**Title: Functional clean-label starch: Sustainable production technologies and food applications**

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**Abstract**

Starch, the major source of carbohydrate and energy in our daily food has been modified by chemical additives for decades in the food industry particularly due to high demand of starch-based food products. But recently there is a boost to the “Clean-label” tag among the health-conscious consumer community. The term clean label starch invariably means starch with least processing, additive free and understandable ingredient list. This movement has inclined the research community towards finding native and underutilized sources of starch. But the major problem is that these native sources are not industrially suitable for food manufacturing and has certain limitations. In this scenario, physical and enzymatic modification of starch plays an important role. Starch modified by above two methods are simply considered as “starch” without any E-numbers. This study also focuses on the use of starch in the food sector, including the microencapsulation of active substances such as nutraceuticals, vitamins, tastes, minerals, and even fertilisers for controlled release and targeted delivery. It is also utilised to make biodegradable and nano-composite films for packaging, as well as starch-protein-lipid complexes for decreased starch digestibility. It is worth noting that starches may be utilised in small amounts alongside protein to create plant-based alternatives to meat. The biocompatibility, biodegradability, low cost, and broad availability of starch make them ideal for all these uses.

**Keywords:**Functional clean-label starch; starch sources; physical and enzymatic modifications; functional properties; food applications; consumer acceptability

**Introduction**

Starch is the most important source of carbohydrates in the human diet. Commercially, starch is available as a white powder. It consists of two polymers-amylose and amylopectin. Amylose is a linear polysaccharide composed of D-glucose units joined by the α-1,4-glycosidic linkages in a helical structure and consist of 10%–30% of natural starch. The characteristic blue-violet colour that appears when starch is treated with iodine is due to the formation of the amylose-iodine complex. Amylopectin is a branched-chain polysaccharide composed of D-glucose units linked primarily by α-1,4-glycosidic bonds but with occasional α-1,6-glycosidic bonds and consist 70%–90% of natural starch. Starch is used extensively in the food business as a viscosity/freeze-thaw agent, emulsifying stabiliser in addition to its nutritional benefits. It has a variety of physical qualities dependent on its composition (for example, swelling, gelatinization, and gelation). But the thermal and shear instability of native starches, as well as their propensity to retrograde after chilling or freezing, limits their use in industrial applications and lowers the quality of food products. Chemical modification is done mostly to counteract the limitations.

But recently, “clean label food” has emerged as a global food trend. It is a consumer driven movement that calls for a return to true food by demanding food containing natural, familiar, and simple ingredients that are easy to recognize, understand and free from synthetic chemicals. Clean label starch refers to a type of starch that undergoes minimal processing to retain its functional properties and is free from chemical modifications, artificial additives, chemicals, and preservatives. Clean label can be achieved by using non-conventional and underutilized starch resources, Physical and enzymatic modification, Nano encapsulation, Nano-sized starch, starch-protein and starch-lipid complexes etc.

Non-conventional and underutilized starch resources include various fruit seed, grains, normally overlooked and discarded plant parts (banana peel, cassava stem), rhizomes, bamboo shoots, bulbs etc. Exploring non-conventional and underutilized starch resources in clean label starch offer opportunities for diversification, sustainability, and innovation in the clean label starch industry, promotes biodiversity, and supports sustainable agricultural practices. Physical and enzymatic modifications offer clean label alternatives to chemically modified starches, as they utilize natural processes and enzymes. These modifications can improve the functionality, stability, texture, and digestibility of starch, thereby enhancing its performance in various food applications. The use of nano-sized starch in clean label starch formulations can provide functional advantages, such as improved texture, reduced staling, enhanced mouthfeel, and increased bioavailability. In nano encapsulation, proteins, polysaccharides or lipids form a matrix around the target substance (flavours, nutrients, bioactive compounds) providing stability, improved solubility, controlled release, and protection against environmental factors. Consumer acceptability and market suitability are to be considered closely before introduction of clean label starch prepared through any of the abovementioned approaches.

**Non-conventional and underutilized starch sources: Identification, selection,** **extraction, and characterization**

The major starch-producing crops include maize, potato, cassava, and wheat. These starches of great economic significance dominate the current markets and have diverse applications in different areas. So, the underutilized, unconventional, and minor starches refer to those starches apart from maize, potato, cassava root, and wheat. (Zhu Fen,2020)

1. Fruits seeds:
2. jackfruit
3. mango
4. avocado
5. litchi
6. banana
7. Millets
8. Pseudo-cereals:

a) Quinoa

b) Amaranth

c) Buckwheat sago palm (*Metroxylon sagu*)

1. Bamboo (*Dendrocalamus asper*)
2. Legumes: Lentils, beans, and peas
3. Rhizomes:

a) Lotus rhizome

b) Turmeric

c) Ginger

1. cassava stem
2. Lily bulb and bulbils

**1.Fruit seeds:**

**a) Jackfruit** *(Artocarpus heterophyllus Lam.)*

Since it is widely cultivated throughout Asia, the Americas, and the Caribbean with low input costs, jackfruit offers potential as a source of commercially available starches. Jackfruit starch is a cheap and sustainable source of carbohydrates because it is the main component of jackfruit seeds (60–80%, dry matter basis), which make up 8–15% of the weight of the fruit. Due to the versatility of crop planting and harvesting, jackfruit trees can be grown in marginal and poor soils, and they are available all year long. In tropical and subtropical areas, jackfruit has emerged as the fruit tree with the fastest rate of growth and the most widespread distribution due to its low labour and environmental requirements. (Swami, Thakor, Haldankar & Kalse, 2012).

According to Anaya-Esparza et al. (2018), jackfruit seeds can be boiled, roasted, or preserved in syrup like chestnuts because they are high in starch (60–80% depending on the dry matter), protein, vitamins, and minerals. Cooked foods use jackfruit seeds, and baked goods use fruit flour. Additionally, a lot of people eat the seeds as a dessert or as an ingredient in Asian dishes (Tan et al., 2013, 2014; Zhang, Chu, et al., 2013). However, the seed is eliminated as a waste component during the manufacturing of jackfruit flesh.

**Extraction and characterisation-**

The extraction methods for jackfruit starch mainly comprised of the wet-grinding method (Hu et al., 2016; Luciano, Franco, Valencia, Sobral, & Moraes, 2017; Noor et al., 2014; Tulyathan, Tananuwong, Songjinda, & Jaiboon, 2002), the alkaline method (Dutta, Paul, Kalita, & Mahanta, 2011; Luciano et al., 2017; Noor et al., 2014; Rengsutthi & Charoenrein, 2011; Zhang et al., 2016, 2018b), and the enzyme method (Chu et al., 2016; Noor et al., 2014), in which starch is treated with water, alkali reagent, and enzyme. The extraction methods have been reported to lead to different starch extraction ratios even for the same jackfruit variety. The jackfruit starch (M1 variety) extraction yields have been reported as 18.92%, 63.82–64.46%, 43.57–66.68% and 70.55% for the wet-grinding, the alkaline, the enzyme and the surfactant, respectively (Hu et al., 2016).



**Table 1: Jackfruit starch extraction methods**

It is important to carefully evaluate a good isolation approach in terms of its ease of use, cost, environmental friendliness, and extensibility. When the same jackfruit sample is extracted using various ways, each method reveals its own unique characteristics depending on the isolation procedure. The jackfruit starch extracted by the alkali approach had smaller particle size than that of the wet-grinding and enzyme methods. However, compared to the enzyme and alkali methods, the wet-grinding method's jackfruit starch showed greater solubility and swelling power (Hu et al., 2016).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Principle | Techniques | Modification | Results of modification | References |
| Enzyme modification | f-amylase modification | 8% of p-amylase (91,500 U/g), pH 5.5, temperature 50-60 °C | Obtained maltose syrup with yellow color, good flavor, transparent and viscous liquid. | *Zhang et al. (2011*) |
| Physical modification | Improved extrusion cooking technology of jackfruit starch | High barrel temperature (90-110 °C), pressure Improved digestion properties (120Mpa), shear forces and low screw speed (20-30 rpm) | Improved digestion properties | *Zhang et al. (2019)* |
| Physical modification | Hydrothermal treatment | Temperature (70 °C) for 20, 30, or 60 min, make starch partially gelatinize | High water holding capacity. | *Tran et al. (2015)* |
| Physical modification | Hydrothermal treatment | Temperature (80 °C) for 15 min. | Insoluble or partially soluble in water at room temperature. Obvious fracture of the granules. Low crystallinity. High gelatinization temperature and low enthalpy | *Kittipongpatana and Kittipongpatana (2011)* |
| Physical modification | Heat moisture treatment | 20-23% of moisture contents and temperature  80-120°C for 6-16 h (between the glass transition and the gelatinization temperatures) | Increased the resistant starch content. | *Kittipongpatana and Kittipongpatana (2015)* |

**Table 2: Modifications of jackfruit starch**

**b) Mango** *(Mangifera indica)*

Due to its nutritional profile and phytochemical content, mango fruit has earned the moniker "King of Fruits" and is bundled with a variety of health benefits. Depending on the mango variety, the amount of the edible section that can be used for processing and eating ranges from 33 to 85% of the fresh weight. The two processing wastes are peels and kernels.

As the major constituent of the mango kernel is starch (58–80%), it can be used to extract starch for multiple applications both in food (stabilizers, thickeners, gels, edible coatings, encapsulating agent) and non-food industries (paper, textiles and cosmetics).

**Extraction-**

Depending on the source of the starch, particularly the neutral, alkaline, or acidic steeping condition, there are many different ways to isolate starch. To achieve high starch recoveries, sodium bisulfite solution is most frequently used to extract the starch from mango kernels. For the extraction of starch over the course of 24 hours, a 0.5% sodium bisulfite solution was used, 2:1 solution to kernel (v/w). To obtain pure starch, the following processes were added to the process: centrifugation, sifting, decanting, and precipitation. The approach was successful in recovering up to 50% of the starch (Ferreira et al). Previously, Tesfaye et al extracted MSS using sodium bisulfite solution, achieving maximum yield at 2.46 hours and 26.74 degrees Celsius.

**Characterisation-**

With granule sizes of 10-13 m and an amylose concentration of 21-33%, mature mango seed starch (MSS) had an oval to disk/elliptical-like structure [**2-4**]. A-type starch was seen in the MSS X-ray diffraction (XRD) pattern. When extracted using the alkali process, MSS revealed lower values for ash, protein, and lipids, demonstrating its excellent purity [**5**]. Digestibility results from numerous studies revealed that MSS contains more resistant starch (RS; roughly 70–75%) than slowly digestible starch (SDS) and readily digestible starch (RDS) [**6**]. The starch from unripe mango kernels exhibited good gelatinization capabilities comparable to those of maize starch with a lesser tendency for amylopectin retrogradation.

**c)Avocado** *(Persea americana mill)*

Avocado is a high-energy, low-sugar fruit containing tocopherols [**8**], plant sterols, dietary fibre, and folic acid [1] etc. Although many fruits have a sweet or acidic flavour, avocado has a buttery consistency, a distinct smooth flavour, and is a popular fruit.

