration properties			
WBC (g·g^{-1})	1.04 ± 0.05b	1.75 ± 0.15a	0.0001
WHC (g·g^{-1})	2.16 ± 0.03b	3.43 ± 0.09a	0.0000
Amylab parameters			
Onset$_{90}$ (s)	46 ± 1 b	56 ± 0 a	0.0099
A1$_{90}$ (g)	1040 ± 14 a	773 ± 11 b	0.0022
Thermal properties (DSC)			
T$_o$ (ºC)	77.46 ± 0.21 b	80.93 ± 0.04 a	0.0019
T$_p$ (ºC)	84.78 ± 0.12	85.53 ± 0.24	0.5610
T$_c$ (ºC)	93.99 ± 0.30 a	91.02 ± 0.68 b	0.0293
Enthalpy (J·g^{-1})	16.54 ± 0.68	16.54 ± 1.01	0.9959

Means in the same raw with different letters are significantly different ($P < 0.05$).

Fiber content varied from 3.29 to 4.38%, being higher in *Colocasia* spp. flour. Fiber values were higher than those reported by Markusse *et al.* (2018). Divergences in composition results might be attributed to variety, growing conditions, maturity at harvest, post-harvest management, and storage (Temesgen & Retta, 2015).

As it was expected for a root crop, carbohydrates were the main constituent (Simsek & El, 2015; Temesgen & Retta, 2015). Both flours contained oxalates, with greater content in *Colocasia* spp. flour. This content is of great relevance since its high intake induces adverse health effects (Temesgen & Retta, 2015), and consequently has been considered a limiting factor to use cocoyam flours. However, oxalate is only harmful when raw or unprocessed foods are consumed (Iwuoha & Kalu, 1995).

3.2. Particle size distribution and morphology

The particle size distribution of the cocoyam flours revealed three main peaks corresponding to particles smaller than 70 µm, between 70 and 630 µm, and higher than 630 µm. The mean particle diameter (D [4,3]) of *Colocasia* spp. flour was larger than that of *Xanthosoma* spp., although no significant differences were detected. However, *Colocasia* spp. flour showed a higher volume of smaller particles (d (0.9)). Furthermore, the polydispersity index (PDI), indicative of the particle size dispersion, was significantly lower for *Colocasia* spp. flour, describing a more homogeneous flour. Low PDI is recommended for bulk flowing limiting the surface contact and cohesion between flour particles (Bian *et al*, 2015). Markusse *et al.* (2018) described a bimodal granulometric distribution of flours from cooked cocoyam tubers used to prepared paste foods. The authors reported peak sizes between 150 and 250 µm and 450–550 µm, showing *Xanthosoma* spp. larger particle sizes than *Colocasia* spp., which agrees with the polydispersity found in the present study. The most suitable particle size for traditional paste foods made from reconstituted flours has been reported with a median between 122 and 143 µm (Njintang *et al.*, 2006). Cocoyam flours in the present study were larger than that value, but considering that *Colocasia* spp., flour has more uniform particle size distribution and lower d (0.9), it might be expected better pasting performance.

Representative SEM micrographs of *Xanthosoma* spp. and *Colocasia* spp. flours are shown in Fig. 1A and B, respectively. Both flours exhibited a very fragmented structure, where starch granules were covered or embedded in a protein-fiber matrix, although *Xanthosoma* spp. flours showed more loose starch granules, likely indicating their fragile attachment to the protein-fiber fragments. For *Xanthosoma* spp. cormels, as it has been reported, two different starch granule po-pulations were observed (Calle *et al.*, 2019). The large granules tend to have truncated shapes and several grooves on the surface, whereas the small granules adopted polygonal shapes (Fig. 1C, E). The average size calculated was 19.5 µm, which agrees with the 20.7 µm reported by Srichuwong *et al.* (2005). The starch granules in *Colocasia* spp. cormels had polygonal shapes and small size (average size 2.7 µm) (Fig. 1D, F), which was lower than the 5.3 µm reported by Srichuwong *et al.* (2005), but within the range of reviewed *Colocasia* spp. starches (0.3–10.0 µm) (Moorthy, 2002).

3.3. Hydration properties of cocoyam flours

Hydration properties, including water binding capacity and water holding capacity, were determined for *Xanthosoma* spp. and *Colocasia* spp. flours, to assess the water strongly retained into the flour and water molecules more loosely absorbed by the flour constituents, respectively. The WBC of flours ranged from 1.04 ± 0.05 g $H_2O\cdot g^{-1}$ (*Xanthosoma* spp. flour) to 1.75 ± 0.15 g $H_2O\cdot g^{-1}$ (*Colocasia* spp. flour), suggesting that better retention of the water could be obtained with *Colocasia* gels. The WHC of flours revealed a similar trend to their corresponding WBC. *Colocasia* spp. flour had a significantly higher WHC, which might be related to the smaller starch granules and in consequence to its larger surface area. In fact, according to de la Hera *et al.* (2013), as particle size becomes smaller, the surface area in contact with water molecules increases, which in turn, increases water intake. Similarly, Markusse *et al.* (2018) reported higher water absorption capacity for *Colocasia* spp. flour than that for *Xanthosoma* spp*.*, and Perez *et al.* (2007) reported also a higher water absorption index for *Colocasia* spp. flour than for *Xanthosoma* spp.

