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Native and modified starches from underutilized seeds: Characteristics, functional properties and potential applications

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ABSTRACT

Seeds represent a potential source of starch, containing at least 60–70% of total starch, however many of them are treated as waste and are usually discarded. The review aim was to analyze the characteristics, functional properties, and potential applications of native and modified starches from underutilized seeds such as *Sorghum bicolor* L. Moench (WSS), *Chenopodium quinoa*, Wild. (QSS), *Mangifera indica* L. (MSS), *Persea americana* Mill. (ASS), *Pouteria campechiana* (Kunth) Baehni (PCSS), and *Brosimum alicastrum* Sw. (RSS). A systematic review of scientific literature was carried out from 2014 to date. Starch from seeds had yields above 30%. ASS had the higher amylose content and ASS and RSS showed the highest values in water absorption capacity and swelling power, contrary to MSS and PCSS while higher thermal resistance, paste stability, and a lower tendency to retrograde were observed in MSS and RSS. Functional properties such as water solubility, swelling power, thermal stability, low retrogradation tendency, and emulsion stability were increased in RSS, WSS, QSS, and MSS with chemical modifications (Oxidation, Oxidation-Crosslinking, OSA, DDSA, and NSA) and physical methods (HMT and dry-heat). Digestibility *in vitro* showed that WSS and QSS presented high SDS fraction, while ASS, MSS, PCSS, and HMT-QSS presented the highest RS content. Native or modified underutilized seed starches represent an alternative and sustainable source of non-conventional starch with potential applications in the food industry and for the development of healthy foods or for special nutritional requirements.

1. Introduction

Starch is an important biomolecule with wide applications in food and non-food industries. Starch is a biopolymer conformed by glucose units linked by α-glycosidic bonds. The shape and size of native starch granules vary according to their botanical source; size can range from 0.1 to 100 μm, and shapes vary from spheres, polygons, irregular tubules, and ellipsoids (Bertoft, 2017a;Vamadevan & Bertoft, 2015). Native starch is formed by amylose and amylopectin. Amylose is a mostly linear molecule with approximately 99% of α-(1,4) glycosidic bonds, and 1% α-(1,6) glycosidic bonds, whereas amylopectin is a highly branched macromolecule with approximately 95% of α-(1,4) glycosidic bonds, and ~5% of α-(1,6) glycosidic bonds (Bertoft, 2017a). Amylose/amylopectin ratio, content, size, and amylopectin arrangement within the granule vary depending on the starch source, and these factors are responsible for starch's semi-crystalline structure (Bertoft, 2017b). Branch points, and chain distribution of amylopectin, have an impact on the functional properties and digestibility rate (Li, 2022) Starch digestion is a multi-scale process, which means that starch is digested at different rates, which has been classified into three fractions: rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) (Bello-Pérez et al., 2020; Chi et al., 2021; Meraz et al., 2022; Vernon-Carter et al., 2022).

Starch is obtained mainly from conventional sources such as corn, rice, potato, and cassava, however, it can obtain from other non-conventional and underutilized sources of rhizomes, root tubers, fruit, bulb, roots, and seeds, among others (Fatokun, 2020) and they are considerably understudied compared to conventional starches. Currently, seeds from white *Sorghum bicolor* L. Moench, *Chenopodium quinoa,* Wild., *Mangifera indica* L., *Persea americana* Mill, *Pouteria*

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campechiana (Kunth) Baehni, and *Brosimum alicastrum* Sw. are underutilized or discarded as waste. In Mexico, these residues are part of the organic matter (46 %) of waste composition (Huisman et al., 2021) and they are considered residual biomass, which is defined as the renewable organic materials generated in different activities (urban, agricultural and agro-industrial). However, this biomass is attractive because its biomolecules such as protein, lipids, minerals, and carbohydrates can be recovered or transformed for multiple products (Gómez-Soto et al., 2019). White sorghum is one of the major cereal crops in the world with a production of 12,000 metric tons (FAOSTAT, 2022; USDA, 2020) and present agronomic advantages, like resistance to drought and high production yields (Taylor, 2019). Sorghum is used mostly as animal feed or for ethanol production. However, its use as a human food source is growing due to its gluten-free characteristic (Rumler et al., 2022). Sorghum like others cereals is rich in starch (60–80%) with wide potential for industrial applications (Ahmed et al., 2016). Quinoa from the Amaranthaceae family can survive in a variety of agronomic zones, and it is tolerant to frost, salinity, and drought (Bilalis et al., 2019). The high nutritional quality makes quinoa a potential strategic crop for food security and nutrition (Andreotti et al., 2022). Starch is the most abundant fraction in quinoa grain (52.2–69.2%) (Vargas-Zambrano et al., 2019) and quinoa flour had been used in the elaboration of bread (Wang, Lao, et al., 2021), instant noodles (Tiga et al., 2021), and as a binder in beef sausages (Tafadzwa et al., 2021) have been reported. Mango is a fruit of the Anacardiaceae family and is the most important food for the tropic population. In the world, more than 50 million tons of mango are produced per year. The edible portion of a mango represents only 30 to 80% of the fruit (FW), and the seed or kernel represents ~9 to 40%, which usually is discarded, causing an annual waste of ~123,000 metric tons globally (Bangar et al., 2021; Ferraz et al., 2019). Starch is the main component of the mango seed (58–80%) (Ferraz et al., 2019; Patiño-Rodríguez et al., 2020). On other hand, according to FAO data, the avocado will be the most commercialized tropical fruit in 2030 with 12 million tons (OECD/FAO, 2021). The avocado pulp is consumed fresh or used in foods such as ice cream, mayonnaise, and sauces, among others. The avocado seed represents about 20–25% of the fruit mass and it is rich in starch (64% dry weight basis) with interesting potential applications in the food, cosmetic, pharmaceutical, and textile industries, among others (Tesfaye et al., 2020). *Pouteria campechiana* (Kunth) Baehni is a tree of the Sapotaceae family and its fruit is known by common names such as canistel, mante, and zapote amarillo among others. The fruit contains 1 to 4 seeds and seed composition has a low content of lipids (1.3%), protein (15.1%), and 39.3 % of total carbohydrates (Pérez-Barcena et al., 2021), which are mainly starch (68.1%, dry basis) (Li et al., 2022). Finally, *Brosimum alicastrum* Sw. is a tree of the Moraceae family and is known by different names such as Ash, Hairi, Juksapuo, Tlatlacotic, Apomo, Capomo, Ramón, Mojo, Ojoche, Oshthé, breadnut or Mayanut, among others (Martínez-Ruiz & Larqué-Saavedra, 2018) and this resource is currently wasted. The tree fruit has 1 to 3 seeds, with a production of 95.5 kg/tree, which represents 28.6 tons/year with a commercial of 300 trees (Hernández-González et al., 2014). Ramón seed flour is characterized by nutritional value in protein content (10.4 to 12.4%), dietary fiber (13–20%), low fat (0.6–1.3%), and carbohydrates such as sugars (4.9–7.6%), and high starch content (~65%) (Carter, 2015; Martínez-Ruiz et al., 2019; Moo-Huchin et al., 2015; Rodríguez-Tadeo et al., 2021; Subiria et al., 2019).

Studies have shown that starch from some seeds has better functional properties such as higher water solubility, gelatinization temperature, and viscosity than conventional starches (corn, potato, cassava), and these starches have potential uses for starch-based food products (Bangar et al., 2021; Esquivel-Fajardo et al., 2022; Ferraz et al., 2019; Indarti et al., 2022; Jiménez et al., 2022) and in industries such as textile, pharmaceutical, paper, cosmetic, among other (Barbhuiya et al., 2021). However, native starches can present limitations in their functional properties such as low thermal stability, loss of viscosity, and high retrogradation tendency, among others, and different modifications methods (Fig. 1) had been used to mitigate these limitations and improve the starch properties (Ashogbon, 2021; Fan & Picchioni, 2020). Initially, modifications were carried out in starches via chemical methods to produce starches more stable to shear stress and storage times (reducing syneresis, and retrogradation), which were suitable as texture enhancers and stabilizers in food products (Altuna et al., 2018; Nurmilah & Subroto, 2021; Otache et al., 2021; Subroto et al., 2021; Wang et al., 2020). Physical methods have been effective methods for the industrial production and commercialization of starches, besides being environmentally safe (Ariyantoro et al., 2018; Iuga & Mironeasa, 2020; Kim & Baik, 2022; Schafranski et al., 2021; Wang, Li, et al., 2021; Wu et al., 2022; Zhu, 2021), and enzymatic modifications applied in by-products allowed obtaining higher yield and specific characteristics of starch (Bangar et al., 2022; Chen et al., 2021; Zhong et al., 2022). All modifications affect the starch structure and therefore have an impact on the functional properties and digestibility of starch. The aim of this review was to analyze the characteristics, functional properties, and potential applications of native starch from some seeds (*Sorghum bicolor* L. Moench, *Chenopodium quinoa,* Wild., *Mangifera indica* L., *Persea americana* Mill, *Pouteria campechiana* (Kunth) Baehni and *Brosimum alicastrum* Sw), as well as the effect of different modifications made to these starches.

2. Methodology

A search of scientific literature related to the plants and seeds of interest was carried out using the Scopus, ScienceDirect, and Academic Google databases. The articles were selected considering the genus and species of the plant and focused on the starch of the seeds. All articles that described the morphological characterization and functional properties of seed starch were included. Also, articles describing modified starches of the same seeds, their effect on the characteristics and properties were analyzed. Special interest was placed on articles with applications of seed starch in the food industry. The review was carried out from 2014 to date, particularly in studies of seed starches, except in plant background some previous references were included. A total of 179 studies were screened of which 112 were selected to be analyzed for the present review.

3. Characteristics and properties of native starches from seeds

Diverse studies have characterized the starch obtained from the seeds such as *Sorghum bicolor* L. Moench, *Chenopodium quinoa,* Wild., *Mangifera indica* L., *Persea americana* Mill, *Pouteria campechiana* (Kunth) Baehni, and *Brosimum alicastrum* Sw. (Table 1). The starch yield was different among seeds indicating that WSS > QSS > MSS > RSS > ASS and PCSS. Starch granules are synthesized in the hilum part of the seed and they grow in concentric circles formed by lamellas of amylose and amylopectin molecules (Bertoft, 2017a). The starch content in the seeds may vary due to the botanical source of origin (Wang & Guo, 2020), as well as the starch-isolation methods used. The conventional methods for starch isolation include the use of salts in solution as sodium metabisulfite or sodium bisulfite at 0.1–0.2% (w/v) (Chel-Guerrero et al., 2016), sodium hydroxide solutions at 0.05–0.1% (w/v) (Chen et al., 2016), or extractions with enzymatic catalysts (xylanase protease) (Buksa, 2018). However, the microwave-assisted extraction method had shown to be effective technology in increasing the yield of avocado seed starch (25%) compared to conventional extractions methods (20%) in fresh weight (Araújo et al., 2020; Chel-Guerrero et al., 2016).