Avocados are used in a variety of products in the food, cosmetics, and pharmaceutical industries and their processing involves removal of the avocado fruit's seeds, which make up around 16% of the dry fruit's weight, results in a large quantity of waste [**9**].

**Extraction-**

Avocado seeds were weighed, dehulled, and then immediately submerged in sodium bisulfite solution (0.5%, w/w) for 20 minutes. After adding about 20 g of the material, the fragments were transferred to a beater and smashed into slurry with two times as much distilled water as raw seeds. A dual-enzyme solution (pectinase/cellulase = 1:2, w/w) was then added to allow hydrolysis to occur for 1 h at pH 5.0 and 45 C. A total of 0.22% of the weight of the avocado seed in enzyme was added. The seed slurry was then passed through a filter with a 120-mesh opening, and the filtrate was spun at 3000 rpm for 15 minutes. The collected sediment was immersed in sodium hydroxide solution (0.3%, w/w), magnetically stirred, for 10 minutes and then centrifuged. The precipitate was dried and kept in a desiccator for later use after being periodically rinsed with sufficient distilled water until the pH was neutral. (Wang et al, 2022)

**Characterisation-**

Avocado seed starch has A- type crystallinity and interestingly, the RS fractions of these avocado seed starches ranged from 63 to 78%, which was much higher than that of most uncooked native starches. This study provides valuable information on projecting the possibility of making use of avocado seeds (a food waste) for the commercial production of RS and latent related food products. (Wang et al, 2022)

**d) Litchi** *(Litchi chinensis Sonn.)*

Litchi seeds are the major by-product of litchi processing. They are normally discarded as waste in litchi fruit consumption. Recently it has been found that litchi seeds are rich in bioactive compounds, including polysaccharides [**12**], polyphenols [**12**], proanthocyanidins [**14**], etc. and have multiple bioactivities, including anti-diabetic effects [**12**], inhibition of α-glucosidase activities [**14**], antioxidant and anti-tyrosinase activities [**15,16**], etc. Litchi seeds are also an abundant source of starch, containing about 52.8% (dry weight of seeds) of starch [**17**].

**Extraction-**

The method outlined by Wang et al. was used to isolate starch from litchi seeds. Crushed litchi seeds were steeped in sodium metabisulfite solution (0.45%, w/v) for an entire night. The combination was then homogenised into a slurry and then passed through a sieve with 106 µm. holes.

The residues were once again homogenised with sodium metabisulfite solution, until there was no longer any residue on the sieve. The filtrate was mixed, and proteins and lipids were eliminated using a 9:1 solution of sodium chloride (NaCl, 0.1 M) and toluene. The mixture was left undisturbed until the upper toluene layer and NaCl layer could be easily separated after 1.5 hours of continuous stirring. Until the toluene layer was completely clean, this procedure was repeated. The starch sample that had precipitated at the bottom was taken out and cleaned with ethanol and water before being dried at 40 ◦C.

**Characterisation-**

The findings of Zhang. et al, 2022 indicated that litchi seed starches were primarily round to oval in shape with smooth surfaces, and no obvious changes were identified among types, indicating that these are typical characteristics for litchi seed starch. All of the types displayed typical bimodal granule size distribution patterns, showing that litchi seed starches are made up of both tiny and large granules with sizes ranging from 40 to 110 m, respectively. The D50 and relative proportions of the small and large particles varied significantly between types.

All of the starches had an A-type crystalline structure, however the relative crystallinity appeared to vary with variety. Huaizhi had the lowest crystallinity (only 20.67%), whereas Guiwei had the greatest (26.76%). Additionally, the semi-crystalline structure was varied.Only little changes in molecular structure existed between the CLDs of different varieties of litchi.

In terms of thermal characteristics, Huaizhi displayed noticeably higher gelatinization temperatures and a lower ∆H than the others, although Guiwei had the greatest ∆H. The digesting characteristics of gelatinized starch samples indicate relatively minor variations among varieties, and it does not appear to be related to variety. These findings would help to clarify the properties of litchi seed starches and offer recommendations for its application as a novel source of starch in a variety of sectors,

* + 1. **Banana** *(Musa × paradisiaca)*

Based on their genomic synthesis, palatable bananas are classified into 3 types: diploid (AA and AB), triploid (AAA, AAB, and ABB), or tetraploid (AAAA, AAAB, and AABB). Nonetheless, most pertinent bananas are triploid and are obtained from the wild species Musa acuminata (A) and Musa balbisiana [**19**,**21**]. Generally, dessert banana cultivars are AA or AAA and cooking bananas (plantains) are prevalently AAB, ABB, or BBB.

Starch can be found in abundance in mature green bananas. On a dry weight basis, the green banana pulp contains up to 70–80% starch [**21].**

**Extraction-**

Due to minute contaminants, a wet milling procedure is effective for isolating banana starch [**24**]. Alkaline [**23,24**] and non-alkaline extraction are two methods for starch isolation that have been documented.

**Characterisation-**

Banana cultivars and ripening phases were found to be the main determinants of yield by Zhang et al. [4]. Banana starch had an extraction yield of 5.78-12.73% and a total starch content of 74.9-84.0%, according to Chávez-Salazar et al. [**25**]. Although the starch mostly consists of carbs, it also contains other substances as ash, lipids, and proteins [**26,27**].

Banana starches present a B-type crystallinity pattern, with slight difference in the crystallinity level. The resistant starch (RS) fraction was the main fraction in the uncooked banana starches. Banana starch cooked samples presented an important amount of SDS and RS. Molecular weight and gyration radius of the four banana starches ranged between 2.88–3.14 × 108 g/mol and 286–302 nm, respectively. The chain-length distributions of banana amylopectin showed that B1 chains (DP 13–24) is the main fraction, and an important number of long chains (DP ≥ 37) are present [**28**].

1. **Millet**

Millets contain between 51% and 79% starch, like other grains. Pearl and finger millets, respectively, have starch contents that vary from 71 to 81 percent and 51 to 69 percent. Typically, the amylopectin and amylose content of millet starches ranges from 20 to 30 percent and 70 to 80 percent, respectively. Starch granules operate very differently when additional elements are added as impurities. Polar phospholipids make up 89% of the composition of millet starch, with nonpolar lipids, principally triglycerides, making up the remaining 16%. These lipids interact with the amylose component of starch to generate complexes that are cohesive and hydrophobic, which may affect the flowability and swelling of the starch.

**Extraction-**

The five small millets, viz., prosomillet (Panicum miliaceum) var CO3, foxtail millet (Setaria italica) var TNAU83, barnyard millet (Echinochloa frumentacea) var K2, kodo millet (Paspalum scrobiculatum) var APK1 and little millet (Panicum miliare) var IPM1164 seeds were obtained from Millet Breeding Station, Tamil Nadu Agricultural University, Coimbatore – 641 003, India. The whole grains of minor millets were used without any polishing and were powdered (80 mesh) using a waring blendor. 50mg of powdered sample were wetted with 2 drops of ethanol and then treated with 5 ml of 1N NaOH at room temperature overnight. The amylose content was estimated based on the intensity of the blue colored complex developed with iodine at neutral pH [**29**].

Then by using the Adkins & Greenwood method [**30**], starch was extracted. To soften the grain and block amylases, it was steeped for 30 hours at 6 °C in 0.2 M acetate buffer (pH 6.5) containing 0.01 M mercuric chloride. The softened grains were then processed via a Waring blendor, slurried in water, then sieved swiftly and sequentially through 80 mesh screens. Until the material remaining on the sieve was free of starch, grinding, slurrying, and sieving were repeated. Shaking the aqueous solution with 1/8 of its volume of toluene, which causes the protein to become denaturized at the water/toluene interface, eliminated the contaminating proteinaceous material from the starch suspension without altering the starch.

**Characterisation-**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Source strach | Modified/native starch | Characteristics | Application | Reference |
| Finger millets | Oxidized and acetylated | In the instance of modified starch compacts, the reduction in disintegration deformability and time is offset by an increase in tensile and crushing strength | Formation of a  tablet and capsule | *Afolabi et al .( 2012)* |
| Pearl millet | Octenyl succinylate | Structural strength and high viscosity | Replacer of fat in low fat ice-creams | *Sharma et al.(2017)* |
| Teff millets | Native | Prevents lipid oxidation, has a strong mechanical and water barrier qualities and has a high radical scavenging action. | Camucamu extract-based antioxidant packaging material | *Ju et al. 2019* |
| Barnyard millets | Native | Solubility in water, water vapour and moisture levels permeability have all decreased, light barrier and antioxidant abilities. | Edible Starch films having oil of borage seed | *Cao et al. 2017* |

**Table 3: Characteristics and Application of millet starch**

**3. Pseudo-cereals:** Pseudo cereals are broadleaf plants considered as the important energy sources due to their starch content.

**a) Quinoa (***Chenopodium quinoa***)**

Quinoa is a pseudocereal native to South America and has been cultivated there for centuries. Quinoa seed structure is significantly different from cereals as the germ (circular) surrounds the starch-rich perisperm and represents the bran fraction together with the seed coat, which is relatively rich in fat and protein [**31**].

**Extraction and characterisation-**

Quinoa starch is extracted either by water steeping and alkaline steeping the grains [**32**]. Alkaline steeping resulted in higher yield than water steeping with quinoa flour showing higher yield, color value and lower residual protein for both steeping methods. Quinoa starch is slightly darker in colour than corn starch and has lower amylose content (12.10%) [**32**].

**b) Amaranth**

Amaranth grains are milled and sieved for preparation of flour and the extraction process still has not been standardized. There are mainly two distinctions found between amaranth starch and cereal starch. Firstly, the primary source of carbohydrates in amaranth is starch, but it is often present in less levels than in cereals. Secondly, amaranth starch is not found in the endosperm but rather in the perisperm [**33**].

**c) Buckwheat sago palm** (*Metroxylon sagu*)

It is native to Southeast Asia and significantly reduces CO2 emissions. Sago palms build up a lot of starch in their trunks until flowering. The amylose concentration in sago starch is comparable to that of regular maize/potato starches. Sago starch has been changed using a number of methods, including physical modification, graft copolymerization, cross-linking, and substitution. Sago starch has been studied for a variety of purposes, including the manufacture of nanoparticles and nanofibers, pharmaceutical and medical uses, lactic acid and pullulanase, as well as food. Sago palms produce a lot of starch (Ehara et al., 2018; Singhal et al., 2008). The palm typically matures in 8 to 12 years, at which point it can be harvested for its starch (Ehara et al., 2018). A sago palm tree may have up to 400 kg or more of dry starch inside of it. The production of sago starch can reach up to 25 MT/ha, which is more than 10 times higher than that of rice and wheat.