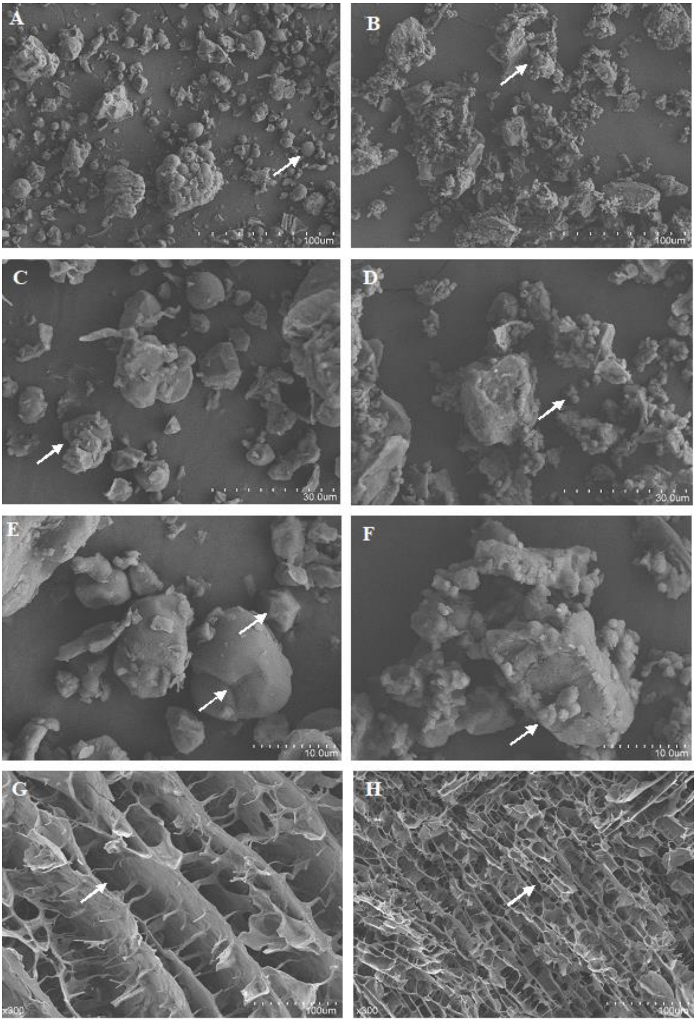

Fig. 1. Scanning electron micrographs of *Xanthosoma* spp. (A, C and E) and *Colocasia* spp. (B, D and F) flours at magnification of x500 (A, B), x1500 (C, D), x3000 (E, F), respectively and gels at magnification of x300 (G and H). Arrows indicated starch granules (A, B, C, D, E, F), weak needle-like walls (G) and dense walls (H).

Therefore, different water hydration properties of both cormels' flours could be directly associated with their dissimilar starch granules size.

3.4. Viscosity force of the cocoyam flours

The Amylab in their testogram mode was applied to both flours to assess the apparent viscosity (Fig. 2). No change was noticeable in the initial part (first 45 s), because starch swelling during gelatinization was not enough to affect the gel strength. *Xanthosoma* spp. flour showed an early increase in the gel strength and reached a higher gel force compared to *Colocasia* spp. flour. Indeed, parameters recorded from the plots (Table 1), indicated significant differences in the force onset (Onset_{90}) and maximum force (A1_{90}). Therefore, this device allowed discriminating cocoyam flours in a very rapid test. The gel performance of both flours might be related to their composition, since positive correlations were observed among Onset_{90} and protein ($r = 0.99$, $P < 0.01$), ash ($r = 0.96$, $P < 0.05$) and oxalate ($r = 0.96$, $P < 0.05$) contents, and negative correlations between A1_{90} with protein ($r = -0.99$, $P < 0.01$), ash ($r = -0.97$, $P < 0.05$) and oxalate ($r = -0.97$, $P < 0.05$) contents.

Presumably, the content of protein, minerals, and oxalate delayed the starch gelatinization, likely they could shield the starch granules impeding its swelling and limiting the maximum gel force (A1_{90}).

3.5. Thermal properties

Differential scanning calorimetry was conducted to assess the thermal parameters of the flours (Table 1). Flours exhibited similar melting enthalpy (ΔH) (~16.5 $J \cdot g^{-1}$), which agrees with previous reports (Mweta *et al.*, 2010). There was no significant difference in the gelatinization peak temperature (Tp) between both flours, and values were within the range of boiling point previously described for different cocoyam starches by Falade and Okafor (2013). Those high gela-tinization temperatures have been related to the resistance of cocoyam starches to swell (Mepba *et al.*, 2009).