On the other hand, the morphological and physicochemical characteristics of the starch granules indicated differences among the described seeds (Table 1). In size, the smallest granules were those of QSS, followed by MSS, PCSS, and WSS (medium size), and ASS presented the largest granules. All seed starch granules, except those from QSS, were within the size of starch granules from sources such as corn (8.6–17.8 μm) and potato (13.5–49.0 μm); while the size of the granules from QSS

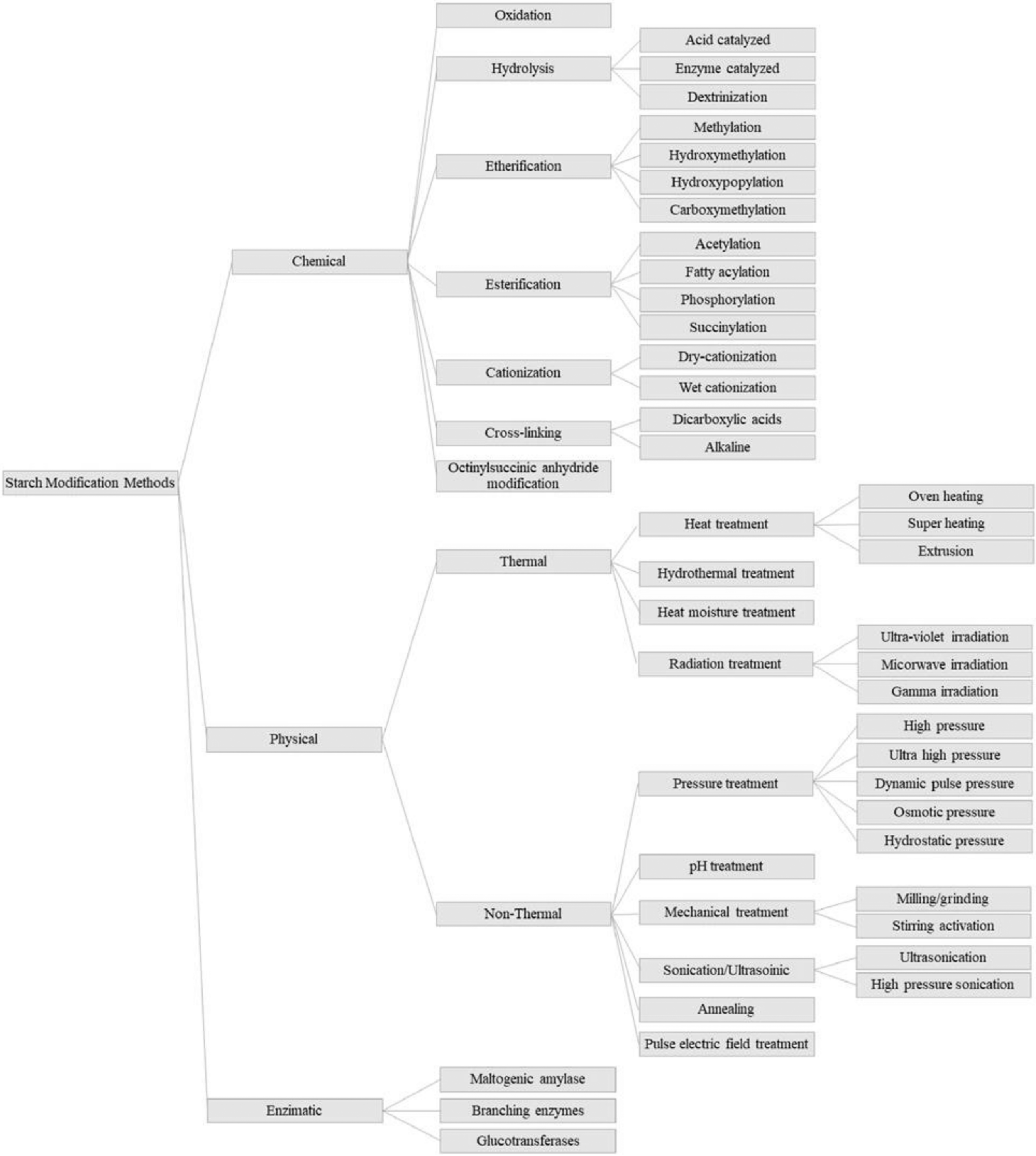

Fig. 1. Starch modification methods.

granules starch size is similar to starch granules from amaranth. The size of starch granules can vary from 1 to 100 μm, considering small (0.3–2.0 μm), medium (5.0–30.0 μm), and large granules close to 100 μm. Furthermore, some types of starch such as potatoes can have starch granules from 1 to 100 μm (Fuentes et al., 2019). Starch granules come in a wide range of shapes such as regular disc, oval, elongated, rounded, kidney/bean-shaped, spherical, polyhedral, and irregular forms. The seeds in this review showed mainly oval shapes (MSS, ASS, PCSS, and RSS), while QSS was polygonal and WSS polyhedral (Table 1). The shapes of MSS, ASS, PCSS, and RSS were similar to starch from other seeds such as *Vigna unguiculate*, *Pisum sativum*, *Hordeum vulgare,* or *Hordeum bulbosum,* and other starch granules from rhizomes (*Zingiber officinale*), fruits (*Musa paradisiaca*), bulbs (*Fritillaria ussuriensis*) or roots (*Nelumbo nucifera*). In addition, the shape of QSS starch granules is similar to other starches from root tuber (*Dioscorea esculenta, Ipomea batatas*), seed kernel (*Hordeum spontancum*), or bulb (*Fritillaria cirrhosa*), and the shape of WSS starch granules is similar to starch from root tuber (*Dioscorea rotundata*). The physiology of the chloroplast and amyloplast of each plant greatly determines the morphology of starch granules, causing wide variability in the size and shape of the starch granules

Table 1
Characteristics and properties of some starches from underutilized seeds.

	WSS	QSS	MSS	ASS	PCSS	RSS	REFERENCES
Yield (g/100 g)	55.0–76.2	50.0	39.0–42.0	18.3–25.0	22.9	30.0	(Agama-Acevedo et al., 2022; Albarracín & Drago, 2020; Araújo et al., 2020; Bangar et al., 2021; Ferraz et al., 2019; Li et al., 2021; Martins et al., 2022; Pech-Cohuo et al., 2021).
Morphological and physicochemical characteristics							
Size (µm)	11.8–24.4	0.4–2.0	10.0–13.0	35.1	14.3	15.0	(Bangar et al., 2021; Contreras-Jiménez et al., 2019; Li et al., 2021; Macena et al., 2020; Pérez-Pacheco et al., 2017; Yang et al., 2019).
Shape	Polyhedral/ spherical	Polygonal/ angular	Oval to disk/elliptical	Oval	Oval to bell shaped	Oval/ spherical	(Bangar et al., 2021; Contreras-Jiménez et al., 2019; Li et al., 2021; Macena et al., 2020; Martins et al., 2022; Pérez-Pacheco et al., 2014; Yang et al., 2019).
Amylose (%)	34.5–36.4	7.7–25.7	23.0–33.1	32.5.48.1	31.5–33.6	25.3	(Agama-Acevedo et al., 2022; Ahmed et al., 2016; Bangar et al., 2021; Li et al., 2021; Li et al., 2016; Martins et al., 2022; Patiño-Rodríguez et al., 2020; Pérez-Pacheco et al., 2014; Wang et al., 2022).
Thermal properties							
T_0 (°C)	70.6–72.5	50.0–58.3	69.8–76.3	66.7–67.2	63.3–67.3	75.0	(Agama-Acevedo et al., 2022; Ahmed et al., 2016; Bangar et al., 2021; de Dios-Avila et al., 2022; Li et al., 2021; Li et al., 2016; 2018; Patiño-Rodríguez et al., 2020; Pérez-Pacheco et al., 2014; Srichuwong et al., 2017).
T_p (°C)	74.1–76.1	56.2–65.0	75.8–80.2	70.3–71.1	68.7–73.3	83.0	
T_c (°C)	79.9–81.5	65.8–74.9	83.0–86.3	76.5–77.4	75.2–82.9	95.0	
ΔH ($J.g^{-1}$)	12.4–13.4	10.8–15.2	9.0–19.4	11.8–13.4	9.9–11.0	21.4	
Cristalinity (%)	15.2–16.4	37.4–38.6	40.1–41.2	14.8–17.2	22.6–39.2	30.5	(Agama-Acevedo et al., 2022; Ahmed et al., 2016; Bangar et al., 2021; de Dios-Avila et al., 2022; Jiang et al., 2021; Li et al., 2021; Li & Zhu, 2018; Moo-Huchin et al., 2015).
*Functional properties**							
WAC (g/g)	1.0–7.8	6.6	1.2	6.0–25.0	0.74	1.0–13.0	(Ali & Hasnain, 2014; Arruda de Souza et al., 2021; Chel-Guerrero et al., 2016; Li et al., 2021; Nadiyan et al., 2022; Pérez-Pacheco et al., 2014, 2017; Velásquez-Barreto et al., 2021).
SI (%)	1.2–7.1	4.1–11.2	0.3–38.9	2.2–20.0	–	0–26.0	
SP (g/g)	2.2–10.3	8.6–16.9	1.5–10.5	7.5–30.0	–	2.1–20.7	
Pasting properties							
PV (cP)	3742.0	2983.0–4700.0	2092.0	5385.5	4612.0	267.0 (BU)	(Agama-Acevedo et al., 2022; Li et al., 2021; Li et al., 2016; Martins et al., 2022; Moo-Huchin et al., 2015; Palavecino et al., 2020).
TV (cP)	2277.0	1600.0–2990.0	1646.0	3085.5	2619.0	265.0 (BU)	
FV (cP)	3949.0	2692.0–4570.0	2383.0	–	3651.0	386.0 (BU)	
BD (cP)	1465.0	313.0–1900.0	443.0	2300.0	1993.0	2.0 (BU)	
SB (cP)	1672.0	442.0–1780.0	734.0	2880.5	1032.0	121.0 (BU)	
PT (°C)	79.9	51.3–72.6	83.2.0	88.5	74.4	82.0	

WSS-White sorghum starch, QSS-Quinoa seed starch, MSS-mango seed starch, ASS-Avocado seed starch, PCSS- *Pouteria campechiana* seed starch, RSS-Ramón seed starch, T_0-initial temperature, T_p-peak temperature, T_c-final temperature, △H-gelatinization enthalpy, WAC-water absorption capacity, SI-solubility index, SP-swelling powder, PV-peak viscosity, TV-trough or minimum viscosity FV-final viscosity, BD-breakdown, SB-setback, PT-pasting temperature. *Values in range from 60 to 90 °C.