**Extraction and characterisation**-

Traditionally, the stem is split lengthwise, the pith is taken out and starch is released by crushing and kneading the pith. The starch is then rinsed off the fibrous residue and filtered to remove it. The raw starch suspension is subsequently gathered in a settling container. Improvement of starch recovery can be achieved using various pre-treatment techniques like ultrasonic, microwave and enzymatic pre-treatments [**34**].

Sago starch has C-type polymorphs, which may be similar to some cassava starches (some cassava starches may have A-type polymorphs due to the influence of growing conditions) [**35**].

**4. Bamboo** *(Dendrocalamus asper)*

The fresh young bamboo culm of *Dendrocalamus asper* is a promising raw material for industrial production due to its high starch (more than 10%) content. This species of bamboo is asexual and perennial, making it an ideal choice for sustainable production. It requires little to no pesticides, unlike other major crops such as wheat, and can last for over 100 years with proper maintenance and harvesting. The high starch content of *Dendrocalamus asper* makes it a suitable candidate for industrial production and a great option for sustainable development.[**36**]

**Extraction–**

Young bamboo culms of varieties ***Dendrocalamus asper***, *B. tuldoides and B. vulgaris* were carefully harvested at the experimental field from FEAGRI/UNICAMP in Campinas, Brazil, at coordinates 22º82’ south latitude and 47º07’ west longitude. Special attention was paid to the age of the culms, with only those of approximately 36 months being collected. All the culms were then cut, the bottom fraction (“bottom - B”) was taken first, followed by the middle fraction (“middle - M”) after discarding 30 cm from the soil. Lastly, the top fraction (“top - T”) was taken after discarding the next 30 cm. To ensure that all culms were cut into three equal parts, the height of the culms from each variety was taken into account. All samples were then discarded from the bottom 30 cm. The young bamboo culms were cut, treated and dried. After drying, the material was passed through a hammer mill to reduce the size of the pieces. Subsequently, a knife mill was used to obtain the flours. The obtained flours were sieved to ensure uniform particle size (Felisberto, Beraldo, and Clerici ,2017)

**Characterisation**-

The young bamboo culms contained a significant amount of starch inside the cellular parenchyma in the culm wall, which was reported to be 16% by Felisberto et al. (2017). This starch is also a by-product from the production of bamboo fibers. The starch has a polyhedral shape with a mean diameter of 5.4 μm, and is classified as an A-type polymorph, with a significant amount of short unit chains in the amylopectin. The amylose content of the starch was similar to that of other starch-producing plants such as potatoes, maize and grains. In addition, the starch of bamboo culms had a lower amylose to amylopectin ratio than other plants. This indicates that bamboo culms starch may have potential applications in the food and paper industries [**36,37**].

**5. Legumes:**

As reported by Hoover and Sosulki (1985), starch isolation from legumes is difficult because of the insoluble flocculent protein and and fibre, which decreases sedimentation and co-settles with the starch to form a brownish deposit. The main processes of isolating starch from legumes are steeping, washing, blending, screening, centrifugation or sedimentation, and drying [**38**].

**Extraction-**

Starch can be extracted from legume in broadly two methods. Dry milling process is suitable for laboratory purpose and wet milling is suitable for industrial purpose.

According to Abu et al. [**39**], the wet milling method generally entails soaking dehulled seeds in distilled water that may or may not contain sodium chloride in order to remove salt-soluble proteins. Numerous studies have suggested adding a modest amount of sodium metabisulphite to the soaking water to prevent potential browning as well as weakening of the protein network [**40, 41**]. After the washed seeds have been homogenised, the homogenate is filtered. Sodium hydroxide solution, whose strength might vary, is often used to treat filtered sediment [**41-43**]. To dissolve the protein impurities, the treatment with 0.1–1.0 M sodium hydroxide is frequently repeated several times [**39,41,43,44**]. This is followed by the treatment with hydrochloric acid and sediment recovery which is then dried, ground, and sieved to produce starch with a higher degree of purity.

For the extraction of starch from beans [**45,46**], Lablab purpureus [**47**], lentil [**48,49**], cowpea, pigeon pea, and yam bean [**50**], wet milling has been employed in several investigations.

**Characterisation-**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Starch source | Yield (%) | Moisture (%) | Lipid (%) | Amylose (%) |
| Kidney bean | 25.00-45.00 | 10.88-11.00 | 0.10 | 42.96-49.28 |
| Green gram | 31.10 | 10.63-11.96 | 0.10-0.32 | 34.47-45.30 |
| Smooth pea | 32.90 | 3.12 | 0.04 | 22.00-27.90 |
| Black bean | 16.40-22.20 | 16.00 | 0.20-0.50 | 27.20-39.30 |
| Lentil | 27.40 | 8.90-9.40 | 0.09-0.40 | 22.10-33.90 |
| Navy beans | 24-25 | 16.00 | 0.09-0.60 | 28.60-41.40 |
| Chick pea | 29.10-46.00 | 8.78-11.45 | 0.29-0.50 | 23.00-33.81 |

**Table 4: Yield and composition of legume starches [51]**

**6. Rhizomes:**

1. **Lotus** *(Nelumbo nucifera Gaertn.)*

**Extraction -**

Following the procedure outlined in the literature (Man et al. 2012), native starch granules were extracted. All rhizomes were quickly cleaned, buffed, and peeled. The rhizomes were peeled, then chopped into small pieces and blended with water in a home blender. The filtrate was collected in a 500 mL glass beaker after the slurry had been filtered through gauze to collect the residue. Gauze residue was washed three times in distilled water to help starch granules come free from the fibres. The residue was then thrown away. With three different mesh sizes—100, 200, and 300—the pooled extract was filtered. The filtrate beakers were left alone so that the starch may settle naturally. The sedimentation was transferred into a 50-mL tube after the supernatant liquid was decanted and centrifuged for 10 minutes at 1500 rpm. The packed white starch granule pellet was delicately scraped off the top of the yellow gel-like layer and thrown away. Up until there was no more unclean material, the centrifugation separation process was done numerous times. The starches were then transferred to clean filter paper and allowed to air dry.

**Characterisation-**

Although many varieties are being cultivated, lotus rhizome can be divided into two categories according to its quality. The main features of the first category include its crispiness due to high water content, low starch, high sugar, and low crude fibre content [**52**]. These characteristics often result in precipitation of starch, gelatinization, and low viscosity during product processing, which leads to crispiness and refreshing taste of good sensory quality. The second type of the lotus rhizome is characterized by high starch, and low water content. High content of starch makes its texture soft, gives it a ductile slip, and increases the viscosity of the products (Wattebled et al. 2002). All A, B and C -type crystalline have been reported for lotus rhizome starch [**52**].

1. **Turmeric *(****Curcuma longa***)**

**Extraction and characterisation-**

Fresh turmeric rhizomes were taken out and sliced into little pieces. The cut pieces were submerged in water for around 12 hours. The material was then removed from the solution, ground into a fine paste, and made into a thin slurry. Slurry should be run through two layers of muslin fabric. The supernatant layer was decanted, and the material was left to settle for one further hour or so. Turmeric starch was centrifuged twice with water to remove contaminants. In order to get rid of the colour matter in starch, soxhelation with methanol is used. The gathered starch was dried in a 400°C oven [**53**]. The starch obtained was very pure. Turmeric contains 20.8% starch.

1. **Ginger**

**Extraction -**

A paste was made using fresh ginger rhizomes, sodium meta-bi-sulphate and required quantity of water. This paste was dissolved in 100ml of distilled water with (1% of 1g) sodium metabisulfite and then filtered. To remove dirt particles and facilitate the formation of a clear supernant, the suspension was centrifuged at 3500 rpm for 10 minutes. It was then decanted, and the mucilage was then scraped off. To obtain the fine extraction of ginger starch, the subsequent centrifugation procedure is carried out four times while maintaining the same rpm and duration. After obtaining the fine starch, it was further baked at 60 degrees in a hot air oven before being weighed and stored [**54**].

**Characterisation-**

Starch content of ginger flour was 82%. It had low values for in vitro starch digestibility (45%), dietary fibre (7.36%) and sugars (2.2%). The blue value of ginger starch was found to be 0.1748 g/dL. The shapes of the granules were disc-shaped as well as ovoid and average granule size was 22.5 3.5 m in length and 16.9-4.8 m in width with a thickness of about 3 m. Ginger starch has a high degree of association between the starch components that maintained the granular matrix. The relatively high gelatinization temperature of ginger starch associated with its resistance to mechanical shear upon gelatinization resembles those starches modified by cross-linking. It can be used as a satisfactory texture agent for foods manufactured at high temperature, or a stabilizing agent for sterilized products such as infant foods and UHT products [**55**]

**7. Cassava stem**

Most commonly cassava root is used for starch extraction. But recent studies have shown that cassava stem, which is normally discarded as a waste product, can also be used to obtain starch.

**Extraction-**

The protocol of starch extraction was from Hedman et al. 18. The milled samples (500 g for stem) were washed 19 in 5 L de-ionized water at room temperature, and stirred manually for approximately 1 min before it was strained through polyester wire net with 120 Mesh. The material left in the container was rinsed and the remaining water was pressed out. The residue remaining on the net was repeatedly washed once more by the same process. The filtrate was left to settle until a firm sediment layer was deposited and the supernatant became transparent. The supernatant was decanted carefully and suction filtration was applied to separate the sediment from the remaining supernatant. The sediment was then collected, dried for 96 h, pooled, and sealed in plastic [**56**].

**Characterisation-**

The mean of granule sizes of cassava stems ranged from 5.65 to 7.64 mm, depending on the environment and position along stems, but not on genotypes. Stem starch has a similar granule shape, X-ray diffraction pattern, crystallinity, and amylose content (20.8% of starch basis) to root starch, but a significantly smaller granule size with narrower distribution range and higher pasting temperature. In addition, the simple water extraction process managed to yield a 66% crude starch from cassava stems [**56**].

**8. Lily bulb**

Starch is the main component of lily bulbs which accounts for 53–69% of their dry weight [**57**]. Bulbs and bulbils are underground and aboveground starch storage organs of *L. lancifolium* respectively.

**Extraction-**

L. lancifolium bulbs and bulbils were isolated from their starches using a modified version of the procedure reported by Berski et al. [**58**]. After being divided into bits, the bulbs and bulbils were thoroughly pulverised in a mortar. The ground samples were successively run through wire screens with mesh sizes of 100, 200, and 400 after being filtered through four layers of gauze. The coloured supernatant from the centrifugation of the samples at 5000 rpm for five minutes was discarded. To get rid of the protein impurities, the starches were collected, resuspended in a 0.05 M NaOH solution, and centrifuged at 5000 rpm for five minutes.The supernatant was cleared after four or five repetitions of this process. Finally, twice-distilled water (ddH2O) was used to wash the starch samples and then oven-dried at 40°C for 48 h [**59**].