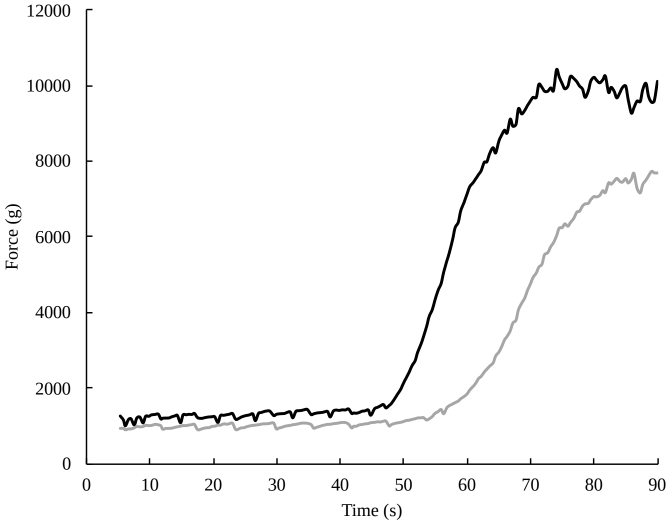

Fig. 2. Rapid heating-stirring curves of *Xanthosoma* spp. (black solid line) and *Colocasia* spp. (grey solid line) flours using Chopin Amylab.

Flour from *Xanthosoma* spp. cormels had significantly lower transition temperature (To) than that from *Colocasia* spp. cormels, and the contrary was observed for the conclusion temperature (Tc). The opposite trend was reported by Perez *et al.*, (2007) when evaluating *Xanthosoma* spp. and *Colocasia* spp. flours. Discrepancies could be ascribed to the use of different tuber part, since authors did not describe if flours were obtained from corms or cormels. Falade and Okafor (2013) described a lower gelling point for *Xanthosoma* spp. starches than that for *Colocasia* spp. starches, which agrees with present DSC results. Likewise, a correlation was found between To and WBC ($r = 0.98$, $P < 0.05$), WHC ($r = 0.99$, $P < 0.01$), protein ($r = 0.99$, $P < 0.05$ and ash content ($r = 0.98$, $P < 0.05$). Again, correlations between chemical composition and onset temperature of gelatinization agree with the previously mentioned role of protein and minerals shielding the starch granules surface, and impeding water absorption and swelling, which resulted in delayed gelatinization. Meanwhile, a strong negative corre-lation was found between Tc and WBC ($r = -0.99$, $P < 0.05$), WHC ($r = -0.99$, $P < 0.05$), and protein (*r* = -0.99, *P* < 0.05). Therefore, non-starch constituents of the flour played a marked role in the starch gelatinization, where apart from the protecting effect on the surface of the granules, some water competition could also contribute to retard starch gelatinization.

3.6. Pasting behavior of cocoyam pastes

Pastes were prepared with *Xanthosoma* spp. and *Colocasia* spp. flours using the RVA for recording their apparent viscosity (Table 2), and also some characteristics of the pastes were determined. During heating and cooling, it was readily evident the higher viscosity obtained with *Xanthosoma* spp. *vs.* *Colocasia* spp. Contrary findings were reported by Perez *et al.* (2007) for pastes made from *Colocasia* spp. and *Xanthosoma* spp. flours. Possibly differences with the present study could be related to the part of the tuber used for preparing those flours because authors did not give details about the use of corms or cormels. In line with the present results, Mepba *et al.*, (2009) reported that the same pattern was observed for cocoyam starches isolated from cormels of *Xanthosoma* spp. and *Colocasia* spp.

The onset temperature indicated an earlier pasting formation in the case of *Xanthosoma* spp. compared with *Colocasia* spp., which agrees with Amylab and DSC parameters. The onset values obtained were lower than the ones reported for starches (Falade & Okafor, 2013) or flours (Falade & Okafor, 2015) from cocoyam corms, which might be attributed to either the influence of the rest of the constituents in the flour or the intrinsic differences between corms and cormels (Calle *et al.*, 2019). Although previous studies have used the blue index value to assess starch gelatinization (Aboubakar *et al.*, 2009; Amon *et al.*, 2014), in the present research RVA was employed and gelatinization of the starch was completed within the assay time. The different pasting behavior observed between tested flours can be associated with diverse starch gelatinization of *Xanthosoma* spp. and *Colocasia* spp., since their corresponding starches had exhibited similar divergences (Falade & Okafor, 2013).