(Fatokun, 2020). The amylose content varied among the different starch seeds (25.3 to 48.1%) (Table 1), where ASS > WSS > PCSS > MSS > RSS > QSS. Amylose content varies between species and organs in plants. Starches from seeds and storage organs such as roots and tubers, generally contain 5–35% amylose, and the amylose content is higher in seeds than in leaves, pods, or nodules in the plants. The amylose content in the starch is low during the early stages of seed or tuber development and increases at the later stages until a final amylose content is reached. The amylose content of PCSS, MSS, RSS, and QSS was within the range reported for starches obtained from conventional seeds such as corn, pea, or wheat (22–33%), while high values for ASS are similar to high amylose barley (46.5–48.0 %) (Cornejo-Ramírez et al., 2018) and QSS had low-amylose content such as starch from Arabidopsis leaves (6–12%) (Seung, 2020). The variation in amylose content has been attributed to different factors such as species, place and growing conditions, harvest time, climate, and variation in genes, among others. The amylose content of the starch is important in the properties of starch such as crystallinity, gelatinization temperatures, paste behavior, and nutritional properties (Martins et al., 2022).

Thermal properties of starch provide information about starch granules' disorganization in presence of water and heat (gelatinization), and the energy necessary for starch fusion (gelatinization enthalpy). These parameters vary on the starch source, amylose/amylopectin ratio, and length and molecular arrangement of the amylopectin chains, among others (X. Liu et al., 2022; Subroto et al., 2022). The thermal properties of the seed starches are shown in Table 1. The onset temperature (T_o) was observed in a range of 50.0 to 76.3 °C, being the highest value for MSS and RSS and the lowest for QSS. Peak temperature (T_p) had a range of 56.2 to 83.0 °C, where RSS and MSS showed the highest values and QSS the lowest value. A similar tendency was observed in end temperature (T_c) in the range of 68.5 to 95.0 °C. Also, RSS and MSS showed higher gelatinization enthalpy (ΔH) values than other seed starches, and PCSS the lowest value (9.0 to 21.2 J. g^{-1}). Low gelatinization temperatures (T_o) have been reported for other seeds such as Brazilian jackfruit seed starch (36.0–61.0 °C) (Makroo et al., 2021) similar to ASS and QS, while MSS, RSS, and WSS are similar to Lichi seed starch (68.8–74.2 °C) (Zhang, Zhao, et al., 2022). Starch gelatinization involves multiple transitions, where T_o, T_p, $T_{c,}$ and ΔH reflect the ease and energy required to melt starch. However different factors such as starch molecular structure, moisture content, and presence of salts, sugars, protein, lipids, and non-starch polysaccharides can affect these thermal properties. Amylose with different chain lengths can interact with amylopectin chains in semi-crystalline lamella and affect the gelatinization temperatures and enthalpy. Also, different groups of amylopectin-amylopectin or amylose-amylopectin can have effects on these properties depending on water content (Li et al., 2022). On other hand, crystallinity was observed in the range of 14.8 to 41.2% (Table 1), indicating that ASS showed the highest value and QSS and RSS the lowest values. The crystallinity values of these seed starches are within the reported range (14.0 to 45.0 %) for typical native starch granules such as corn, wheat, potato, banana, soybean, and tapioca, among others. A high crystallinity degree in the starch is considered a starch with low reactivity and this starch needs to be pretreated for improved mechanical and rheological properties (Dome et al., 2020). MSS and RSS by their thermal characteristics may have an elevated thermal resistance (Liu et al., 2022), and mango and Ramón seed starches could be interesting ingredients to use in foods that require processes with high temperatures.

In relation to the functional properties of starch obtained from seeds, water absorption capacity (WAC), solubility index (SI), and swelling power (SP) were observed. WAC corresponds to the amount of water that the starch granule is capable of absorbing and the swelling power (SP) is related to the ability for retaining such water. The SI indicates the level of degradation of the polymers contained in the starch granules. These properties are directly correlated to the increment in temperature (Pérez-Pacheco et al., 2014, 2017). A higher WAC was observed in ASS > RSS > WSS > QSS than in MSS and PCSS, which showed the lowest water retention capacity. This trend was similar in SP, only that QSS has shown greater swelling power at 90 °C than in WSS and MSS. In SI, a trend of MSS > RSS > ASS was observed, while QSS and WSS indicated the lowest solubility. Limited information was identified on these functional properties of *Pouteria campechiana* seed starch, more studies are necessary to obtain more characteristics of this starch. In general, the water absorption capacity of starch depends on factors such as the amorphous and crystalline regions within of starch granule, the molecular structure, and granule size, among others, to trap water molecules in the starch structure (Arruda de Souza et al., 2021). High starch solubility can provide good aqueous dispersion in food systems, as well as higher water absorption and retention (Chel-Guerrero et al., 2016). Also, the variation in the proportion of amylose and amylopectin present in the starch granules contributes to determining the distinctive physiological and chemical characteristics of the starches from different biological sources. It has been proposed that the swelling power of starches is inhibited by a high amylose and lipids content (Fatokun, 2020) because lipids can form a complex with amylose (P. dos Santos et al., 2021). The swelling power (SP) of the granule is a very important functional property for the application of starch. An increase in SP with temperature results from an increase in the mobility of the starch molecules, which facilitates the entry of water and consequently increases swelling. The swelling of the starch granules and the solubilization of amylose and amylopectin cause a gradual loss of granular integrity, generating a viscous paste. However, starches with low swelling power are also important to be used in foods such as frozen foods that require greater stability (Arruda de Souza et al., 2021; Chel-Guerrero et al., 2016).

The pasting profile of starches establishes the temperatures required for starch paste formation and viscosity during a heating and cooling cycle (50 °C to 90 °C) at constant stirring, where starch undergoes different processes like granule swelling, dispersion, fragmentation, and solubilization. The starch structure determines the viscoelastic characteristics of the paste and gel produced and along with thermal resistance are important factors that determine the functional properties and applications of the starch (Balet et al., 2019). The pasting properties of the seed starches reviewed showed that ASS had the higher pasting temperature (PT °C), followed by MSS > RSS > WSS > PCSS > QSS (Table 1). The PT of ASS is similar to black rice starch (88.8 °C) (Martins et al., 2022), and WSS, PCSS, and QSS are similar to the range reported for potato starches (69.1–79.9 °C) (Liu et al., 2023). Pasting temperature is the indicator at which the viscosity of the starch begins to develop during the heating process. High pasting temperatures of the starches indicate a high resistance to swelling and rupture (Kumar & Khatkar, 2017). Different starch intrinsic characteristics had been related to pasting behavior starches such as granules size and morphology, amylose content, and amylose/amylopectin ratio, among others (Castanha et al., 2021). In this analysis, the ASS was characterized by higher values in granule size and high amylose content compared with the others seed starches, while QSS showed lower values in these characteristics. The peak viscosity (PV) of most of the seed starches was higher than that reported for normal maize starch (2910 cP) (Obadi et al., 2023), showing the following tendency ASS > QSS > PCSS > WSS > MSS (Table 1). PV shows the highest degree of swelling of gelatinized starch granules during heating (Tarahi et al., 2022). In maize starches, the PV range has been reported in a wide range (23–4085 cP) and it has been suggested that low PV corresponds to low swelling power (SP) values (Obadi et al., 2023), a characteristic that was observed in MSS. Also, intermolecular interactions such as amylose-amylopectin, amylose-amylose, and amylose–lipid or amylose-protein complexes can affect the PV of starches (Obadi et al., 2023; Tarahi et al., 2022). Other important parameters of the pasting profile that impact the starch functionality are the breakdown (BD) and setback (SB) viscosities. The BD evaluates the stability of the starch paste under conditions of high temperature and mechanical stirring and is directly related to the peak viscosity (T. dos Santos et al., 2016). The BD is the difference between peak viscosity (PV) and trough viscosity (TV). The SB corresponds to the gelation process of the starch, where amylose chains rearrange to form a gel structure (retrogradation) (Balet et al., 2019). In BD, ASS showed again the higher value followed by PCSS > QSS > WSS, and the lowest value was observed in MSS (Table 1). Higher BD values could mean higher crystalline region melting, and amylose leaching that result in faster water uptake, and therefore lower viscosity. Low BD values indicate higher gel stability and pasta cohesiveness (Obadi et al., 2023), where there is less leaching of amylose and disruption of the swollen granules (Balet et al., 2019). For the setback viscosity (SB), ASS showed a higher value followed by QSS > WSS > PCSS > MSS (Table 1). During the final pasting stage (cooling at 50 °C), viscosity tends to increase again, as the gelatinized starch granules are cooled, and the disorganized molecules tend to reorganize. High values of SB are related to a higher tendency for retrogradation and low SD values indicate the lowest tendency to retrograde. Starch with low retrogradation tendency such as MSS can be interesting for applications in foods such as bakery products or snacks (Magallanes-Cruz et al., 2020; Şimşek, 2020). Starches with high retrogradation tendency such as ASS and QSS may be tested in the preparation of sweet foods since a favorable effect of low sugar concentrations to reduce starch retrograde has been reported (Allan & Mauer, 2022). In the case of the RSS, pasting data are reported by only one study, and the pasting parameters are reported in Brabender Units (BU) (Table 1), which cannot be compared with the ones reported for the other seeds in centipoise (cP), nevertheless, when compared with corn starch (CS) on the same study, Moo-Huchin et al. (2015) reported that RSS PT and PV are above CS (72 °C and 252 BU, respectively) with lower BD and SB values than CS (16 and 303 BU, respectively), these results showed that RSS had higher gel paste stability with less tendency to retrograde than corn starch, probably due to a higher heat resistance and lower amylose leaching during heating, leading to a lower increase in paste viscosity. These RSS pasting characteristics can be suitable to use this starch in soups, baby food formulations, and sauces that require specific textures (Moo-Huchin et al., 2015). Overall pasting profiles for seed starches showed that are promising sources for the development of low-cost sustainable raw materials, nevertheless, native starches from every source still have limitations that modifications had overcome, this review offers further insights in modification of seed starches and the impact in thermal, functional and pasting properties.