**Characterisation-**

The amylose content, granule size, shape, and surface morphologies of bulb and bulbil starches varied, as well as their amylose concentration. Bulb starch exhibited a comparatively greater level of crystallinity as compared to bulbil starch. Similar to bulbil starch, bulb starch has an organised structure in the area of the exterior granules. The solubility, onset temperature, and gelatinization enthalpy of bulb starch were also noticeably greater than those of bulbil starch. Bulb starch shown greater resilience to enzymolysis but had more acidolysis than bulbil starch when it was broken down by a-amylase and hydrochloric acid. Native and gelatinized bulb starches had more resistant starch (RS) content than bulbil starch, according to in vitro digestion, but bulbil starch had lower levels of slowly digested starch (SDS). Both bulb and bulbil had regressed starch [**59**].

**Production Technology & Their Characterisation and functional properties**

The native starches have some fundamental drawbacks that make them unsuitable for use in the food manufacturing industry, including thermal and shear instability, insolubility in water and organic solvent, a tendency towards retrogradation, poor cold-storage stability, high viscosity at low concentrations, and poor resistance against acid and extreme temperatures. (Masina et al., 2017 (13); Punia et al., 2019 (24)). To address this issue and obtain “Clean Label Starch”, native starch is modified by physical, enzymatic and starch blending methods (2). Starch modified by these methods is considered ingredients rather than additives and is accompanied without any E-numbers (Radeloff, 2016 (2)).

**Physical Modification**

Physical modification causes packing of the molecules in the starch granules which results in damage/ rearrangement of them. This leads to changes in functionalities properties and characteristics of the starch like digestibility, thermal stability and nature of its gels and hot pastes (3,12). Native starches are subjected to several mechanical actions and shear pressure, combinations of temperature & moisture, and irradiation treatment to alter the starch granules’ size and interactions of amylose and amylopectin in the crystalline as well as amorphous region (Ashogbon and Akintayo, 2014 (3); 13). Although these changes are not so significant and persistent as those brought about by chemical modification methods, physical treatments can create starches with characteristics that are fairly similar to those achieved by chemical modification (3). Physically starch can be modified thermally and non-thermally. Thermal treatments include pre-gelatinization, hydrothermal treatment (heat-moisture treatment and annealing) and granular cold-water swelling. On the other hand, non-thermal treatment comprises ultrasonication, high hydrostatic pressure (HHP) treatment, pulsed electric field (PEF) treatment, use of cold plasma, freezing, thawing and freeze drying and irradiation. Physical modifications are very suitable for industrial large-scale production due to high efficiency, no by-products of chemical reagents, less expensive and involves easy operations (3,12,13).

**Thermal Methods**

**Pregelatinization**

Pregelatinization is the most widely used physical process of modifying starch that involves total gelatinization followed by drying (Alca´zar-Alay and Meireles, 2015 (2); 3). There are three methods to produce pre-gelatinized starch – drum and roll drying, extrusion drying and spray drying (He et al, 2020; Majzoobi et al, 2011; von Borries-Medrano et al, 2018 (12)). These procedures cause the starch granules to swell-up irreversibly and dissolution of the hydrogen bonds between starch molecules, in such a way that the least amount of molecular rearrangement occurs (Radeloff, 2016 (2); BeMiller, 2018 (3)). These starches when placed in water, instantly swell, and produces a viscous slurry (12). As a result, no further application of heat is necessary which makes it suitable for manufacturing heat-sensitive foods (Alca´zar-Alay and Meireles, 2015 (2)). The characteristic features of pre-gelatinization include disrupted granular structure, the absence of optical birefringence, and entire fragmentation (Ashogbon and Akintayo, 2014 (3)).

In drum and roll drying as the interior of the drum dryer gets heated, the starch slurry is coated as thin layer on the drum outside surface. A knife linked to the dryer obtains the instantly dried starch slurry in the form of film/flake after one revolution. The scraped-off dried film is then processed into flake or dust form (Radeloff, 2016 (2)). In the experiment of Wiriyawattana et al. (2018) (2) on the results of drum drying, they found that compared to the control group, each sample of pre-gelatinized rice berry flour exhibited significantly higher water absorption indices and swelling capabilities. The peak, trough and final viscosities, pasting temperature and setback value of the rice berry flour are also decreased following drum drying. For items like porridge and gruel, this is a typical technique in the food manufacturing industry (Bjo¨rck et al., 1984 (2)).

Extrusion drying is a high-temperature short-time (HTST) technique with a wide range of applications. Starch is compressed by an extruder and is subjected to mechanical shear force, high temperature, and generally low humidity conditions during the process (Radeloff, 2016 (2); Ashogbon and Akintayo, 2014 (3)). The extrudate is dried and crushed into different sizes through this procedure (Fu et al, 2012 (12)). According to Colonna et al, 1984; Doublier et al, 1986 (12) during the production of pregelatinized starch depolymerization may occur, and the molecular weight of wheat starch amylose and amylopectin is reduced during the extrusion process. These modifications were attributed to the significant shear force created in the extruder. Koa et al. (2017) (12) evaluated the impacts of extrusion on barley and observed that extrudates had a greater transverse expansion, faster starch digestion, and rapidly digestible starch than non-extrudates.

Spray drying has emerged as the most often used microencapsulation technology for components because it provides great solubility, excellent drying and emulsifying qualities, non-hygroscopic behaviour, bland taste, inertness, and economic efficiency (Reineccius, 2006; Shefer and Shefer, 2003; Murúa - Pagola et al., 2006 (3)). Izidoro et al. (2011) (2) looked into the impact of this technique on green banana starch that has undergone ultrasonic treatment. When the starch received concurrent spray drying and ultrasonication, the amount of resistant starch was noticeably lesser, most likely as a result of less starch crystallisation. The researchers showed that the swelling ability, solubility, and the capacity to absorb water starch were all boosted by the spray drying approach.

**Hydrothermal Treatment**

Hydrothermal treatment alters the physicochemical and functional characteristics of starch without causing disruption in the structure of granule. Generally, two methods are followed – 1) Heat-moisture treatment and 2) Annealing. It occurs when starch polymers change from an amorphous to a semicrystalline state. Hydrothermal treatment takes place under the starch gelatinization temperature, preserving the granular structure and keeping the starch in a movable rubbery condition throughout modification (Zavareze and Dias, 2011; Jacobs and Delcour, 1998; Adebowale et al., 2005; (2); Ashogbon and Akintayo, 2014; Ashogbon and Akintayo, 2014; Olu -Owolabi et al. 2011 (3)).

**Heat Moisture Treatment**

HMT is performed by heating starch at temperatures (80-140°C, usually over 94°C) above its glass transition temperature for a defined amount of time (1-24 h) with restricted moisture levels (10-40% w/w, commonly 35%) (Chung et al., 2009 (2); 12). When different kinds of starch were subjected to HMT treatment, gelatinization temperatures, peak temperatures, and conclusion temperatures all tended to rise while gelatinization enthalpy typically fell (Pinto et al, 2015; Shin et al, 2005; Vasanthan et al, 1995; Vermeylen et al, 2006 (12)). Granule size grows, viscosity properties diminish, and enthalpy reduces when HMT treatment is carried out at a higher temperature (Malumba et al, 2010 (12)). During treatment, the solubility and swelling power decrease as the water content and temperature rise, which results in more crystallinity (crystalline perfection), higher gel density and increase amylose cross-linking (Hoover, 2010; Varatharajan et al, 2011) (12); Jacobs and Delcour, 1998; Liu et al., 2000; Cham and Suwannaporn, 2010; Eerlingen et al., 1997; (2)). The pasting temperature and pasting time rose (significantly at 25% and 30% moisture content) whereas the peak viscosity and breakdown seemed to decrease in various experiments on the viscosity properties of HMT starch (BeMiller and Huber, 2015 (12); Puncha-arnon and Uttapap, 2013 (2)). Depending on the kind of starch, HMT has different impacts on a setback or final viscosity. According to reports, depending on the kind of starch, qualities including the stability of paste gels might change (Gunaratne and Hoover, 2002; Hoover et al, 1993; Takaya et al, 2000 (12)). HMT is used to make RS (resistant starch) and SDS (slowly digestible starch) with high thermal stability (Song et al., 2011; Chung et al., 2009 (2)). According to Cham and Suwannaporn (2010) (2), HMT is better suited for the manufacturing of dried and semi-dried rice noodles because they need stronger tensile strength and gel hardness. HMT starches might also be employed in the preparation of bread, noodles and pasta (Bourekoua et al., 2016 (2)).

**Annealing**

ANN is carried out in a surplus of water (more than 60%) at a temperature higher than the glass transition temperature but lower than the starch gelatinization temperature (usually 5-15 °C lower) (Zavareze and Dias, 2011 ([2](C://Users/ANKAN/OneDrive/Desktop/Research%20Papers/Starch/Modification/2.pdf))). Annealing different forms of starch under different moisture content, temperature, and duration circumstances results in uneven trends in several functional qualities. It has been done for as little as 0.5 hour and as much as 192 hours (Gomes et al, 2004 (12)). According to studies, ANN causes higher granule stability, decreased birefringence, increased porosity, crystalline perfection, and an increase in number of starch chain interactions, and reduction in amylose leaching (Chung et al., 2009 (2); (Gough and Pybus, 1971; Rocha et al, 2012; Shi et al, 2021 (12)). Increased gelatinization temperature and decreased temperature range of phase transition with increased annealing temperature are well recognised changes in thermal characteristics (BeMiller and Huber, 2015; Jacobs and Delcour, 1998; Jayakody and Hoover, 2008; Liu, 2013 (12)). Chung et al. (2000) (2) also observed that ANN induces rearrangement of starch molecules, resulting in decreased swelling power and solubility as well as increased gel strength. Annealing raises the pasting temperature and thermal stability while decreasing peak and final viscosity (Adebowale and Lawal, 2002; Adebowale et al, 2005; Olu-Owolabi et al, 2011; Shih et al, 2007; Simsek et al, 2012; Song et al, 2014 (12)). At the same time, Jacobs et al.'s (1996) (2) studies show a deviation from this pattern, noting that ANN increases the peak as well as final viscosities of rice and wheat starches. Like HMT, ANN is also utilized to produce RS and SDS with high thermal stability (Song et al., 2011; Chung et al., 2009 (2)). ANN treatment is useful when rice noodles needed to have a softer texture (Cham and Suwannaporn (2010) (2)).

**Granular Cold-Water Swelling**

Granular cold-water-swelling (GCWS) starch, also known as instant starch is a form of pre-gelatinized starch which can be prepared in four methods. The first approach involves heating amylose-containing starch in an alcoholic solution. The heated starch suspension is spray dried in the second approach. This method has been used for a long time and reports of Pitchon et al. (1981) confirms variation in properties of starch in accordance to properties. The starch is treated by using an aqueous alkaline alcohol solution in the third way at room temperature. Instantaneous controlled pressure drop (DIC) is the fourth approach (Eastman and Moore, 1984; Rajagopalan and Seib, 1991; Chen and Jane, 1994b; Pitchon et al, 1981; (BeMiller and Huber, 2015) (12)). The methods modify the elemental structure of the D-glucopyranosyl unit, resulting in only physical modification. According to (Hedayati et al, 2016a, b (12)). In research with buckwheat starch, GCWS demonstrated stronger light transmittance and solubility than PG while having lower crystallinity and swelling power (Li et al, 2014 (12)). It can be used with other non-thermal physical therapy methods such as ultrasonication or high-pressure treatment.