Table 2. Physical, pasting and nutritional characteristics of pastes obtained from flours of *Xanthosoma* spp. or *Colocasia* spp. cormels

Paste properties	***Xanthosoma* spp.**	***Colocasia* spp.**	***P*-value**
pH	6.29 ± 0.02	6.31 ± 0.01	0.3333
TTA (ml NaOH/ 10 g gel)	2.00 ± 0.00a	1.51 ± 0.01b	0.0001
Color			
*L**	49.05 ± 0.28a	52.30 ± 0.09b	0.0000
*a**	1.87 ± 0.03a	1.98 ± 0.03b	0.0005
*b**	7.91 ± 0.14a	11.16 ± 0.07b	0.0000
Pasting properties (RVA)			
Onset temperature (ºC)	79.85 ± 0.00a	82.35 ± 0.00b	0.0000
Peak viscosity (cP)	1763 ± 10b	1161 ± 12a	0.0003
Trough (cP)	1691 ± 13b	1084 ± 11a	0.0004
Breakdown (cP)	73 ± 4	93 ± 12	0.1526
Final viscosity (cP)	2701 ± 19b	1628 ± 1a	0.0002
Setback (cP)	1010 ± 6b	560 ± 1a	0.0001
Protein and starch digestibility			
IVPD (%)	70.91 ± 0.49b	67.56 ± 1.17a	0.0102
k	0.0050 ± 0.0003a	0.0140 ± 0.0006b	0.0024
C_∞	91.89 ± 4.99a	38.42 ± 0.65b	0.0033
*e*GI	65.84 ± 0.30b	61.29 ± 0.07a	0.0000

Each row represents the analyzed parameters and the column represents the samples. Different letters within the same row indicate significant differences ($P < 0.05$).

Nevertheless, the rest of the constituents might also affect the pasting performance because, protein content was negatively correlated with peak and final viscosity ($r = -0.98$, $P < 0.05$ and $r = -0.98$, $P < 0.05$, respectively), in agreement with results obtained in the Amylab. Similar correlations were found with ash and oxalate content. Interestingly, both samples showed similar breakdown values, but *Colocasia* spp. exhibited significantly lower setback, suggesting its lower tendency to retrograde.

3.7. Physical properties of cocoyam pastes

SEM images, indeed, showed differences between paste structures (Fig. 1G and H). Both gels micrographs showed an aligned structure that could be induced by the mucilage, since hydrocolloids tend to lead that ordered structure (data often observed by authors). The structure of pastes containing *Xanthosoma* spp. flour consisted of big holes with homogeneous distribution and with weak needle-like walls. Conversely, a more compact structure with smaller cavities and dense walls was noticed for pastes containing *Colocasia* spp. flour.

The pH of the resulting pastes did not show significant differences between samples. It was lower than the pH reported for corms flours (Falade & Okafor, 2015), but similar to that reported by Perez *et al.* (2007). In contrast, the total titratable acidity (TTA) values were lower for pastes containing *Xanthosoma* spp. flour than that found for pastes containing *Colocasia* spp. flour. Furthermore, significant differences were observed on the pastes color (Table 2).

Pastes containing *Colocasia* spp. flour showed significantly higher L^*, a^* and b^* parameters, which might result from its colored pigments that vary within cultivars, affecting also the chemical composition (Aboubakar *et al.*, 2008). In fact, in the current study, correlations between L^* values and protein ($r = 0.99$, $P < 0.05$), ash ($r = 0.98$, $P < 0.05$) and oxalate ($r = 0.96$, $P < 0.05$) contents were identified. On the other hand, a^* values were positively correlated with ash ($r = 0.99$, $P < 0.01$) and fat ($r = 0.98$, $P < 0.05$) contents. Correlations that confirmed the impact of the chemical composition on the paste color parameters.

When syneresis of the pastes was evaluated during storage (Fig. 3), no changes were observed in *Colocasia* spp. but a progressive increase in the syneresis was observed in *Xanthosoma* spp. after 48 h storage. Therefore, the lower viscosity of the paste related to the greater protein content led to more compact gels with lower retrogradation and better ability to retain water within its structure. In addition, the very tight microstructure of the *Colocasia* spp. paste might have a significant contribution in retaining the water molecules during the storage.

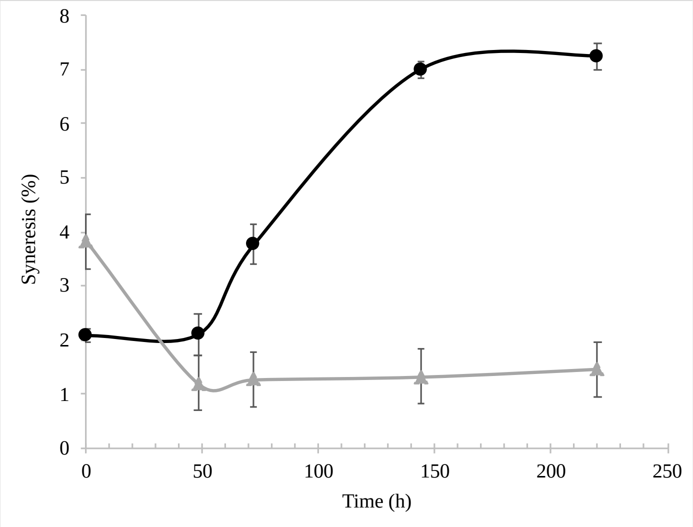

Fig. 3. Syneresis (%) of the starch gels obtained from *Xanthosoma* spp. (black solid line) and *Colocasia* spp. (grey solid line) flours during 90 h storage at 4 °C.