4. Modifications in starches from underutilized seed and potential applications

Starch represents one of the most widely used biomolecules in the industry such as the production of foods, paper, adhesives, textiles, and packaging, among many others. However, starch can be modified (chemically, physically, and/or enzymatically) (Fig. 1) to improve or adapt its native properties for a specific application. Factors such as application, starch availability, and economics are important for selecting the starch and the type of modification to perform (Alcázar-Alay & Meireles, 2015). Briefly, chemical modifications involve the introduction of functional groups that generate significant changes in starch properties such as starch behavior, gelatinization capacity, retrogradation, and paste characteristics. Food and non-food industries have increased and improved the starch properties using chemical modifications (Alcázar-Alay & Meireles, 2015; Altuna et al., 2018; Nurmilah & Subroto, 2021; Otache et al., 2021; Subroto et al., 2021; Wang et al., 2020). Physical modifications cause changes in the morphology and three-dimensional structure of the starch granule. Physical factors such as milling, moisture, temperature, pressure, pH, radiation, pulse-electric field, and ultrasonic waves, among others, generate changes in the particle size, surface properties, solubility index, and functional properties such as water absorption, swelling power, pasting and gelation capacities of starch. This type of modification is simple, cheap, and safe, and it is therefore preferred when the product is for human consumption (Ariyantoro et al., 2018; Iuga & Mironeasa, 2020; Kim & Baik, 2022; Nawaz et al., 2020; Schafranski et al., 2021; Wang, Li, et al., 2021; Wu et al., 2022; Zhu, 2021). Enzymatic modifications include modifying the native structure of starch to obtain a new structure. Properties such as molecular mass, branch chain-length distribution, and amylose/amylopectin ratio can be modified by enzyme action. Also, modifications with hydrolyzing enzymes allow for starch production with higher yield and hydrolysis by-products with specific characteristics. This modification affects the properties of starch such as freeze–thaw stability of gel and retardation of retrogradation during storage. The food industry has used enzymatic methods for new applications of starches such as food ingredients, to improve product quality, and to increase the efficiency of food processing (Bangar et al., 2022; Chen et al., 2021; Zhong et al., 2022).

Starch from underutilized seeds represents an interesting non-conventional source of starch. Some modifications have been carried out in these starches (Table 2), analyzing their potential uses in the industry (Table 3). Below this review summarizes different modifications reported in starch and products from seeds such as white *Sorghum bicolor* L. Moench, *Chenopodium quinoa,* Wild., *Mangifera indica* L., *Persea americana* Mill, and *Brosimum alicastrum* Sw. White *Sorghum bicolor* L. Moench starch has undergone different modifications that change its functional properties (Table 2). Oxidized sorghum starch showed an increase in the gelatinization conclusion temperature (T_c) and enthalpy, lower swelling power, and a reduction in the pasting temperature. Also, the lowest gel hardness was observed compared to the native starch. The increase in gelatinization temperature may be related to the introduction of functional groups into the starch structure, indicating a weakening of the granule. The oxidation is a depolymerization reaction that causes the hydrolysis of glycosidic linkages, disintegrating the granular structure, which generates less ability to hold water (Ali & Hasnain, 2014; Biduski et al., 2017; Olayinka et al., 2015). However, the acetylation improved the water retention capacity in sorghum-oxidated starches (dual modification). This modification (oxidation-acetylation) of sorghum starch increased the pore size and swelling power of the granule, improving the viscosity peak and retrogradation tendency. The oxidized and oxidized-acetylated sorghum starch showed a lower tendency to retrograde and greater stability under refrigerated conditions than native sorghum starch, with potential applications in foods with high solids content without excessive thickening required (Ali & Hasnain, 2014). Acid-thinned sorghum starch increased the water solubility, decreased the swelling power, amylose content, gel hardness, gelatinization conclusion temperature (T_c), pasting temperature, and viscosity; and presented a lower tendency to retrograde, except when the acid treatment is combined with acetylation, compared to native starch (Mehboob et al., 2015; Palavecino et al., 2019). The acid treatment on sorghum starch elevated the water and oil absorption capacities and gelatinization enthalpy, while the starch modified by acid hydrolyzation-acetylation treatment increased the gelatinization enthalpy, and water and oil absorption capacities, and the lowest amylose content, and crystallinity were observed (Palavecino et al., 2019). Also, dual modification (acid-oxidation) of sorghum starch showed potential applications in the production of biodegradable films with good mechanical properties and good appearance (Biduski, et al., 2017), and the succinylation of acid-thinned sorghum starch decreased the thermal, functional and pasting properties, except the solubility index that tended to increase. Succinylated sorghum starch improved the viscosity characteristics, reduced the retrogradation tendency, and refrigerated starch gels of the modified starch presented reduced gumminess, hardness, and chewiness with potential uses in frozen foods such as pie fillings where low paste viscosity, high clarity, and storage stability are required. Also, this modified sorghum starch can be a valuable thickening agent to use in soup, snacks, and refrigerated products (Mehboob et al., 2015). Physical modifications using the heat-moisture treatment (HMT) in sorghum starch (Table 2) elevated the gelatinization temperature and enthalpy, and decreased, solubility index, swelling

Table 2

Characteristics and properties of some modified-starches from underutilized seeds.

Starch source	Modification	*Morphology*		AM (%)	*Thermal properties*				RC (%)	*Functional properties*			*Pasting properties*						References
		Size (µm)	Shape		T_0 (°C)	T_p (°C)	T_c (°C)	ΔH (J.g^{-1})		WAC (g/g)	SI (%)	SP (g/g)	PV (cP)	TV (cP)	FV (cP)	BD (cP)	SB (cP)	PT (°C)	
WSS	Oxidation	-	-	25.2↓	67.9↑	71.0↑	75.5↑	9.4↑	16.7↑	-	1-8↓	2-14↓	3347↑	-	2379↓	1630↑	1013↑	74.2↓	(Ali & Hasnain, 2014; Karmvir et al., 2018; H. Liu et al., 2016; Mehboob et al., 2015; Olayinka et al., 2015; Palavecino et al., 2019, 2020; Sun et al., 2014; Tobías et al., 2018; J. Zhang et al., 2021)
	Oxidation	225-275↑	Distorted granules	-	-	-	-	-	-	0.9-5.7↓	3.5-18.4↑	2.1-6.6↓	54.5↓ (BU)	12↓ (BU)	18↓ (BU)	42↓ (BU)	6↓ (BU)	72.0↓	
	Oxidation/ cross-linking	-	-	4.1↓	69.3↓	73.2↓	95.0↑	6.8↑	16.5↑	0.6↓	1.0↑	10.0↓	3110↑	1954↑	3114↑	1156↓	1160↓	76.8↓	
	Acid-thining	-	-	-	70.5↑	73.9↑	81.2↓	9.6↓	-	-	11.0↑	4.5↓	9.5↓ (BU)	1.0↓ (BU)	5.0↓ (BU)	8.5↓ (BU)	0.5↓ (BU)	60.6↓	
	Acid-treated	5-25↓	Clustered	32.4↑	61.9↓	65.4↓	70.4↓	9.8↑	-	0.9↓	1.3-1.9↑	4.7↓	386.9↑	100.6↓	234.2↓	280.6↑	127.8↓	75.8↓	
	Acid hydrolyzation/ acetylation/ esterification	-	Spherical/ polyhedral with flat face	19.7-22.0↓	66.2-69.4↑	-	-	4.5-10.5↑	16.2-21.2↓	1.9-2.7↑	-	-	3243-4464↑	1507-2306↓	2583-4943↑	1651-2158↑	1076-2637↑	73.5-80.0↓	
	Succinylation	-	-	-	67.3↓	71.8↓	80.7↓	13.6↓	-	-	12.0↑	5.2↓	16.0↓ (BU)	2.5↓ (BU)	6.5↓ (BU)	13.5↓ (BU)	4.0↓ (BU)	66.7↓	
	HMT	-	Larger dented granules	29.7↑	74.1↑	78.1↑	81.3↑	11.9↑	31.9↑	-	1.25-18.8↓	2.1-14↓	1680↓	1413↑	2575↓	284↓	1162↓	83.0↑	
	HHP treatment	-	Irregular oval, spherical and polygonal	29.8-34.6↑	63.0-69.7↓	67.5-75.8↓	72.1-82.6↓	10.6-20.6↓	24.4-35.8↓	0.7-4.3↑	-	2.5-15↓	1611-4327↓	-	2916-3219↓	1862-2684↓	1249-1613↓	63.7-65.8↑	
QSS	ACP*	-	Irregular granules	-	70.8-94.4↑	96.2-101.1↑	107.1-115.8↑	635.6-1395↑	-	2.4-3.7↑	0.5-3.3↑	6.2-6.7↑	-	-	-	-	-	-	
	HHP*	122.8↑	Gelatinized	-	ND	ND	ND	ND	-	-	34.6-37.3↑	6.8-10.1↓	ND	ND	440↓	ND	280↓	-	

(continued on next page)

Table 2 (*continued*)