**Non-thermal Methods**

Non-thermal methods of physical modification are most effective to overcome the limitations of thermal methods. Due to application of high temperature in thermal methods, loss of nutrients, flavours, vitamins & minerals, colour, texture etc. takes place. In this context, non-thermal methods are useful to prevent these losses in food (Li et al., 2008; Marselles -Fontanet and Martin -Bellose, 2007 (3)).

**Ultrasonication**

Ultrasonication is the application of sound waves of greater frequency than the human hearing threshold (>20 kHz) on native starch granules suspended in solution or gelatinized starch (Majid et al., 2015; Franco and Bartoli, 2019 (2); Zuo et al., 2009 (3)). Ultrasound induces a high temperature, significant shear stress, and free radicals that alter the functionalities and structural alterations of starch in a starch-water system. The magnitude of these alterations is determined by the ultrasonic frequency, duration, temperature, moisture content of the entire system, and starch kind (Zhu, 2015 (7)). Since starch molecules cannot absorb ultrasound's sonic energy, it must be converted into a chemically useful form in order to generate cavitation, which in turn causes shear pressures that rupture polymer chains, thereby damaging starch granules and rapid breakdown of microbubbles (Zhu, 2015; Kardos and Luche, 2001; Jambrak et al., 2010; Herceg et al., 2010; Zuo et al., 2012 (2); Monroy et al., 2018 (7)). The amount of degradation was observed to rise with longer treatment times and was shown to be more powerfully influenced by starch with bigger granules (such as potato starch). Additionally, locations around the Maltese cross showed more severe granule fractures (Carmona-Garcı´a et al., 2016; Bai et al., 2017 (2). According to studies, in oxygen, less damage was done to the starch's surface, whereas it was rugged in the presence of air. In either vacuum or CO2, nothing was damaged. The pits were deep and huge, and the surface was smoothened in hydrogen (Gallant et al., 1972 & Degrois et al., 1974 (2)). Due to the damage to the starch granules' surface caused by sonication, water solubility and swelling power are increased (enhanced results obtained for granules sonicated in water than in ethanol) while crystallinity, peak and final viscosity, pasting properties, and the corresponding level of polymerization are decreased (Kong, 2018 (7); Zuo et al, 2009 (12); Sujka and Jamroz, 2013 (2)). But in the studies of Cham et al. (2010) & Carmona-Garcı´a et al. (2016) it was concluded that peak viscosities have increased followed by ultrasonication. With 15 minutes of ultrasonication, the rheological characteristics increased in G’ and G’’, and they reduced after 30 minutes (3). The retrogradation enthalpy was decreased as a result of the high ultrasonic power and high intensity that successfully raised the onset temperature & decreased the enthalpy of rice starch (Yu et al., 2013 (2)). Ultrasound-treated starch has many applications like it is used as an emulsifier, edible film, an enzymatic encapsulation and delivery system, V-type inclusion complex formation and formation of bioethanol (Wu et al., 2011; Xing et al., 2014; Zhu, 2017; Abbas et al., 2014; Tian et al., 2013; Khanal et al., 2007; Nitayavardhana et al., 2010 (2)).

**High Pressure Treatment**

High hydrostatic pressure processing (HHP) is a technique that uses high pressure (generally between 100 and 600 MPa) to alter starch in an aqueous solution over a relatively brief period of time (under 30 minutes) (Leite et al., 2017 (20)). Under high-pressure treatment settings, the properties of starch vary significantly depending on the treatment pressure, pressurisation temperature, and pressurisation duration (Pei-Ling et al., 2010 (2)). HHP encourages water molecules to penetrate the starch granules, weakening the double helices in the crystalline area and destroying the internal crystalline structure (Hu et al., 2017 ; Liu et al., 2016b ; Wang et al., 2017 (13)). Many starches, such as maize, waxy corn, rice, and wheat, partially gelatinize at steady temperatures and pressures over 300 MPa, but totally gelatinize at 600 MPa. Since potato starch is more pressure-resistant than other starches, it requires a pressure greater than 600 MPa to fully gelatinize (Kawai, Fukami, & Yamamoto, 2012; Słomińska et al., 2015; Kawai et al., 2012 (7)). All kinds of starch may be gelatinized using HPP at temperatures below zero, as long as the pressure is high enough. If heat is employed in addition to pressure, a lesser starch gelatinization pressure is required (Pei-Ling et al., 2010 (7)). In an experiment, after subjecting potato starch to a 600 MPa high-pressure treatment for two to three minutes, Baszczak et al. (2005) (2) found that the outside of the granules appeared to be more resistant to change and showed a very compact, condensed layer, while the interior of the granules, which had a relatively coarse structure, clearly showed destroyed and gel-like structures. Under pressure, starch became gelatinized as evidenced by the decrease in birefringence and the emergence of a gel-like structure (Pei-Ling et al., 2010 (2)). The degree of gelatinization grew significantly as the pressurisation treatment period increased up to 60 min, following which a plateau level was established. Additionally, with increasing pressure and pressurisation duration, the consistency index, melting enthalpy, and differential scanning calorimetry peak temperature all rose (Pei-Ling et al., 2010 (2); 2). Guo et al. (2015) (2) discovered that compared to native starch, high-pressure (100–500 MPa) treated lotus seed starch had a significantly greater pasting temperature, peak viscosity, trough viscosity, and final viscosity values. For breakdown and setback, however, the findings were the reverse. The moduli of most starch gels dramatically increased as the treatment pressure level increased, according to several previous research on the impact of high-pressure processing on the rheological properties of different starches, including those of sorghum, rice, and mung bean (Vallons and Arendt, 2009; Jiang et al., 2015a; Jiang et al., 2015b (2)). High‐pressure homogenized starch also shows s reduced values of T0, Tp, and enthalpy of gelatinization (∆H). In many food corporations and bakeries, high-pressure processing offers tremendous potential for energy savings. The resultant creamy texture paste can substitute oil in low-fat foodstuffs (such as mayonnaise, confectionery food items, sweets, and dairy items) without heat treatment when starch pastes having a concentration of more than 15% go through processing using this method. It also produces RS which is effective to control colorectal cancer and diabetes (Nasehi and Javaheri, 2012 (2)).

**Pulsed Electric Field Treatment**

Pulsed Electric Field treatment is a promising non-thermal technology that uses electric pulses of high-intensity (more than 10 kV cm-1) for brief (<40 µs) periods to treat starch materials in a processing chamber (Han et al., 2012 (2)). The morphology of the starch is almost completely disrupted when the intensity approaches 50 kV cm-1, and it results in the formation of a gel network from the clustering of fragments (Li et al., 2019; Han et al., 2009b; Han et al., 2012; Zeng et al., 2016 (2)). PEF treatment damages the outer protective dense layer of the granule. This results in increased water-absorption and swelling of granule, causing particle aggregation (Han et al., 2009a (13)). During pasting at high electric field intensity of more than 50 kV cm-1, there is reduction of setback value, peak viscosity (as seen in case of tapioca starch–water dispersion solutions), and breakdown viscosity (Han et al., 2009a; 2009b; Han et al., 2012 (2)). PEF tends to lower gelatinization temperature and ΔH, according to thermal analysis using differential scanning calorimetry. Additionally, the lower gelatinization temperature raises the possibility that PEF disorganizes the crystalline region (Zhu, 2018 (2)). PEF might vary the starch digestion rate, creating RS, SDS, and RDS when combined with wheat, potato, and pea starches. RDS amount enhanced remarkably with electric field intensity for all starches, whereas in all electric field intensities, SDS amount was decreased in the treated specimens. Different tendencies for RS were seen for various forms of starch. When potato starch and wheat flour were treated with PEF of low-intensity (2.86 and 4.29 kV cm-1, respectively), the RS content rose considerably. The value, however, did not vary much when the strength of the electric field enhanced (5.71, 7.14, and 8.57 kV cm-1). At any electric intensity, the RS of pea starch didn’t change significantly (Li et al., 2019 (2)). The strength of the electric field, the length of the treatment, and the temperature of the food are some variables that affect how effective PEF treatments are (Bendichoy et al., 2002 (7)). Considering its significant benefits of low temperature of processing, quicker treatment, and consistent intensity of treatment, PEF has been widely used in pasteurisation, enzyme deactivation, aiding extraction, molecular modification, and chemical reaction enhancement (Agcam, Akyıldız, & Akdemir, 2014; Luengo, Condón-Abanto, Álvarez, & Raso, 2014; Sun, Yu, Zeng, Yang, & Jia, 2011 (13)).

**Plasma**

The plasma technique of starch modification is a novel approach that changes starch in various ways based on the type of plasma and the excited gas, the conditions, and the energy generation (Lii, Liao, Stobinski, & Tomasik, 2002; Wongsagonsup et al., 2014 (7)). This method causes increased surface energy, increased or decreased hydrophilicity, oxidation, bond breakage or depolymerization, and crosslinking of starch (Wongsagonsup et al., 2014 (7)). During plasma treatment, two important competing processes are cross-linking and depolymerization. Cross-linking improves starch integrity and inhibits dissociation, whereas depolymerization results in more fragmented starch molecules and a lower capacity to reflect light. These responses are affected by the type of plasma used and the treatment circumstances (Chaiwat et al., 2016 (7)). Wongsagonsup et al. (2014) (7) used jet atmospheric argon plasma treatment to nonchemically modify tapioca starch. They employed two types of starch suspension - granular starch and cooked starch, each of which was exposed to with 50 W and 100 W plasma for 5 minutes. They discovered that granular starch treated with 50 W and cooked starch treated with 100 W had reduced paste clarity when compared to untreated control samples, whereas granular starch treated with 100 W and cooked starch treated with 50 W had the reverse effect, i.e., higher paste clarity. The cross-linking process was prominent in the first example, whereas the depolymerization reaction ruled in the second. In comparison to untreated samples, the water binding capacity and swelling power of plasma-treated corn and tapioca starches increased. The plasma treatment reduced the peak temperature (Tp) and enthalpy H of corn starches while increasing the Tp and enthalpy H of tapioca starch. When the pasting qualities of corn and tapioca starch were examined, it was discovered that after the treatment, the pasting temperature for corn and tapioca starch decreased, but the peak viscosity (PV) elevated. SEM revealed that there were no cracks or holes created on the surface of either starch granule, while corn starch granules displayed uneven surfaces and deposits following exposed plasma treatment (Banura et al., 2018 (7)). Cold plasma treatments are believed to have no or limited effects on the physical, chemical, nutritional, and sensory properties of different products due to their nonthermal character (Pankaj, 2018 (7)).