3.8. *In vitro* digestion of pastes containing cocoyam flours

In vitro protein (Fig. 4A) and starch digestions (Fig. 4B) of formulas containing flours from *Xanthosoma* spp. and *Colocasia* spp. cormels were evaluated. Despite the relatively low protein content of these flours, in vitro protein digestibility was determined, since the above results revealed its important role in the techno-functional properties of the pastes. Protein digestibility test showed a faster pH drop in *Xanthosoma* spp. gels leading to higher IVPD (70.91% ± 0.49) than that obtained for *Colocasia* spp. gels (67.56% ± 1.17). Considering the pastes microstructure (Fig. 1G), the higher IVPD of *Xanthosoma* spp. could be associated with the more open gel microstructure that could favor the accessibility of proteases to the protein hydrolysis.

To further investigate the starch enzymatic susceptibility, pastes were subjected to *in vitro* digestion and the glycemic index estimated (Fig. 4B).

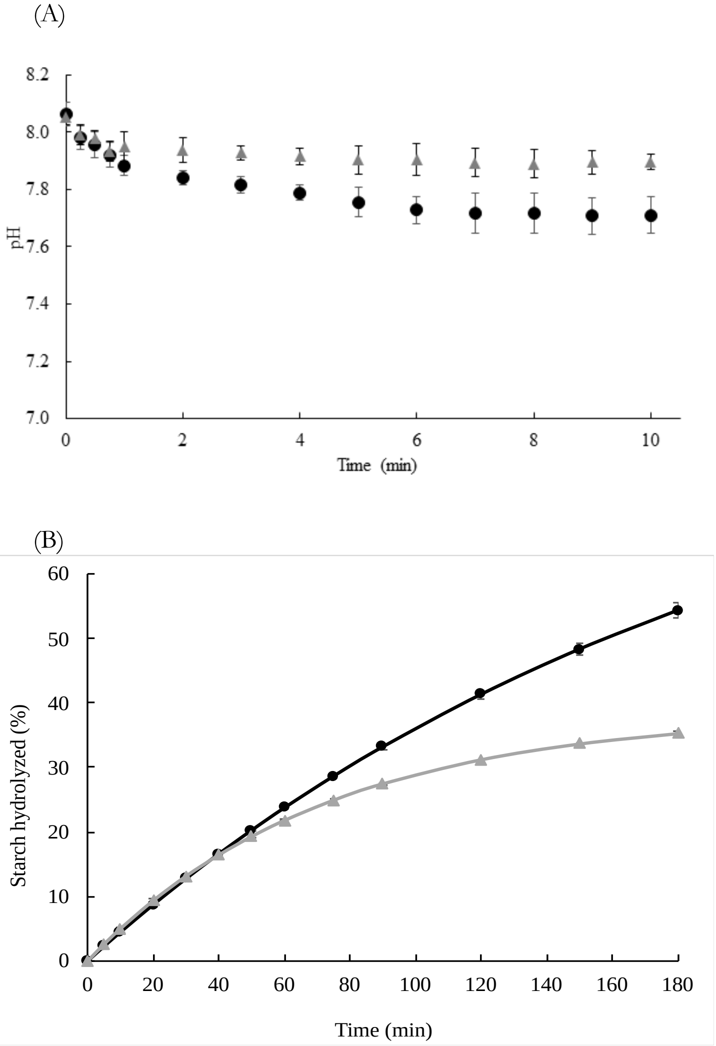

Fig. 4. *In vitro* protein (A) and starch (B) digestibility of the *Xanthosoma* spp. (black symbols or line) and *Colocasia* spp. (grey symbols or line) gels.