Starch source	Modification	*Morphology*		AM (%)	*Thermal properties*				RC (%)	*Functional properties*			*Pasting properties*						References
		Size (µm)	**Shape**		**T_0 (°C)**	**T_p (°C)**	**T_c (°C)**	**ΔH (J.g^{-1})**		**WAC (g/g)**	**SI (%)**	**SP (g/g)**	**PV (cP)**	**TV (cP)**	**FV (cP)**	**BD (cP)**	**SB (cP)**	**PT (°C)**	
QSS	Ultrasound*	-	-	-	61.0↓	70.2↓	78.9↓	6.3↓	-	-	20.7-25.6↑	3.4-8.6↑	ND	ND	112↓	ND	ND	-	(J. Ahmed et al., 2018; Almeida et al., 2022; Hadi et al., 2020; R. Huang et al., 2021; Jiang et al., 2021; G. Li et al., 2019, 2022; G. Li & Zhu, 2018, 2021; S. Li et al., 2019, 2020; Selma-Gracia et al., 2020; Sharma et al., 2022; Xing et al., 2021; Zare et al., 2022; L. Zhang et al., 2021; Zhou et al., 2021; Zhu & Li, 2019a, 2019b)
	Pearling*	-	-	-	-	-	-	-	-	0.9↓	23↑	12.5↑	1248↑	-	1634↑	227↑	632↑	90.4↑	
	Thermal*	-	-	-	-	-	-	-	-	0.2-0.3↑	6.4-10.0↓	6.8-8.5↑	-	-	-	-	-	-	
	Extrusion*	-	Destroyed granules	-	ND	ND	ND	ND	-	5.4-7.2↑	21.5-23.2↑	9.4↑	371↓	67↓	133↓	305↑	66↓	59.0↓	
	Germination*	-	Dented angular polyhedral	3.6-4.3↑	52.1-57.1↓	58.4-63.4↓	68.7-75.1↑	16.2-17.6↑	35.2-37.3↓		0.5-5.0↓	1.0-14.0↓	3190-3882↓	2393-3449↓	-	433-936↑	650-1422↑	61.4-66.9↓	
	OSA	-	Polygonal, irregular	-	52.1↓	60.1↓	68.5↓	13.9↓	-	-	-	-	4300↑	-	1930↑	2630↓	260↑	76.2↓	
	DDSA	1.4-1.7↑	Polygonal	-	58↓	63.4-64.3↓	71.6-72.5↑	12.1-15.3↓	27.8-32.6↓	-	0.2-0.5↑	8.5-26.7↑	3090-7040↑	2660-5150↑	3450-6750↑	440-1890↑	800-1600↓	65.8-69.0↓	
	NSA	-	-	-	50.6-60.0↓	61.6-66.2↓	73.1-76.1↑	12.3-14.2↓	-	-	-	-	750-1860↑	430-950↑	740-1290↑	320-910↑	310-340↑	57.9-69.0↓	
	Repeated dry heat treatments	-	Aggregate, porous and collapsed granules	-	137.2-161.0↑	145.3-166.7↑	195.0-198.0↓	33.9-60.0↓	41.6-44.8↑	0.8-1.0↓	7.3-10.6↑	9.6-11.5↓	4639-6919↑	2755-4126↑	5213-7110↑	653-3937↑	2714.5-2983.5 ↑	55.4-58.2↓	
	Continuous dry heat treatments	-	Aggregate, porous and collapsed granules	-	125.2-145.2↑	139.4-159.8↑	194.0-199.0↑	48.8-59.0↓	41.0-42.9↑	0.7-0.8↓	5.8-10.9↑	8.6-9.5↓	4698-7874↑	4049-4797↑	6623-7923↑	648.5-3335.5 ↑	2573.5-3177.5 ↑	55.0-57.8↓	
	HMT	-	-	30.1-38.1↓	73.1-73.9↑	80.1-81.5↑	82.1-83.3↑	2.9-3.7↓	19.3-21.2↓	-	7.9-10.0↑	7.2-15.6↑	-	-	-	-	-	-	
	HHP (500-600 MPa)	7.1-19.3↑	Disrupted granules	-	59.2-ND↓	66.4-ND↓	76.0-ND↑	4.1-0↓	-	-	12.2-1.8↓	13.5-8.4↓	548-598↓	-	-	-	-	50.0-62.7↓	
	HP (300-600 MPa)	100-115↑	Disrupted granules	-	57.6↓	64.5↓	-	-	1.6↓	7.2-8.8↑	3.4-3.8↑	-	-	-	-	-	-	-	
	Enzymatic method	1.0-0.9↓	Rough granules, crack, broken	-	-	-	-	-	17.7-19.6↑	-	-	-	-	-	-	-	-	-	

(*continued on next page*)

Table 2 (*continued*)

Starch source	Modification	*Morphology*		AM (%)	*Thermal properties*				RC (%)	*Functional properties*			*Pasting properties*						References
		Size (μm)	Shape		T_0 (°C)	T_p (°C)	T_c (°C)	ΔH ($J.g^{-1}$)		WAC (g/g)	SI (%)	SP (g/g)	PV (cP)	TV (cP)	FV (cP)	BD (cP)	SB (cP)	PT (°C)	
MSS	OSA (3%)	38.6↑	Oval with pores, agglomerated clusters	-	75.0	-	-	-	66.4↓	-	-	-	-	-	-	-	-	-	(Bet, et al., 2017a; Bharti et al., 2019; Ferraz et al., 2019; Ferreira et al., 2019; Kalaivendan et al., 2022)
	Acid treatment	L 15.9-8.1↓ W 11.1-12.8↓	Ellipsoidal shape	-	73.3-75.1↑	78.5-79.1↑	83.9-84.3↓	11.3-15.4↑	-	-	-	-	790-2092↓	-	456.0-1725↓	553.6-1161↓	221.5-794.1↓	75.2-76.8↓	
	Oxidation	-	-	23.3↓	95↓	105.8↓	120↓	10.5↓	-	-	22.6-42.5↑	5.9-7.3↑	-	-	-	-	-	-	
	Spray dried	6.0-13.0	Oval disk-like shape	25.2↓	58.3↓	63.5↓	67.6↓	-	28.3↓	-	-	-	-	-	-	-	-	-	
	HMT	-	Elongated, triangular, oval, irregular granules	41.9-43.6	-	-	-	-	22.7-26.9↓	0.9-1.2↑	3.0-7.0↓	6.0-15.0↓	2026-4722↑	-	2763-6256↑	112-992↓	849-2349↑	81.8-87.5↑	
	Atmospheric pressure	-	Elliptical, crinkle-surfaced	27.2-30.3↓	73.2-75.1↑	84.9-91.1↑	89.1-147.9↑	5.3-16.4↓		7.3-12.1↑	3.4-7.9↑	7.6-13.3↑	918.9-1172↓	-	987.9-1192↓	58.3-125.1↓	958.3-1079↓	-	
ASS	Acetylation	26.0-36.0	Round bell shaped		41.4↓	88.6↑	94.6↑	797.4↑		0.6↓	5.0↓	11.0↓	321.9↑	205.9↑	509.5↑	116.0↓	303.5↓	79.2↓	(Bet, et al., 2017b; Cornelia & Christianti, 2018; Silva et al., 2017)
	Crosslinking	5.0-20.0↓	Ovoid, oblong, elliptical and circle shapes	39.1↓	-	-	-	-	-	-	3.0↓	4.1↓	4890↑	-	4943↑	-	1709↓	80.9↓	
	Lactic acid	20.9-20.5	Round oval	-	69.0-69.5↓	73.2-73.8↓	77.4-78.1↓	9.7-10.2↓	14.5-14.6↓	-	-	-	-	-	-	-	-	-	
RSS	Oxidation	6.5-15.0	Oval-spherical-shape	23.3-29.5↑	-	-	-	-	-	-	17.9-25.3↓	18.9-23.0↑	-	-	-	-	-	-	(Pérez-Pacheco et al., 2017)

Modifications carried out on starches isolated from seeds. *Modification applied on seed flour. WSS-White sorghum starch, QSS- Quinoa seed starch, MSS-Mango seed starch, ASS- Avocado seed starch, RSS-Ramón seed starch, AM-amylose, T_0-initial temperature, T_p-peak temperature, T_c-final temperature, △H-gelatinization enthalpy, RC-relative crystallinity, WAC-water absorption capacity, SI-solubility index, SP-swelling power, PV-peak viscosity, TV-trough or minimum viscosity, FV-final viscosity, BD-breakdown, SB-setback, PT-pasting temperature. Arrows (↑-increase, ↓-decrease) indicate the effect of the modification treatment on the seed starch compared to its native starch in the same study.

Table 3
Potential applications of flour and isolated starch (native and modified) from underutilized seeds.

Source	Sample	Starch state	Potential Applications	References
WSS	Starch	Native	Gluten-free foods, frozen foods	(Ahmed et al., 2016; Albarracín & Drago, 2020; Rumler et al., 2022)
	Starch	Modified (Oxidation, Oxidation-acetylation)	Frozen foods, pasta, and noodles formulations, biodegradable films	(Ali & Hasnain, 2014; Biduski et al., 2017)
	Starch	Modified (succinylation-acid treatment)	Frozen foods, pie fillings, thickening agent in soups, snacks, and refrigerated products.	(Mehboob et al., 2015)
	Starch	Modified (HMT)	Thickening and gelling agent for dressings, soups, and sauces.	(Sun et al., 2014)
	Starch	Modified (HHP)	Baked goods and cookie-making	(Liu et al., 2016)
	Starch	Modified (Extrusion/ phosphorylation)	Extruded snacks	(Escobar-Puentes et al., 2019)
QSS	Flour	Native	Bread, instant noodles, and binder in sausages-making.	(Tafadzwa et al., 2021; Tiga et al., 2021; Wang, Lao, et al., 2021)
	Flour	Modified (HP)	Gluten-free products	(Zhu & Li, 2019a)
	Flour	Modified (Ultrasound)	Baked goods, and beverages	(Zhu & Li, 2019b)
	Flour	Modified (Pearling)	Enhance food processing conditions	(Jiang et al., 2021)
	Flour	Modified (Extrusion)	Infant and elderly food preparation	(Huang et al., 2021)
	Flour	Modified (Germination)	Pickering emulsions, sauces, cream soup, and pie fillings	(Xing et al., 2021)
	Starch	Modified (Esterified)	Pickering emulsions, pharmaceutical formulations	(Hadi et al., 2020)
	Starch	Modified (OSA)	Encapsulation of hydrophobic bioactive compounds	(Li, Zheng, et al., 2019, 2020)
	Starch	Modified (DDSA, NSA)	Emulsifier and Pickering emulsions stabilizer	(Li, Xu, et al., 2019; Li & Zhu, 2021)
	Starch	Modified (RDHT, CDHT)	Thickening agent in foods	(Zhou et al., 2021)
	Starch	Modified (HMT)	Food additive	(Almeida et al., 2022)
	Starch	Modified (Thermal pre-treatment)	Formulations for patients with altered glucose metabolism	(Selma-Gracia et al., 2020)
	Starch	Modified (HHP 500–600 MPa)	Pre-gelatinized starch in instant foods	(Li & Zhu, 2018)
	Starch	Modified (HP 300, 450, and 600 MPa)	Foods for celiac patients	(Ahmed et al., 2018)
	Starch	Modified (Enzymatic)	Emulsifying and Pickering emulsions stabilizer	(Zhang, Xiong, et al., 2021)
MSS	Flour	Native	Extruded snacks	(Patiño-Rodríguez et al., 2021)
	Starch	Modified (OSA)	Plastic films	(Ferraz et al., 2019)
	Starch	Modified (Acid hydrolysis)	Gum and confectionary products	(Bet, Cordoba et al. (2017))
	Starch	Modified (Ox)	Edible films	(Vellaisamy et al., 2021)
	Starch	Modified (HMT)	Noodles and pasta formulations	(Bharti et al., 2019)
	Starch	Modified (Atmospheric pressure)	Sauces, dressings	(Kalaivendan et al., 2022)
ASS	Starch	Native	Sizing agent in textiles	(Tesfaye et al., 2018)
	Starch	Modified (Acetylated)	Instant puddings, desserts, and frozen foods	(Silva et al., 2017)
	Starch	Modified (Cross-linking)	Cream soup	(Cornelia & Christianti, 2018)
PCSS	Starch	Native	Healthy food additive	(Agama-Acevedo et al., 2022)
RSS	Flour	Native	Beverage and bread for specific nutritional requirements	(Martínez-Ruiz et al., 2019; Rodríguez-Tadeo et al., 2021)