**Freezing, Thawing and Freeze Drying**

Because of syneresis, amylose and amylopectin are leached upon thawing, resulting in a change in chemical characteristics. Freezing and thawing of potato starch resulted in particle corrosion and higher specific surface area. Furthermore, the water matrix created during severe freezing compacts the starch granules, which might result in amylopectin leaking from the interior to the surface. Lyophilization has also been shown to reduce crystallinity in the inner structure of starch and impact the surface. This damage allows enzymes to enter the starch granules and boost digestibility (Szymońska et al, 2000; Szymońska and Wodnicka, 2005; Apinan et al, 2007 (12)).

**Irradiation**

Electromagnetic radiations such as gamma (γ) rays and microwaves are recognised as physical ways of modifying starch (Braşoveanu & Nemţanu, 2014; Zhu, 2016 (20)).

Cobalt-60 (60Co) and caesium-137 (137Cs) are the chief sources of gamma radiation used for starch modification. Irradiation by gamma rays generates free radicals that not only break starch chains but also result in the production of carbonyl groups along with carboxylic acids (Chung & Liu, 2009; Zhu, 2016 (20)). Sofi et al. (2013) (20) irradiated faba bean starch at various dosages (0-15 kGy) with a 60Co-ray source. The results demonstrated a decrease in relative crystallinity with a rise in carboxyl content, as well as lower pasting viscosities and better freeze-thaw stability. This might be connected to the irradiation-induced shortening of starch chains. These very intense and penetrating radiations may also influence the morphological characteristic of starch, which are dosage dependant (Gani et al., 2014; Polesi et al., 2016 (13)).

The fundamental effect of the microwave treatment method is based on dielectric heating, which induces fast dipole reorientation of polar molecules in the starch system, resulting in the formation of structural changes (Brasoveanu & Nemtanu, 2014 (13)). The first step of microwave modification mostly includes the disintegration of the amorphous area (the internal chain), whereas the second stage primarily encompasses the destruction of the crystalline region (the external chain) (Yang et al., 2017 (13)). Yang et al. (2017) discovered that after 5 minutes, 10 minutes, and 20 minutes of microwave irradiation, the relative crystallinity of waxy maize starch reduced by 10.47%, 6.42%, and 2.91%, respectively, implying that microwave could cause significant damage to the crystalline areas, the disappearance of the double helices, and degradation of the starch granules. Furthermore, the moisture content rose (from 30% to 50%), however the relative crystallinity of millet starch fell considerably (from 23.3% to 3.2%) (Li, Hu, et al. 2019; Li, Zhu, et al. 2019 (13)). As a result, the greater moisture content may boost the microwave effect on starch by increasing the rate of heating (due to its high dielectric characteristics) and enhancing the hydration in the amorphous area. As reported by Li et al., 2019 (13), when treated with microwave at 700 W for 60 s, starch with moisture contents of 30% retained its shape but a few cracks and cavities could be encountered on the surface, starch granules with 40% water aggregated together to produce larger starch clusters, and granules with 45% moisture content deformed completely and developed big gel blocks.

**Enzymatic Modification**

Enzymatic treatment has recently been introduced as another "clean-label" approach for improving the functionalities of starches. Alternatively, enzymatic changes can be used in conjunction with other methods, like physical treatments, to get the desired functionality of the modified starches (Li et al., 2020; Lu et al., 2018; Shi et al., 2014; 20). Other advantages of enzymatically modified starches include better purity, consistency of high-quality products, lower cost, and absence of undesired products (Park & Kim, 2021 (24)). Starches modified by enzymes undergo de-branching actions phosphate substitution, and disproportionation, which alters the starch chain length and branch point creation. These starches are characterized by lowered paste viscosity, showed different rheological characteristics, and improved starch elastic behaviour and digestibility. When starches are exposed to enzymatic activity, holes and pits emerge in the starch granules, resulting in a porous structure that allows water molecules to enter to assist gelatinization, liquid absorption, or delay the release of enclosed fluid (Woo et al., 2021; Zhang & Bao, 2021; Kim et al., 2017; Singla et al., 2020; Purcell et al., 2014 (24)). Starch modifying enzymes include – 1) α-glucanotransferases (αGTases) which comprises (i) branching enzyme (BE, EC 2.4.1.18), (ii) cyclodextrin glycosyltransferase (CGTase, EC 2.4.1.19) and (iii) 4-α-glucanotransferase (4αGTase, EC 2.4.1.25); 2) Maltogenic amylase (MA, glucan 1,4-α-maltohydrolase, EC3.2.1. 133); 3) α-amylase (endo-acting enzyme); 4) β-amylase (exo-splitting enzyme); 5) Amylo-sucrase (AS, E.C. 2.4.1.4); 6) Debranching enzymes - (i) pullulanase (EC 3.2.1.41) and (ii) isoamylase (EC 3.2.1.68) (van der Maarel et al., 2002 (2); Miao et al., 2018; Rha et al., 2020; 24; Cai & Shi, 2013; Li et al., 2020; Lu et al., 2018; Ma et al., 2019 (20)). Starting with 4aGTase (amylomaltase) or D-enzyme (disproportionationg enzyme), catalyses the process of transglycosylation processes on starch substrates through several steps : disproportionation, cyclization, coupling, and hydrolysis. By inter and intramolecular transglycosylation, this enzyme can produce modified aggregates of amylopectin and cycloamyloses (cyclic a-1,4-glucan derivatives) or large-ring cyclodextrins. This enzyme may also be used to create a thermoreversible starch gel (Takaha et al., 1996; Nimpiboon et al., 2020 (2)). CGTase may produce cyclic oligosaccharides known as cyclodextrin (6, 7, and 8 glucose residues) capable of forming inclusion complexes with appropriate guest molecules (Uekama et al., 1998 (2)). Branching enzyme is responsible for the in vivo synthesis of α-1,6-glucosidic bonds in both glycogen and starch. It breaks down an α-1,4-glycosidic linkage like the other two. Only difference, it shifts the cleaved α-glucan chain to the free 6-hydroxyl group in the acceptor glucan chain, resulting in the formation of an a-1,6-glycosidic bond (van der Maarel and Leemhuis, 2013 (2)). The products of α-GTases-treated starch includes cyclodextrin, thermoreversible starch gel, highly branched cyclic dextrin, slowly digestible starch (SDS) and resistant starch (RS) (Li et al., 2014; Szente and Szejtli, 2004; Jo et al., 2016; Takii et al., 2007; Patil, 2013 (2)). Maltogenic amylase induces the hydrolysis of 1,4-glucosidic linkages in starch, releasing maltose as the primary product from the chain's non-reducing ends. MA-treated starch provides improved cold storage endurance, slower retrogradation, and decreased viscosity. As a result, MA is widely used in the food manufacturing sector as an antistaling compound (maintain moisture and softness) in bread as well as other baked products to extend their duration of storage (Miao et al., 2018; Miao, Xiong, Jiang, et al., 2014; Miao, Xiong, Ye, et al., 2014; (24)). α -amylase operates to break α-1,4 bonds of amylose and amylopectin at random, whereas β-amylase acts to break α-1,4 bonds in amylose and amylopectin sequentially and produce monomeric or oligomeric compounds. Pullulanase and other debranched enzymes break α-1,6 glycosidic bonds (14). Amylo-sucrase transfers a D-glucopyranosyl moiety from sucrose to the non-reducing end of an acceptor molecule, such as maltose, glycogen, maltodextrin, or sugar polysaccharide, resulting in an amylose-like polysaccharide with only α-(1 4)-glucosidic linkages, making it a powerful glucosylation approach for the production of novel amylopolysaccharides (Seo et al., 2019 (24)).

**Starch Blending**

Blending distinct native or physically modified starches is one technique to improve the functional properties of native starches. By combining various component starches, additive and non-additive behaviour for all starch qualities may be created. If additive effects are seen, the properties of the blend may be predicted with the component starches. In the event of non-additive effects, forecasts deviate from actuality, resulting in interactions. Several parameters influence the qualities of starch blends like amylose content, amylose leaching, concentration of starch and water content, relative granule size, and swelling power (Waterschoot et al., 2015; (2)). When the overall starch concentration was low, Liu and Lelievre (1992) discovered that the blend’s thermal parameters were the sum of its component starches. However, because of the struggle for water between the blended component starches, non-additive behaviour develops at high starch concentrations. Waterschoot et al. (2015) discovered that in the presence of adequate water, each starch gelatinizes independently; however, in the absence of enough water, the starch which has a gelatinization temperature lower than the other, gelatinizes first, and leaves less water for the gelatinization of the other starch. This causes the other starch to gelatinize at high temperatures, changing its properties (2). In the context of relative granule size, when there is a bigger variation in granule size between the starch components in the mixture, the non-additive impact becomes more obvious (Puncha-arnon et al., 2008). As per reports each time restricted-swelling starches were combined in a comparable ratio with easily swelling starches, swelling power was dramatically lowered and gelatinization temperature was raised (Chen et al. 2003). Mixing with unusual starches, such as potato starch (which consists of phosphorus in the amylopectin section and has a much larger granule size than other starches) and waxy corn starch, results in linear changes in peak viscosity as well as pasting temperature (additive), yet no changes in setback and breakdown (non-additive), based on the mixture ratio of the two starches (Tomasik, 2009; Park et al. 2009). Blending techniques are mainly used for noodles , cakes and , wheat replacements (Go´mez et al., 2008; Koca and Anil, 2007; Oladunmoye et al., 2014). The 1:1 combination of potato starch & rice starch produced high-quality noodles in terms of duration of cooking, transparency, and texture (Sandhu and Kaur, 2010). Starch blending techniques are especially useful for gluten free food (Holmes et al., 1989).

**Microencapsulation Properties of Starch**

Microencapsulation is a versatile technology that involves the encapsulation of active substances within a protective matrix, allowing controlled release and targeted delivery. Over the years, starch has emerged as a promising material for microencapsulation due to its biocompatibility, biodegradability, low cost, and widespread availability. Starch, a polysaccharide composed of glucose units, exhibits unique physicochemical properties that make it an ideal candidate for microencapsulation. Starch can form a gel-like matrix when heated with water, enabling easy entrapment of active compounds within its network structure. Furthermore, the presence of hydroxyl groups on starch molecules facilitates chemical modifications and enhances the stability and functionality of the microencapsulated products (Johnston & Hurler, 2018). Various techniques have been employed to encapsulate active ingredients using starch as the encapsulating material. The most commonly used techniques include spray drying, coacervation, and emulsion methods. Spray drying involves atomizing a solution or suspension containing the active ingredient and starch, followed by rapid drying to obtain microcapsules. Coacervation utilizes phase separation between the core material and the starch matrix, forming a coacervate phase that encapsulates the active compound. Emulsion methods involve the emulsification of a starch solution containing the active substance, followed by solvent evaporation or gelation to produce microcapsules (Smith et al., 2020).