The extent of starch digestion ($C\propto$) was significantly ($P < 0.05$) higher for pastes containing *Xanthosoma* spp. flour (91.89% ± 4.99) than that found for pastes containing *Colocasia* spp. flour (38.42% ± 0.65). In contrast to this, the fitting of hydrolysis kinetics showed that the starch digestion rate (k) of *Xanthosoma* spp. pastes was significantly ($P < 0.05$) lower than that for *Colocasia* spp. pastes. Finally, *Xanthosoma* spp. pastes led to the highest *e*GI that went from 65.84 ± 0.30 in pastes containing *Xanthosoma* spp. flour down to 61.29 ± 0.07 in the pastes containing *Colocasia* spp. flour. Simsek and El (2015) reported an *e*GI for boiled *Colocasia* spp. corm, by *in vitro* method, of 90.2 ± 3.6 and 63.1 ± 2.5 using white bread and glucose as references, respectively. Likewise, despite differences in the experimental procedure, Perez *et al.* (2007) also reported a lower hydrolysis index for *Colocasia* spp. (37.34%) than for *Xanthosoma* spp. (52.99%) after 60 min of *in vitro* amylolysis of the boiled flours, relating the different starch digestibility to their structural characteristics besides possible interactions with other components of the flours. Therefore, regardless of the significant differences found between *Xanthosoma* spp. and *Colocasia* spp. hydrolysis patterns, *e*GI suggested that both pastes would be classified as medium glycemic index (56 < *e*GI < 69), foods (Foster-Powell, 2002).

4. Conclusions

Despite the significant differences in the physico-chemical properties of cocoyam flours from cormels of *Xanthosoma* spp. and *Colocasia* spp., both of them could be used to make paste foods. Particularly, *Xanthosoma* spp. flour had lower protein, ash, and oxalate content. Paste formation from *Xanthosoma* spp. flours occurred at lower temperatures and showed higher viscosity during heating and cooling than pastes from *Colocasia* spp. which was related to the starch granules sizes. Nevertheless, pastes from *Colocasia* spp. showed better stability, as indicated by the lower syneresis during storage, which was associated with its very tight and closed microstructure. Protein and starch digestibility of the pastes confirmed the suitability of both cormel's flours to produce paste foods with a medium glycemic index. In this sense, the extent of protein and starch digestions ($C\propto$) was significantly higher in pastes containing *Xanthosoma* spp. flour.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foodchem.2020.128666.

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IV. General discussion

Malanga represents a healthy alternative rhizome to turn into starch or flour. There are some methods to obtain both raw materials for being included in food applications, but the scientific community precise more research to really explore this commodity. The interest in this topic becomes evident with the 1946 results obtained from the citation report covering the period 1900 and 2021. Searched terms in different databases included *Colocasia* spp and *Xanthosoma* spp. A few studies were carried out from 1940, but it was not until 1980 when a significant increase in the number of researches was registered. Since 2000, the increase in these crops became more significant and in 2020 was recorded the highest number of published articles. Plant sciences and agriculture research areas represented around 64.29% and 63.21%, respectively, of the total records studied, while food science technology and nutrition field represents 30.63% and 22.61%, respectively, being EE. UU (17.5%) and India (15.8%) leaders in that research and number of publications.

Current researches are mainly focused on healthy properties, functional, technological and characterization of both raw materials. Specifically, these studies have been carried out to provide useful information for the food industry in order to consider *Colocasia* spp. and *Xanthosoma* spp. for its technological quality, functional and healthy ingredients.

An updated review of the current knowledge regarding their technological properties and healthy effect of *Xanthosoma* spp. and *Colocasia* spp. was initially carried out (Chapter I). From that revision it was identified the existing misunderstanding around the nomenclature assigned to these tubers and also the confusion regarding the physiological part of the rhizome used for technological applications. Following, the revision describes the extended healthy properties of these tubers, including antihyperglycaemic, antihepatotoxic, hypogly-cemic, anticancer activity, anthelmintic and hypolipidemic properties, among others, of the plant leaves, as well as the extracts and flours from their rhizomes (Kubde *et al.*, 2010; Patil & Ageely, 2011). Furthermore, it was identified the bioactive compounds present in the flours with healthy benefits and their mechanism of action in the organism, tested by clinical assays. Thus, the research presented in the previous chapters shows the scientific and technological strategies applied to understand the functional and structural properties of rhizome flour and starch from both species. Those studies extend the knowledge about their properties and the way of flour incorporation into cereal-based and pastes products contributing to healthier and improved foods.

Scientific literature carried out with malanga flour and/or starch is not clear about the physiological part of the rhizome used in the studies. For that reason, the second chapter of this thesis describes the functional, technological and morphological structure of corms and cormels starch isolated from *Xanthosoma* spp. In order to differentiate both parts and to characterize them, their hydration properties and behaviour during heating was studied. Granular morphology of *Xanthosoma* spp. corms starches showed significantly two different populations of granules. The specific morphology and characteristics for each population of granules were: large A-type granules with truncated shapes and several grooves on the surface having the ability to form aggregates possibly due to some remnant protein (1.10%) and small B-type granules with polygonal shape. Starch from cormels presented similar shape to the corms A-type with larger size and many truncated granules. Amylose starch content of *Xanthosoma* spp. cormels was higher than *Xanthosoma* spp. corms. These results showed that amylose content depended on the part of the plant from which the starch was isolated. Hydration properties of both starches revealed similar trend, with exception of solubility index, being unexpectedly higher for *Xanthosoma* spp. cormels starch, despite the smaller size of corms starches. Gani *et al.* (2014) attributed this effect to the formation of aggregates, that could affect the solubility. Therefore, amylose content, besides the formation of aggregates in corms starch seems to play a crucial role on the functional properties of starches. In consequence, starch from corms had lower capacity to absorb water, and higher transition and conclusion temperature during gelatinization than starch from cormels. That performance during gelatinization led to different behaviour during the heating and cooling of starch: water blends. Specifically, corms showed lower apparent viscosity during heating and cooling. In general, correlation analysis confirmed that granule size and amylose content played a determinant role in the functional behaviour of starch granules.