WSS-White sorghum starch, QSS- Quinoa seed starch, MSS-Mango seed starch, ASS- Avocado seed starch, RSS-Ramón seed starch. HMT-Heat-moisture treatment; HHP-High hydrostatic pressure; HP-High pressure; OSA-Octenyl succinic anhydride; DDSA-Dodecenyl succinic anhydride; NSA-Nonenyl succinic anhydride.

power, and, breakdown and setback viscosities compared to native starch. HMT promotes cross-linking between amylose and amylopectin within the starch granules that decreases its swelling power resulting in increased gel hardness and higher paste stability, improving textural properties, gel hardness, shear stability, and reducing the retrogradation tendency, which is desirable in sorghum food products (Sun et al., 2014). High hydrostatic pressure (HPP) treatment increased the amylose content, water absorption capacity, alkaline water retention, and pasting temperature, while oil absorption capacity, swelling power, crystallinity, and viscosity decreased compared with native starch. This modification promotes disruption of the starch amorphous lamellae with the resulting loss of molecular order and further amylopectin reordering, and formation of amylose–lipid complexes, limiting amylose leaching during pasting, thus increasing PT and decreasing BD and SB. The sorghum modified by HHP indicated potential uses for cookie-making and baked products due to the pasting properties and thermal stability (Liu et al., 2016). In a dual modification (chemistry-physical treatments), extruded phosphorylated sorghum starch presented higher values of resistant starch and expansion index values than native sorghum starch and its application in extruded snacks showed acceptable physical and sensorial characteristics (Escobar-Puentes et al., 2019).

Quinoa (*Chenopodium quinoa,* Wild.) flour is used in different foods such as bread (Wang, Lao, et al., 2021), instant noodles (Tiga et al., 2021), and as a binder in beef sausages (Tafadzwa et al., 2021). Some modifications have been carried out to improve the flour functionality (Table 2). Cold plasma treatment in quinoa flour increased starch gelatinization enthalpy and gelatinization temperature (except for treatment at 5 min at 60 kV with no statistical difference with untreated flour), water absorption capacity, solubility index, and swelling power. This treatment particularly influenced the modification of the starch and protein structures and different complexes were formed (starch-starch, starch-protein, and protein–protein), which significantly determine the technological properties and uses of quinoa flour (Zare et al., 2022). High hydrostatic pressure (HHP) was applied to grain quinoa flour (up to 600 MPa), which completely gelatinized starch granules decreasing the paste viscosity, gel formation capacity, and gelatinization enthalpy. Applications of HP-treated quinoa flour are suggested in gluten-free products and as an additive for wheat-based formulations (Zhu & Li, 2019a). While ultrasound treatment of quinoa flour increased the water solubility, swelling power, total phenolic content, and *in vitro* antioxidant activity, and a decrement in all thermal properties was observed. Due to the degradation of the granule integrity, no pasting properties were detected, except FV, which was explained by the granular damaging of starch induced by the cavitation effect of ultrasound waves creating cracks and pores on the starch surface leading to the physicochemical changes in quinoa starch. The quinoa flour treated may be used in bakery or beverage products or in wheat-bakery products enriched with quinoa flour (Zhu & Li, 2019b). The pearling of quinoa decreased the water absorption capacity but increased the water solubility index, swelling power, oil absorption capacity, pasting temperature, peak viscosity, breakdown, and setback. Pearled flour can improve processing conditions in foods with nutritive properties and good taste (Jiang et al., 2021). Quinoa flour subjected to different thermal processes (roasting, autoclaved, and microwaved) increased water absorption capacity and swelling power and decreased water solubility index and oil absorption capacity. Quinoa flour treated exhibited high preservation of phenolic and flavonoid compounds, and particularly microwave processing enhanced the techno-bifunctionality of quinoa flour which can be utilized in conventional industrial protocols for the preparation of diverse products (Sharma et al., 2022). Extrusion of the quinoa flour showed higher peroxide value and malondialdehyde value when compared to the non-modified flour; besides, extrusion increased water absorption capacity, water solubility, and swelling power, and decreased the pasting properties, but no gelatinization temperatures and enthalpy were detected due to the complete gelatinization of quinoa flour starch granules during extrusion, where extrusion conditions such as temperatures and water content had an important effect on physicochemical properties of quinoa flour extrudates. A defatting process did not change any technological properties but prevented lipid oxidation. The extruded quinoa flour can be used in the preparation of food for infants or the elderly (Huang et al., 2021). The germination treatment of quinoa grains decreased the crystallinity of starch granules, with no changes in the crystalline structure. Also, a decrease in gelatinization temperatures and enthalpy, water absorption capacity, solubility index, and swelling power, while an increment in amylose content, temperature, and the peak of viscosity was observed, increasing the paste stability and low retrogradation tendency. The germination treatment caused high starch granule porosity which increased starch swelling susceptibility and therefore induced favorable changes in the thermal, functional, and pasting properties of this starch. Germinated quinoa starch can be used as an ingredient for Pickering emulsions, sauces, cream soups, and pie fillings (Xing et al., 2021).

On other hand, quinoa starch had been modified by different chemical methods (Table 2). Esterification is highly focused on the development of starch Pickering emulsions, taking advantage of the small size of the starch granules. Esterification of quinoa starches with short-chain fatty acids (acetylation, propionylation, and butyrylation) increased the emulsification capacity of quinoa starch. Higher levels of modification increased the emulsion index and stability, and the emulsifying capacity was improved by increasing the chain length of the short-chain fatty acid used (propionylated and butyrylated). The potential use of this modified quinoa starch is as an emulsion stabilizer in functional foods, pharmaceutical formulations, or the food industry in general (Hadi et al., 2020). The esterification of starch with octenyl succinic anhydride (OSA) has been widely studied. In quinoa starch the octenylsuccinylation did not change the polygonal and irregular shape of the native starch granule; increased the mean particle size and increased the surface hydrophobicity. The modification decreased the cream layer and the oil-off at the top phase of fresh emulsions of native quinoa starch, another study also used octenylsuccinated quinoa starch to stabilize Pickering emulsion gel as a carrier for lutein. Also, modified quinoa starch decreased gelatinization temperatures and enthalpy, pasting temperature, and breakdown, while the peak viscosity and setback were increased, indicating that the quinoa starch modified by octenylsuccinylation can be used in starch-based formulations to encapsulate and release hydrophobic bioactive compounds in foods and pharmaceutical products (Li, Xu, et al., 2019, Li et al., 2020). As an alternative to octenylsuccinylation of quinoa starch, other succinic anhydrides have been evaluated. The modification with dodecenyl succinic anhydride (DDSA) and nonenyl succinic anhydride (NSA) reduced the onset gelatinization temperature and enthalpy in comparison with native quinoa starch with a marked decrease, especially in the nonenyl succinic anhydride treatment. The treatment with dodecenyl succinic anhydride increased the particle size of the emulsions, water solubility, and swelling power; while decreasing the relative crystallinity of the starch. Low degrees substitution in DDSA-modified quinoa starch increased the viscosity and gel elasticity, while high degrees substitution decreased these parameters. The modification with nonenyl succinic anhydride increased the pasting peak viscosity, and gel hardness and decreased the pasting temperature. In DDSA and NSA treatments, the size of each molecule can generate different effects. The introduction de smaller molecules into starch facilitates the disruption of the packing helical structure in the crystallites of starch granules, and bigger molecules have high capacity forming Pickering emulsion, due to that longer carbon chains may induce more hydrophobicity to starch granules, which enhance their ability to form Pickering emulsions (Li, Xu, et al., 2019; Li & Zhu, 2021).

Regarding physical modifications, thermal modification of quinoa starch by dry heat treatment and heat moisture treatment (HMT) has been applied (Table 2). Repeated and continuous dry heat treatment (RDHT and CDHT, respectively) did not change the crystal type of quinoa starch and remained A-type, the relative crystallinity, water-solubility, and the pasting parameters of quinoa starch increased, while the water absorption capacity and swelling power decreased compare with native quinoa starch. Relative crystallinity, and water absorption capacity were significantly higher in RDHT starch samples than in CDHT starch samples for the same period, and it was observed the formation of aggregates after the treatments. CDHT and RDHT starch samples showed an increase in thermal properties like gelatinization temperature and enthalpy, and in pasting properties like peak, trough, final, and breakdown viscosities showing a higher tendency to retrograde than native starch. Overall, RDHT showed better performance in altering the physicochemical and structural properties of quinoa starch compared with CDHR. Dry heat treatment increased the water solubility and peak viscosity of quinoa starch, and its use as a thickener in food is suggested (Zhou et al., 2021). Modification of quinoa starch by HMT did not change the chemical structure of the starch observed by FTIR and did not change the A crystalline type but reduced the relative crystallinity. The amylose content decreased with higher times of continuous HMT in comparison to the native starch. The solubility and swelling power of quinoa starch increased with continuous HMT in a treatment time-dependent manner. All the gelatinization temperatures increased while gelatinization enthalpy decreased with the HMT, making the starch more resistant to thermal processes. The quinoa starch treated by HMT with 3 h process showed the greatest changes in thermal, structural, and morphological properties and its application in the food industry is suggested (Almeida et al., 2022). Quinoa starch partially gelatinized (thermal pretreatment 60 °C/1min) presented higher peak viscosity and low breakdown and reflected modifications in the quinoa starch structure which were related to increased digestibility. Thus, quinoa starch pretreated could be potentially beneficial in the design of more digestible formulations for specific nutritional treatments in patients with glycogen storage disease and other diseases with altered glucose metabolism (Selma-Gracia et al., 2020). Quinoa starch subjected to high hydrostatic pressure (HPP) at 500 and 600 MPa was completely gelatinized, and a decrease in gelatinization temperatures and enthalpy, water solubility, swelling power, viscosity, peak and pasting temperature of quinoa starch. The gel stability improved during cooling, enhanced the elasticity of the starch gels, and did not affect the amylopectin recrystallization and gel textural properties of starch. The quinoa starch treated by the HPP method may be used as a new pre-gelatinized starch in instant foods or as a thickening agent in foods (Li & Zhu, 2018). Also, quinoa starches treated with high pressure (HP) (300, 450, and 600 MPa for 15 min) increased the water absorption capacity and solubility index. A large size of starch granules is reported in this modification of quinoa starch, and was attributed to the aggregation or agglomeration of small starch granules after the treatment. The complete gelatinization of quinoa starch occurred at 600 MPa by breaking down amylopectin crystals causing a decrease in gelatinization temperature. Additional thermal processing of the pressure-treated starch improved the gel rigidity except for the sample treated at 600 MPa. The quinoa starch modified by HP-treatment can be applied in foods for celiacs or in the development of new food products with functional benefits (Ahmed et al., 2018).