The versatile properties of starch-based microencapsulation have found numerous applications in different industries. In the food industry, microencapsulation of flavors, vitamins, and nutraceuticals using starch provides enhanced stability, controlled release, and targeted delivery, thereby improving the quality and shelf life of food products (Ravi et al., 2019). Flavor encapsulation is crucial for improving the stability and shelf life of volatile compounds in food products. Starch-based microencapsulation has been utilized to protect and preserve flavors, allowing their controlled release during consumption. For instance, microencapsulation of citrus oils using starch-based systems has been shown to enhance the stability and release of the flavors in various applications, such as beverages, confectionery, and bakery products (Ravi et al., 2019). The encapsulated flavors remain protected from degradation, evaporation, or interaction with other food ingredients until they are released, resulting in enhanced sensory experiences for consumers.

Vitamins are essential micronutrients that are prone to degradation due to environmental factors, such as heat, light, and oxygen exposure. Microencapsulation using starch offers a solution for improving the stability and bioavailability of vitamins in food and dietary supplements. Starch-based microcapsules have been used to encapsulate vitamins, such as vitamin C, vitamin E, and B-group vitamins, providing protection against degradation and ensuring their controlled release during digestion (Singh & Pal, 2020). These encapsulated vitamins can be incorporated into functional foods, beverages, and dietary supplements, offering improved nutritional value and prolonged shelf life.

In the pharmaceutical field, starch microcapsules have been utilized for the controlled release of drugs, protecting them from degradation and enabling sustained drug release, reducing dosing frequency and improving patient compliance (Gupta et al., 2021). Nutraceuticals, including bioactive compounds and herbal extracts, possess various health-promoting properties. However, their incorporation into food products is challenging due to issues related to stability, solubility, and taste. Starch-based microencapsulation has been employed to overcome these challenges and enhance the delivery of nutraceuticals. For example, curcumin, a bioactive compound found in turmeric, has been successfully encapsulated within starch microcapsules. This encapsulation approach improves the stability, solubility, and bioavailability of curcumin, enabling its incorporation into functional foods and dietary supplements (Ravi et al., 2019). Similarly, polyphenols from plant extracts, such as green tea or grape seed extract, can be effectively encapsulated using starch-based systems, providing protection against degradation and allowing for their controlled release in the body (Singh & Pal, 2020). Furthermore, the agricultural sector has also benefited from starch microencapsulation, with controlled release formulations of fertilizers and pesticides offering improved efficiency, reduced environmental impact, and enhanced nutrient utilization (Wu et al., 2022).

However, despite its many advantages, starch-based microencapsulation also presents some limitations. One major challenge is the susceptibility of starch to moisture, which can lead to premature release of encapsulated materials. This issue can be mitigated by incorporating hydrophobic coatings or blending starch with other polymers to improve its moisture resistance (Zhang et al., 2021). Furthermore, starch-based microcapsules may suffer from limited encapsulation efficiency and poor mechanical strength, particularly when exposed to harsh processing conditions. Ongoing research focuses on developing novel approaches to optimize the encapsulation process and improve the performance of starch microcapsules (Mittal et al., 2023). The field of starch microencapsulation is constantly evolving, with ongoing research aimed at addressing the existing limitations and exploring new possibilities. One exciting avenue for future development lies in the incorporation of functional additives into starch-based microcapsules. By introducing bioactive compounds, such as antioxidants or antimicrobial agents, into the encapsulation matrix, the resulting microcapsules can offer additional health benefits and extended product shelf life (Chen et al., 2023). Furthermore, the combination of starch with other natural polymers or nanoparticles holds great potential for enhancing the encapsulation properties, stability, and release kinetics of microcapsules (Li et al., 2022). Another area of active research is the development of stimuli-responsive starch microcapsules. By modifying the surface properties or incorporating specific components, such as pH-sensitive polymers or temperature-responsive materials, the release of encapsulated substances can be triggered or modulated in response to external stimuli. This approach allows for precise control over the release profile, enabling targeted delivery and customized release patterns (Sinha et al., 2021).

Moreover, advances in nanotechnology have paved the way for the development of nanoscale starch particles for microencapsulation purposes. Nanosized starch particles exhibit enhanced surface area, improved dispersibility, and increased reactivity, resulting in improved encapsulation efficiency and stability. Furthermore, nanoscale starch particles can be employed in novel encapsulation techniques, such as electrostatic assembly or layer-by-layer deposition, providing precise control over the encapsulation process (Wang et al., 2023). The microencapsulation properties of starch have revolutionized various sectors, offering improved product stability, controlled release, and enhanced performance. As research and development in this field progress, the potential applications of starch-based microencapsulation are boundless, promising a bright future for this versatile technology.

**Starch for biodegradable films, nanoparticle based composite films, and their food applications**

Packaging materials are crucial for food hygiene and quality, and petroleum-based polymers and materials account for the vast bulk of commercialised packaging worldwide. These materials offer strong processing qualities such as water and vapour barrier capabilities, transparency, and cheap cost, but they can have severe environmental implications such as carbon dioxide emissions and accumulation over time owing to recycling issues with synthetic packaging (Mukurumbira, Mellem & Amonsou, 2017; Hasan et al., 2020a; Nawab, Alam, Haq, Lutfi & Hasnain, 2017b (28)). Consumer worries about disposing of plastic in the environment have increased the industrial interest in biodegradable films. Starch is commonly utilised in the manufacturing of biodegradable and edible films due to its excellent film-forming characteristics, neutral organoleptic features, low cost, and availability (Requena, Vargas & Chiralt, 2018; Sudheesh et al., 2020; Valencia-Sullca, Vargas, Atar´es & Chiralt, 2018; 28). By breaking the polymer chains into smaller components of monomers or dimers, biodegradable films are bioassimilated into the environment (Zoungranan et al., 2020 (28)).

Starch-based biodegradable films are made using a variety of techniques, including solvent casting, extrusion, tape casting, compression moulding, and injection moulding. Solvent casting is the primary method employed at small scale to research and create new film compositions (Siqueira, Arias, Maniglia & Tadini, 2021 (28)). A polymer solution (in a volatile solvent) is applied to a flat die and sequentially deposited onto a stainless-steel belt in commercial solvent casting. Viscosity and temperature in the casting solution are crucial factors since they impact thickness; filtration is used to get rid of bubbles and contaminants. The solvent is blown away using dry air, after which the film is cooled and taken off the belt. Though it seems like a straightforward process, there are a number of interaction processes that depend on the circumstances of the process and the characteristics of the starch granule. The starch film production starts with heating a dispersion of starch in water. Amylose as well as amylopectin leach into the solution during this process, generating a structureless paste known as gelatinisation. The process is divided into two stages, the first occurring between 60 and 70 degrees Celsius and the second occurring above 90 degrees Celsius. During the cooling stage, amylopectin and amylose have high molecular mobility, which aids in organising and achieving intermolecular hydrogen bonding of amylose and amylopectin into a semi-crystalline form, a process known as retrogradation. Plasticisers are frequently used in casting solutions to boost film flexibility and film-forming performance. Water is most used 0as a plasticiser in films, a non-toxic and food-friendly substance (Thakur et al., 2019; Hafizan, Yaakub, Hamdan & Asmah, 2016; Nawab et al., 2017b (28)).

**Table**. **Characteristics of biodegradable films made of starch for food packaging**

|  |  |  |
| --- | --- | --- |
| Properties | Description | References |
| Structural properties | Atomic force microscopy & Fourier transform infrared (FR-IR) spectroscopy were utilised to investigate the chemical structure and content of packaging material. The surfaces of starch, as well as PVA films, are uniform and smooth. Phase separation, which happens solely in amylopectin starches, is one-factor impacting structural characteristics. The quantity of starch and phosphate groups causes phase separation. The thickness of biodegradable packing material must be less than 254 m, according to the recommendation. | Hu et al., 2018; Cerqueira et al., 2016 |
| Mechanical properties | When compared to polylactic petroleum films, biodegradable polylactic films have lower mechanical characteristics. The weight of the properties, additive concentration, distribution, and the polymer's crystallinity and amylose content all affect mechanical properties. The low molecular weight of starch films results in strong tensile strength & elongation break. | Sajjan et al., 2020; Zhou et al., 2019; Aung et al., 2018; Mali et al., 2002 |
| Permeability properties | The polymer matrix displays efficient gas permeability, extending the shelf life of food goods. Food shelf life and freshness are directly linked to the amount of water transferred between the food item and its surrounding environment. As a result, the primary function of packing is to reduce water transmission. According to research, the presence of silica nanoparticles in biodegradable films reduces moisture permeability. | Jiménez et al., 2012; Yu et al., 2018 |
| Optical properties | Overexposure to ultraviolet (UV) & visible rays causes decolourization and degradation of packaged food goods. Transparency & UV screening are required for the inspection of quality in packaged food goods. According to the findings, nanocomposites boost the opaqueness of starch films, implying that nanoparticles serve as UV blockers, limiting the permeability of light. | Vaezi et al., 2018 |
| Solubility properties | The hydrophilic character of polymers determines their solubility qualities. The solubility of starch film and PVA has been determined to be 0.208 g dissolved/g dry films and 0.19 g dissolved/g dry films, respectively. The aqueous medium is recommended for packing and storage due to its relatively low solubility values, which demonstrate strong stability. | López et al., 2004 |

For several reasons, including their poor mechanical, barrier, and processing qualities, starch-based packaging films have not been extensively used in the packaging sector. To compensate for these shortcomings, starch films are frequently produced by including various filler elements, such as nanoparticles, in the starch matrix. The addition of starch nanoparticles to composite films alters the films' physicochemical, functional, including mechanical characteristics. The nanocomposite films exhibit unique properties such as low solubility, low water vapour transfer rate, nontoxicity, and biodegradability, making them an appealing option for food and non-food applications (56). The incorporation of nanoparticles forming a dispersed phase in the film's matrix restricts biopolymer chain mobility. The water vapour permeability (WVP) of composite films can be reduced by reducing biopolymer chain mobility (Brahmi et al., 2019). The thickness of nanocomposite films increased when starch films having varied amounts of nano starch were used. Because of its nanometric scale, nano starch reduces the WVTR of nanocomposite films, which increases the ratio of surface to volume and disrupts the mobility of the polymer chain. Because of its nano-size, nano starch improves the density of nanocomposite films, which increases water vapour resistance. The mechanical characteristics of the films are affected by the flexibility and ductility of the nanoparticles. The inclusion of starch nanocrystals raises the melting temperature of films. These nanocomposites are potential future alternatives and important subjects of study, but practical uses are limited because of limited manufacturing and high cost. Although nanocomposite technology has enhanced the water barrier and mechanical characteristics of natural biopolymers, these advancements have only found a few uses in the food business. Optimum film composition combined with affordable and effective production processes might be a viable alternative for the development of novel food packaging materials (56).