Having in mind the importance of the technological exploitation of malanga and the economical constrains that the production of gluten-free foods produce in Cuba, the further objective was to design gluten-free breads using malanga flour. Therefore, flour from *Colocasia* spp. cormels were used to develop gluten-free breads applying a range of strategies (Chapter 3). The unique information about the technological potential of malanga in gluten-free bakery was ascribed to its inclusion in a formula blended with rice, sorghum and cassava flour to make gluten-free cookies (Giri & Sajeev, 2020). Considering that gluten-freebreads are fermented and baked foods that need to overcome mechanical and thermal constraints, the challenge was to make gluten-free breads completely based on malanga flour. Thus, several strategies have been employed, like the use of pre-gelatinized *Colocasia* spp. flour, addition of hydrocolloids, enzymes and potato starch at different concentrations, in order to obtain a product with good technological and digestibility properties. In this sense, the bread obtained had similar nutritional value to other types of bread made with rice and maize (Hager & Arendt, 2013). According to the different strategies studied, it was evident that the effect of protease on the technological properties depended on the type of protease utilized. In general, all breads presented lower crumb hardness than that reported for commercial gluten-free breads (Matos & Rosell, 2012) and estimated glycemic index similar to reported values (de la Hera *et al.*, 2014; Liu *et al.*, 2018). These results could be of great applicability in Cuba and other countries producers of these crops. Thus, malanga flour could be used to produce gluten-free bread, making possible the reduction of imported mixes.

The most consumed malanga based meal in Cuba is as mashed cooked malanga giving like a puree. Considering that in Cuba only corms from *Colocasi*a spp. are used for human consumption and cormels are used for sowing (Figueroa-Aguila *et al.*, 2019), the study of cormels for making that type of food could extend the utilization of all parts of malanga as human food. With that aim, *Xanthosoma* spp. and *Colocasia* spp. cormels flours were characterized regarding their functional and morphological structure. Besides to that their use to make a paste food was evaluated assessing the *in vitro* starch and protein digestibility (Chapter 4). Analysis of proximal composition of *Colocasia* spp. and *Xanthosoma* spp. flours confirmed that these rhizomes had similar composition to other crops like potato (Lewu *et al.*, 2010) but they were higher in protein content than yam, cassava or sweet potato (Temesgen & Retta, 2015).

In general, *Colocasia* spp. cormels flour had higher protein and fiber content than *Xanthosoma* spp. cormels flour. Nevertheless, the evaluation of several crops and varieties would be needed to confirm those differences, since composition could vary with variety, growing conditions, maturity at harvest, post-harvest ma-nagement and storage conditions (Temesgen & Retta, 2015). Furthemore *Colocasia* spp. flour showed better pasting performance and higher water absorption capacity than *Xanthosoma* spp flour. Gelatinization enthalpy were similar among them, although transition temperatures during gelatinization were significantly different, which has been attributed to differences in granular structure (Truong & Avula, 2010). *Xanthosoma* spp. flour showed earlier pasting formation and exhibited higher setback, suggesting higher retrogadation during storage, which was also confirmed by the higher syneresis of the pastes obtained from *Xanthosoma* spp. Finally, protein and starch digestibility of *Xanthosoma* spp. paste was higher than that observed for *Colocasia* spp. paste, likely due to its more open structure observed by SEM. In general, research results demonstrated that *Colocasia* spp. and *Xanthosma* spp. flours can be used to make semi-solid food products. These results open up a new market opportunity for the malanga industry, increasing the utilization of cormels from malanga as food functional ingredient to development products like pastes. Considering previous results, *Colocasia* spp. flour would be more advisable than *Xanthosoma* spp. flour, from the technological and nutritional point of view.

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V. Conclusions

The conclusions of the present thesis are summarized as follows:

1. *Colocasia esculenta* (L.) Schott and *Xanthosoma sagittifolium* (L.) Schott are related with certain antihyperglycemic, antihypertensive, hypoglycemic and prebiotic effects. Owing to their functional properties, different component from these rhizomes, specially starch, mucilage and powders are being used by the food industry. Their ability to behave as thickener and gelling agent has allowed their incorporation in baked food, food paste and beverages.