Modification of quinoa starch by enzymatic hydrolysis with α-amylase and saccharifying enzyme did not change the type-A crystal structure and increased the relative crystallinity in comparison with the native starch and decreased the particle size of starch granules. The surface of modified starch particles develops surface roughness, the angular structure was partially lost, cracked, broken and aggregated starch granules appear. The use of the enzymatically modified quinoa starch increased the emulsifying properties with higher values of emulsification index values and with smaller oil droplet sizes. The modified quinoa starch has potential application as an emulsifier in stabilizing Pickering emulsions in high-oil foods such as salad dressings (Zhang, Xiong, et al., 2021).

Mango (*Manguifera indica* L.) seed starch has been modified by chemical methods (Table 2) such as esterification with octenyl succinic anhydride (OSA). The OSA-modified mango seed starch presented a high degree substitution, increasing the granule size, and decreasing relative crystallinity, but thermal properties were not altered by the esterification reaction. This modified starch showed lower mass loss (degradation) than native starch, and the OSA-modified mango seed is suitable to be used in plastic film, due to its amphiphilic character (Ferraz et al., 2019). Acid-hydrolyzed mango seed starch increased gelatinization temperature and enthalpy, showing higher thermal stability than native starch. A decrease in pasting temperature, viscosity peak, breakdown, setback, and final viscosity, indicating that the modified seed starch's internal molecular structure tended to dissociate easier than native starch. The modified seed starch showed less retrogradation tendency, which may be a positive feature for long storage periods. The use of this modified starch in gum and confectionary industries is suggested (Bet, Waiga, et al., 2017). Mango seed starch modified by oxidation showed a decrease in amylose content, gelatinization temperature and enthalpy, and an increase in water solubility and swelling power was observed. Oxidation promotes partial disruption of starch glycosidic linkages resulting in starch depolymerization and further solubilization with less energy needed, indicating that acid-hydrolyzed mango seed starch has the potential to form nano-composite films with improved strength, and water vapor barrier properties, which could be used in the manufacture of renewable and biodegradable edible films for the food industry (Vellaisamy et al., 2021).

Modification of mango seed starch by physical methods had been carried out (Table 2). Spray-dried mango seed starch resulted in lower amylose content, relative crystallinity, and gelatinization temperatures, and higher content of amylopectin short-chains than native starch. Also, amylose–lipid complex formation was reported in dried sprayed mango seed starch. These results in starch structure physical modification indicate that spray-dried mango seed starch can be used in a broad range of industrial applications involving heat treatments (Ferreira et al., 2019). Heat moisture treatment (HMT) has also been applied to modify mango seed starch. The influence of HMT on mango seed starch showed a significant increase in water binding capacity, and a decrease in swelling power and water solubility compared to native starch. Pasting properties indicated an increase in pasting temperature, peak, and final viscosities, and a decrease the breakdown, possibly due to HMT treatment promoted partial gelatinization, and protein denaturation during high heat treatment, which might have led to changes in the starch structure preventing the complexation with amylose molecules and enhancing the oozing out exudates, increasing the starch viscosity. HMT-MSS properties suggest its utilization in noodles and pasta formulations due to lower SI and SP and paste stability, attributes desirable for this type of products (Bharti et al., 2019). Atmospheric pressure on mango seed starch decreased amylose content, and gelatinization enthalpy, possibly due to depolymerization of the starch that resulted in less energy needed to disorganize its structure, and an increased water absorption capacity, water solubility, and swelling power. Also, these changes in modified-MSS encouraged the formation of less viscous pastes (decrement of pasting properties), and a lower tendency to retrogradation than native MSS. Atmospheric pressure treatment may lead to more crystalline starch due to the leaching of amylose from damaged granules, which enhances the functional properties of modified starch. This starch treatment can be a positive alternative, compare to thermal or chemical methods, to obtain an environmentally safe ingredient with potential applications in foods such as sauces or dressings that required long storage periods, maintaining a desirable consistency (Kalaivendan et al., 2022).

Avocado (*Persea americana* Mill.) seed starch has been modified by chemical methods (Table 2). Acetylation of avocado seed starch showed changes in starch shape, from an oval shape (native) to a round bell shape with a deformed surface and the presence of channels in acetylated starch, this being due probably to an alteration in the starch structure by substitution of hydroxyl groups with acetyl groups during the modification, nevertheless, the granule average size did not change. Acetylated-avocado seed starch decreased water absorption capacity, water solubility swelling power, and increased gelatinization temperatures and enthalpy. In pasting properties, a decrement in pasting temperature, breakdown, and setback values was observed, while the peak viscosity increased, showing a more stable paste during stirring and heating and a lower tendency to retrogradation. Also, this modified starch showed a reduced syneresis during freezing and enhanced oil absorption capacity. Acetylated-avocado seed starch has the potential as an ingredient in instant puddings, desserts, and frozen foods (Silva et al., 2017). Cross-linking of avocado seed starch showed a decrease in granule size with no changes in shape, lower amylose content, solubility, and swelling power than native starch. Also, cross-linked avocado starch presented lower pasting temperature due to alteration and weakening of granule structure, however, modified starch showed an increase in the peak viscosity, possibly due to cross-linking of amylose and amylopectin that leads to stronger structure of starch granule and increases its hydration capacity and peak viscosity during the heated. The application of this modified starch in cream soup showed a product sensory accepted and with better viscosity stability than commercial cream soup (Cornelia & Christianti, 2018). Lactic acid has been used to modify avocado seed starch, and a decrement in thermal properties and relative crystallinity was observed. Lactic acid can promote partial hydrolysis of amylopectin, decreasing the crystallinity, gelatinization temperatures, and enthalpy, generating a thermally less stable starch. However, more studies are necessary to corroborate the effects and potential applications of this modified starch (Bet, Waiga, et al., 2017).

Pouteria campechiana (Kunth) Baehni seed starch (PCSS) has begun to gain interest in exploring its properties and potential applications, however no reports related to the modification of PCSS were found. Some related studies on *Pouteria campechiana* have carried out modifications in the starch from the pulp. Briefly, PC pulp starch modified by HMT treatment caused a decrement in amylose content, viscosity peak, and breakdown and increased the pasting temperature. Applications as a texture enhancer in noodles, cakes, and other baked goods are suggested (Pertiwi et al., 2022). On other hand, drying treatments produced changes in PC pulp starch. Hot air drying (HAD), freeze-drying (FD), and vacuum drying (VD) were applied to modify the pulp starch. The modified pulp starch showed an increment in amylose content and relative crystallinity, while a decrement in water solubility, swelling power, and gelatinization properties was observed. Modified pulp starch can have potential applications as a thickener and gelling agent (He et al., 2021). Considering these first results obtained in PC pulp starch, PC seed starch is an interesting topic to explore different types of modification on its structural and functional properties and compare with those performed on PC pulp starch.

Brosimum alicastrum Sw. seed starch (RSS) was modified by oxidation (sodium hypochlorite) (Table 2). The modification of this starch by chemical method (oxidation with sodium hypochlorite) did not affect the shape and size of the starch granule, due to little granular fragility and the presence of residual phenolic compounds in native starch that

Table 4
Digestibility properties of native and modified flours and starches from underutilized seeds.

Botanical source	Sample	Starch state	Total starch (%)	Digestibility				References
				RDS *(%)*	*SDS* *(%)*	*RS* *(%)*	*Hydrolysis* *(%)*	
Sorghum seed (*S. bicolor* L.)	Flour	Native	42.7	–	–	–	65.5	(Irondi et al., 2022)
White Sorghum seed *(S. bicolor*)	Flour	Native	72.2	–	–	–	48.0–52.0 (240 min)	(Srichuwong et al., 2017)
	Starch	Native	–	–	–	–	60.0–62.0 (240 min)	
Sorghum seed (Nine varieties)	Starch	Native	–	18.1–36.5	43.0–53.8	10.6–35.5	–	(Xu et al., 2022)
Sorghum seed (M35-1 variety)	Flour (CE)	Modified (Infrared 30% moisture)	–	19.0	51.0	30.0	55.0	(Semwal & Meera, 2021)
Quinoa seed (*Chenopodium quinoa* Wild.)	Flour	Native	58.9	–	–	–	80.0	(Zhang, Hu, et al., 2022)
Quinoa seed	Flour	Native	–	7.3	58.5	2.1	–	(Muñoz-Pabon et al., 2022)
Quinoa seed	Flour	Modified (HMT)	61.6	5.3	18.3	38.0	70.5	(Dong et al., 2021)
Quinoa seed (*Chenopodium quinoa*)	Flour	Native	66.8	–	–	–	>90.0 (120 min)	(Srichuwong et al., 2017)
	Starch	Native	–	–	–	–	90.0 (240 min)	
Mango seed	Flour	Native	48.7	14.5	9.7	75.7	∼32.0 (240.0)	(Patiño-Rodríguez et al., 2021)
Mango seed	Starch	Native		6.3	19.9	73.7	67.0 (175 min)	(Patiño-Rodríguez et al., 2020)
Avocado seed (*P. americana* v. Hass)	Flour	Native	30.2	56.8	32.8	10.3	83.6	(Rivera-González et al., 2019)
	Starch	Native	85.8	75.3	23.9	0.7	93.2	
Avocado seed (*P. americana* Mill.) (Eight cultivars)	Starch	Native	–	6.2–21.6	6.5–28.0	63.8–77.8	–	(Wang et al., 2022)
Avocado seed	Starch	Native	–	–	–	8.0	–	
		Modified (Autoclaving-Cooling)	–	–	–	17.0–27.0	–	(Ismail et al., 2020)
Pouteria campechiana seed	Starch	Native	85.7–99.0	22.8	24.1	53.1	∼65 (250 min)	(Agama-Acevedo et al., 2022; B. Li et al., 2021)
Brosimum alicastrum Sw. *seed*	Starch	Native	92.5	–	–	–	–	(Pérez-Pacheco et al., 2014)

RDS-Rapidly digested starch; SDS -Slowly digested starch; RS-Resistant starch; CE-corneous endosperm; HMT-Heat moisture treatment.

reduce the effectiveness of oxidation modification. However, a decrease in water solubility and an increase in swelling power and amylose content were observed in oxidated-RSS. These effects varied depending on the degree of oxidation. Also, oxidated-RSS presented lower values of paste clarity and greater whiteness (L*) than native starch, but yellow or green tones remained in the modified starch. The oxidation in starch can be used to produce whiter starches with functional properties for industrial applications (Pérez-Pacheco et al., 2014, 2017). On other hand, a thermal pre-treatment (90 °C/ 30 min) of Ramón seed flour was effective for bioethanol production. The treatment modified the protein matrix promoting starch granule release and maintaining granule integrity and its physicochemical properties (Olguin-Maciel et al., 2017). More studies about Ramón seed starch are necessary for a better understanding of different modification methods that can affect the morphological, physicochemical, and/or functional properties and to establish the potential applications.

5. Digestibility of starches from seeds

Starch digestibility is an important characteristic that has been studied *in vitro* digestion models mainly. Englyst et al. (1992) classified starch according to the digestibility rate: starch digested during the first 20 min in the upper part of the small intestine (duodenum) was denominated as Rapidly Digested Starch (RDS), starch digested during the following 20 to 120 min approximately on the middle and distal part of the small intestine (jejunum and ileum) was denominated Slowly Digested Starch (SDS), whilst the starch fraction that is not digested in the small intestine and reaches the colon was denominated Resistant Starch (RS). The total starch content and starch digestibility results obtained in different studies in flour or isolated starch from sorghum, quinoa, mango, avocado, *Pouteria campechiana,* and Ramón seeds (native and modified) are shown in Table 3. The total starch content in the flours obtained from sorghum, quinoa, mango, and avocado seeds was observed between 42.7 and 72.2% (Table 4). In Ramón (*Brosimum alicastrum* Sw.) and *Pouteria campechiana* seed flour, the total starch content has not been reported, but considering an estimated ∼62.2% (calculated from its proximal composition) in Ramón seed flour (Carter, 2015; Pérez-Pacheco et al., 2014) and the total carbohydrate content in *Pouteria campechiana* (39.3%) (Pérez-Barcena, et al., 2021), these seeds underutilized can be considered as a non-conventional alternative source of starch since that yields higher than 30% can be potential alternatives for starch extraction with commercial purposes (Tagliapietra et al., 2021). However, the total starch in Ramón and *Pouteria campechiana* seed flour must be determined experimentally. Starch extraction methods play an important role in yield, however, methods to obtain high yields are not always the most suitable for the study of native starches, since some agents used can cause chemical modifications in the starch structure (Tagliapietra et al., 2021). The starch purity (85.7–99.0%) has been reported in starch from seeds such as avocado, *Pouteria campechiana,* and Ramón. This parameter is an important factor to consider in the starch quality and the application types (Makroo et al., 2021).

The studies indicated that the RDS fraction was in the range of 5.3–36.5% for seed flours and seed starches mentioned in this review, and only a study by Rivera-González et al. (2019) reported high content of RDS in avocado seed flour and starch (Table 4). The lowest RDS rates were observed in HTM-modified quinoa starch (Dong et al., 2021), avocado seed starch (Wang et al., 2022), and mango seed starch (Patiño-

Rodríguez et al., 2020). High RDS fraction has been associated with a higher rate of glucose absorption, thus higher glycemic response that eventually can lead to insulin resistance, diabetes, and other metabolic complications (Cornejo et al., 2022; Hasek et al., 2020; Trinh & Le, 2022). The microstructure of starch is a factor that modulates its digestibility. Non-starch polysaccharides such as gums, proteins, and/or lipids in flours can form barriers around starch granules that limit the action of digestive enzymes (Tian et al., 2019). On other hand, the SDS fraction was in the range of 6.5–58.5%, where starch from quinoa and sorghum seed flour showed the highest values. Studies on the SDS fraction of starch have stated that the slow, controlled and prolonged glucose release on the jejunum and ileum is related to health benefits like glucose metabolism homeostasis, a decrease of postprandial insulinemia, beneficial for diabetes monitoring (Huang et al., 2018). SDS has proven to have a positive impact on satiety via stimuli of incretin hormones secretion like glucagon-like peptide 1 (GLP-1), and YY peptide (PYY) that induce a response mechanism that controls intestinal transit time (ileal brake), decreasing gastric emptying rate and promoting longer periods of satiety (Chegeni et al., 2022; Hasek et al., 2020; Zhang et al., 2015). The resistant starch fraction (RS) was observed in the range of 0.7 to 77.8% with the highest values reported for avocado seed starch (Wang et al., 2022), mango (Patiño-Rodríguez et al., 2020, 2021, and *Pouteria campechiana* (Agama-Acevedo et al., 2022). RS is the most studied fraction of starch as much focus has been to produce RS through different methods (genetic, chemical, and physical), due to studies showing that RS fermentation in the colon promotes the production of short-chain fatty acids (SCFA), mainly butyric acid contributing to preventing colon cancer cells development. There is growing interest in research to increase the RS in foods promoting a lower digestibility of starch, and the prevention of colon cancer, among others (Bello-Pérez et al., 2020; Li, 2018; Zhong et al., 2019, 2022). Starches with high fractions of SDS and/or RS can be an alternative to be incorporated as an ingredient in the development of healthy foods. RS-rich diet can contribute to maintaining the health of the intestinal microbiota, which has been proposed as a key factor in the prevention and treatment of some metabolic diseases (Magallanes-Cruz et al., 2017). However, the starch digestibility of these seeds has been little studied (e.g., *Brosimum alicastrum* Sw. seed starch, no report was identified), so far and more studies are necessary for a better understanding of this property and its potential applications, particularly in the development of starch-based foods.

6. Future scope

Starch is one biomolecule with wide applications at a commercial and industrial level. One of the main applications of starch is as an ingredient in food products such as sauces, mayonnaise, jam, ice cream, candies, puddings, fruit fillings canned meat and vegetables, yogurts, and prebiotics, among other. Also, starch is used for non-food applications such as adhesive, aerogel, films, bio-plastic or edible coatings, among others, in the pharmaceutical, chemistry, cosmetic or textile industries (Makroo et al., 2021). Conventional sources of starch such as corn, wheat, or potato may be replaced by other alternative sources of starch. There are many underutilized or non-conventional sources of starch, including seeds (Tagliapietra et al., 2021). However, further studies with detailed analyzes of the characteristics, functional properties, and digestibility of the starch (flour and isolated starch) obtained from underutilized seeds should be carried out to establish their potential and best applications, as well as the most effective types of modification for a specific purpose. In this review, seed starches such as ASS, MSS, PCSS, and RSS need to be fully characterized as native starch and study the impact of different modifications to improve their properties and broaden their potential uses. The use of these underutilized seeds or by-products, as a source of starch, would help to reduce their environmental impact and satisfy the current industrial demand for starch, freeing up other conventional sources of starch.

7. Conclusions

Characteristics and functional properties of non-conventional starches obtained from underutilized seeds were reviewed. Yield and purity of starch obtained from seeds of *Sorghum bicolor* L. Moench (WSS), *Chenopodium quinoa*, Wild. (QSS), *Mangifera indica* L. (MSS), *Persea americana* Mill, *Pouteria campechiana* (Kunth) Baehni (PCSS), and *Brosimum alicastrum* Sw. (RSS) showed that these seeds represent a good starch source with potential technological applications. Functional properties analysis of the native seed starches revealed that ASS and RSS showed higher values in WAC and SP properties, while MSS and PCSS had lower values. In pasting properties MSS, WSS, PCSS, and RSS showed high stability gel and low retrogradation tendency. These native seed starches have the potential for different applications in starch-based products as thickening agents, frozen foods, and improvement of shelf life preventing staling in bread. Nevertheless, native starches present limitations and susceptibility to thermal treatments. Different modifications carried out in starches of these seeds favored some of their properties. Chemical modifications such as oxidation treatment increased water solubility and swelling power in RSS and cross-linking treatment improved the thermal stability of ASS, while dual modification (oxidation-cross-linking) increased water solubility, and thermal resistance and reduced the retrogradation tendency of WSS, OSA, DDSA, and NSA treatments and in QSS increased the oil absorption capacity and the stability of emulsions. Physical treatments such as HMT, and dry-heat (RDHT and CDHT) improved the water solubility, pasting properties, and thermal stability in WSS, QSS, and MSS, while also less tendency to retrogradation was presented by HMT-WSS. Enzymatic treatment increased the relative crystallinity of QSS. Some potential applications have been identified for these modified seed starches until the moment, WSS in food processing such as confectionery, canned goods, bakery products, soups and creams, sauces and dressings, and non-food products such as biodegradable films. QSS may use as an ingredient in sauces, dressing, baby food, and Pickering emulsions, while MSS can be applied in noodles and pasta formulations, ASS in cream soups, and RSS as thickening. Also, *in vitro* digestibility tests have indicated that native starches such as WSS and QSS present high fractions of slow digestion starch (SDS), while ASS, MSS, and PCSS of resistant starch (RS) and QSS modified by HMT increase the RS fraction. According to these characteristics, these seed starches may be interesting for their potential application in the development of healthier foods and for special nutritional treatments.

CRediT authorship contribution statement

Perla A. Magallanes-Cruz: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Luisa F. Duque-Buitrago:** Formal analysis, Investigation, Writing – original draft. **Nina del Rocío Martínez-Ruiz:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Project administration, Funding acquisition.

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.

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