2. Corms and cormels from *Xanthosoma* spp. contained morphologically different starch granules. Starch isolated from corms exhibited smaller granules with an aggregate disposition which, besides the lower amylose content, might be responsible of their hydration properties, lower apparent viscosity during heating and cooling, higher To and Tp, as well as lower gel syneresis after 7- days storage. In fact, correlation analysis confirmed that granule size and amylose content play a determinant role in the functional behaviour of starch granules. Differences noticed between starches isolated from corms and cormels of *Xanthosoma spp.* stressed the importance of identifying the starch source within the botanical parts of araceas to allow understanding and comparing research studies.

3. *Colocasia* spp. flour can be used as gluten-free commodity to make breads. For improving breadmaking performance of *Colocasia* spp. flour, proteases were used to increase the specific volume of breads, but that effect was dependent on the type of proteases. Other strategies like the use of hydrocolloids or pre-gelatinization of the flour could be used for making gluten-free breads with malanga flour. Breads obtained had high amount of soluble digestible starch and resistant starch than other reported gluten-free breads. Overall, *Colocasia* spp. flour can be used to produce gluten-free breads with similar technological quality parameters than those previously reported with common gluten-free flours, but with significantly better estimated glycemic index.

4. In spite of the significant differences in the physico-chemical properties of flours from cormels of *Xanthosoma* spp. and *Colocasia* spp., both could be used to make paste foods. Differences between those flours were observed in their paste formation behavior. *Xanthosoma* spp. flours led to pastes formed at lower temperatures and having higher apparent viscosity during heating and cooling than pastes from *Colocasia* spp., which might be related to their differences in the size of starch granules. However, pastes from *Colocasia* spp. flour had better stability during storage. Protein and starch digestibility of the pastes confirmed the suitability of both flours to produce paste foods with medium glycemic index.

5. In general, the results have shown that both crops are a good alternative to transform them into flour or starch to be used in different processed foods. Its technological, functional, and healthy properties are the main reasons to extend its application. In addition, this alternative guarantees the responsible and sustainable use of these rhizomes in order to reduce the ecological footprint, minimizing garbage or waste and the environmental impact. In addition, it contributes to a circular economy by transforming waste and turning it into new ingredients for use in new foods. This thesis provides the work methodology to reduce imports of gluten-free premixes in Cuba and lays the foundations for the transformation of other crops in Cuba and on an international scale to use them in new developments.

List of original publications

The present thesis is based on the following publications:

Book chapter:

1. Calle, J., Gasparre, N., Benavent-Gil Y., Rosell M. C (2021). Aroids as underexplored tubers with potential health benefits. Advances in Food and Nutrition Research 8 (97). https://doi. 10.1016/bs.afnr.2021.02.018

Journal article:

2. Calle, J., Benavent, G. Y., Garzón, R., & Rosell, C. M. (2019). Exploring the functionality of starches from corms and cormels of *Xanthosoma sagittifolium*. *International Journal of Food Science & Technology*. https://doi.org/10.1111/ijfs.14207

3. Calle, J., Benavent, G. Y., & Rosell, C. M. (2020). Development of gluten-free breads from Colocasia esculenta flour blended with hydrocolloids and enzymes. *Food Hydrocolloids, 98*, 105–243. https://doi.org/10.1016/j.foodhyd.2019.105243.

4. Calle, J., Benavent-Gil, Y., & Rosell, C. M. (2020). Use of flour from cormels of *Xanthosoma sagittifolium* (L.) Schott and *Colocasia esculenta* (L.) Schott to develop pastes foods: Physico-chemical, functional and nutritional characterization. Food Chemistry, 344, 28666. https://doi: 10.1016/*j*.foodchem.2020.128666.

List of abbreviations:

***Xanthosoma* spp.**	*Xanthosoma sagittifolium* (L.)
***Colocasia* spp.**	*Colocasia esculenta* (L.)
WAC	water absorption capacity
WBC	water binding capacity
SV	swelling volume
SI	solubility index
OAC	oil absorption capacity
FC	foaming capacity
FS	foam stability
OT	onset temperature
PV	apparent peak viscosity
TV	trough viscosity
BV	breakdown viscosity
SVy	setback viscosity
SARS-CoV	severe acute respiratory syndrome coronavirus
***e*GI**	estimated glycemic index
SDS	slowly digestible starch
RS	resistant starch
HI	hydrolysis index
SEM	scanning electron microscopy
INIVIT	National Institute of Tropical Food Research Farms
DSC	differential scanning calorimetry
To	transition temperature
Tp	peak temperature
RVA	rapid viscosity analyzer
TPA	texture profile analysis
GF	gluten free
HPMC	Hydroxypropylmethylcellulose
GOPOD	glucose oxidase–peroxidase
HI	hydrolysis index
ANOVA	analysis of variance
k	kinetic constant
AUC	area under the hydrolysis curve after 180 min
TTA	total titratable acidity
ΔH	melting enthalpy

IVPD	*in vitro* protein digestibility
PDI	polydispersity index
$C_{\propto}$	starch digestions