**Starch-protein-lipid complexes and it’s uses**

The three macronutrients that compose most foods — lipid, proteins, and starch, are the main suppliers of energy in the average person's diet. The macronutrients in question experience alterations throughout the preparation of foods, and their interactions, which are frequently complex, determine the final quality of food items, nutritional content, and organoleptic qualities [1,2][2]. In order to sustainably generate energy and produce short-chain fatty acids, the digestibility of starch should be controlled, particularly by enhancing the proportion of slowly digestible starch (SDS) or resistant starch (RS) (Raigond, Ezekiel, & Raigond, 2015; Sajilata, Singhal, & Kulkarni, 2006) [1]. Starch multi-scale systems, such as lamellar structures, crystalline structures, morphology features and chain length distribution (Liu et al., 2018; Yu, Tao, & Gilbert, 2018, Lee, Lee, & Chung, 2017; Liu, Chi, Huang, Li, & Chen, 2019, Chi et al., 2017; Liu et al., 2018, Wang et al., 2018) have been shown to regulate starch enzymatic hydration. Lipids, proteins, phenolic compounds, and protein-containing components (Chi, Li, Feng, et al., 2018; Liu et al., 2019) are examples of non-starchy substances that affect the digestibility of starch by generating starch-ordered structures et/or reducing activity of enzymes. Through non-hydrophilic and electrostatic interactions of starch with proteins and lipids have been resulted into increased starch ordered structures for retarding the rate of digestibility starch (Chao, Yu, Wang, Copeland, & Wang, 2018). For the purpose of starch to develop into structured molecules and for its bioavailability to be modulated, proteins or lipids must interact with starch (Chao et al., 2018; Zheng et al., 2018).

In recent years, substantial research has been done on modifying the digestibility of starch using ternary systems of protein, lipid, and starch. However, it hadn't been clear whether the proteins affected the creation of starch-protein-lipid aggregates (Chi, Li, Feng, et al., 2018; Liu et al., 2019) [1]. The hydrophobic tail from fatty acids is thought to react alongside starch to produce starch-fatty acids inclusion complexes, while the charge-negative carboxyl group of the fatty acid is thought to engage alongside protein to shape a ternary complex of starch-protein-fatty acid in ternary systems containing starch, lipids, and protein (Bhopatkar et al., 2015; Chao et al., 2018) [1]. The development of starch-lipid inclusion complexes with the adhesion of protein to the starch interface led to a considerable reduction in starch digestibility whilst the starch-protein-fatty acid aggregates have developed (Zheng et al., 2018) [1]. Amylose-lipid complex development lowers starch sensitivity to digestive enzymes and expansion strength, delays starch retrogradation, raises gelatinization temperature, and reduces starch solubility [2,11,12 57]. Via hydrophobic or electrostatic interactions between their lipophilic/hydrophobic domains, proteins may also build compounds containing lipids [13 59]. Starch and protein are capable of producing combinations, given the right circumstances, that can change the physiochemical characteristics of the two - starch and protein parts [14].

While examining the pasting properties of sorghum flour, development of fatty acids (FAs), starch and protein ternary complexes were described [15] [2]. With the use of differential scanning calorimetry (DSC), high performance size exclusion chromatography (HPSEC), X-ray diffraction (XRD) and multi angle laser scattering (MALLS) has been useful to investigate the interactions among lipids, starch and proteins [16,17,18] [2]. Application in the field of nutritional health products and release and delivery of non-hydrophilic drugs has been concluded as the result to the studies in regards of a self-assembled ternary complex which is able to carry sparingly soluble small molecules in the lumen of the amylose helix [19][2].

Modifications in the pasting and gelatinization capacities of a hypothetical system of starch in the presence of FAs and/or β-lactoglobulin (LG) have been observed in order to clarify the development and configurations of the starch-protein-lipid group [2]. An array of XRD, Fourier Transform infrared spectroscopy (FTIR), and Raman spectroscopy were used to characterize the multiple scale frameworks of the ternary complexes made from RVA pastes [2]. Additional studies have been done in case of proteins having isoelectric point value of less than pH 6, such as LG and whey protein isolates (WP) (Zhang, Maladen, Campanella, & Hamaker, 2010) [1].

The development of these complexes during manufacturing can have a substantial impact on the nutritional value as well as the quality of meals made of starch. For instance, adding lipids to foods made from wheat at the extrusion process alters the final texture of the product and nutritional value, which is thought to be connected to the development of starch-lipid combinations (De Pilli et al., 2011; De Pilli, Giuliani, Buléon, Pontoire, & Legrand, 2016) [3]. Starch-lipid-protein combinations are frequently employed as a component in applications in industry in addition to processing owing to their unique functional qualities, such as nongeling behaviour, high viscosity, and excellent flexibility [3]. starch-lipid-protein complexes may be used as fat substitutes in order to create meals with less calories, (Agyei-Amponsah, Macakova, DeKock, & Emmambux, 2019) [3]. Additionally, to deal with the rising prevalence of diet-related disorders and weight gain, starch-lipid-protein complexes, being types of resistant starch can be employed as useful components in food formulations (Zhao et al., 2014) [3]. Considering the targeted delivery and regulated release of the bioactive compounds, vacant regions in the lumen of the amylose helices of starch-lipid-protein complexes could serve as potential transporters for accommodating small molecules with poor solubility in aqueous media (Liu et al., 2009) [3]. The hydrophobic lumen of the amylose helix of the ternary starch-lipid-protein nanoparticle has been modified to contain the chemotherapeutic medication 5-fluorouracil (Zhang et al., 2015) [3]. Additional study is needed in this domain, particularly on the possible health advantages of starch-lipid-protein complexes, particularly with reference to their gut prebiotic qualities. The unique activity of starch-lipid-protein combinations offers potential for the development of novel uses, as the article mentioned above illustrates.

**Starch in development of plant-based alternatives and consumer acceptability**

Starches are probably among the next most prevalent natural polymers after cellulose and lignin. Starch is mostly derived from cereals like corn and wheat in the United States. In both the food and industrial sectors, starch is used in a wide range of applications, most of which benefit from its propensity to dissolve in hot water (BeMiller and Whistler, 2009). For instance, starch pastes are used in food as a thickening and stabiliser. In many different goods, including paper, cardboard, medicine tablets, and many more, starch is frequently employed as an adhesive and binder. It also has undesirable characteristics, such as restricted solubility in cold water, a loss of viscosity and thickening power after cooking, a high tendency to retrograde, a low shear resistance, and a low thermal resistance.[39] As a result, starch is frequently mildly chemically altered to adapt its physicochemical and functional qualities for use in food.[[39](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0039),[40](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0040)]  (Din et al., 2017). For applications including food packaging, chemical containers, and mulch films during fumigation, laminated films—which include a central TPS layer that is shielded from moisture by outer polymer layers—might be an efficient barrier material (Wang et al., 2000; 128 Dilkes-Hoffman et al., 2018).

Various research and development initiatives have been made throughout the years with the goal of creating blends and composites by combining natural polymers with synthetic polymers [1–7]. Starch, a type of polysaccharide, is one of these extensively studied polymers. (Laftah, 2017; Probhu and Prashantha, 2016; Halley and Averous, 2014). This was made possible by starch's low cost, biodegradability, ease of manufacture, abundance, and status as a renewable resource. Granular starch has also been used to create composite materials with polyethylene, polypropylene, polylactic acid, and many other polymers. (<https://doi.org/10.1007/s00289-018-2402-2>)

Global interest in meat-replacing goods has grown over the past few decades, and experts expect that it will continue to expand in the years to come.[1-5] As a result, there are more goods on the market that resemble meat or provide customers with protein-rich substitutes. Creating the right texture, flavour, and colour for these items is one of the toughest production problems.[6] Protein (typically derived from wheat and legumes), fat or oil, binding agents, flavours, and colouring additives make up a frequently used combination of components.[8] Starch is frequently included as a minor ingredient alongside other purified ingredients, including protein isolates, and is typically used in small amounts in commercially accessible meat substitutes and actual meat products. **Table 1** lists the ways in which starch is used in the processed meats and meat substitutes that are currently available on the market.

**Table 1.**Collection of meat and meat replacing products on the market that contain starch

|  |  |  |  |
| --- | --- | --- | --- |
| **Application** | **Starch** | **Meat/vegetarian/vegan** | **Ref.** |
| Albert Heijn Hamburger | Potato | Meat | [[10](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0010)] |
| Albert Heijn Runderbraadworst | Potato | Meat | [[11](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0011)] |
| Albert Heijn Shoarmareepjes | Potato | Meat | [[12](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0012)] |
| Albert Heijn Biologische Rundergehaktballetjes | Potato | Meat | [[13](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0013)] |
| GoodBite Vers Gehakt | Potato, corn, wheat | Vegetarian | [[14](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0014)] |
| GoodBite Hamblokjes | Potato, corn, wheat | Vegetarian | [[15](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0015)] |
| Quorn Meatless Nuggets | Wheat starch | Vegetarian | [[16](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0016)] |
| Garden Gourmet Schnitzel | Wheat flour, corn | Vegetarian | [[17](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0017)] |
| Vivera Kaasschnitzel | Wheat | Vegetarian | [[18](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0018)] |
| Vivera Wokreepjes | Wheat | Vegetarian | [[19](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0019)] |
| Albert Heijn Stukjes Als Van Kip | Wheat | Vegetarian | [[20](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0020)] |
| De Vegetarische Slager Visvrije Tonyn | Unknown | Vegetarian | [[21](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0021)] |
| De Vegetarische Slager MC2 Burger | Wheat | Vegetarian | [[22](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0022)] |
| Moving Mountains Burger | Wheat | Vegan | [[23](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0023)] |
| Moving Mountains Sausage | Wheat | Vegan | [[24](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0024)] |
| Beyond burger | Potato | Vegan | [[25](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0025)] |
| Vivera Krokante Schnitzel | Wheat | Vegan | [[26](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0026)] |
| Vivera Balletjes | Potato | Vegan | [[27](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0027)] |
| Vivera Steak | Wheat | Vegan | [[28](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0028)] |
| Vegan Zeastar Zalmon Sashimi | Tapioca | Vegan | [[29](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0029)] |
| Gardein Beefless Strips | Wheat | Vegan | [[30](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0030)] |
| Gardein Beefless Tips | Potato | Vegan | [[31](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0031)] |
| Gardein Chicken Strips | Potato | Vegan | [[32](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0032)] |
| Tofurky Chick'n | Corn | Vegan | [[33](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0033)] |
| Like Schnitzel | Corn, potato | Vegan | [[34](https://onlinelibrary.wiley.com/doi/full/10.1002/star.202100157#star202100157-bib-0034)] |

A lot of basic research as well as commercialization have focused on thermoplastic starch (TPS). Starch can be melt processed in an extruder like other more common polymers by adding small amounts (10%-30%) of water and/or plasticizers including glycerol, sorbitol, propylene glycol, urea, and triethylene glycol. TPS-based polymers include drawbacks such as low strength, moisture sensitivity, and propensity for brittleness. The average tensile strength of TPS formulations is less than 6 MPa (Zhang et al., 2014), which is significantly lower than that of commercial oil-based polymers such cellulose acetate (which has the highest tensile strength), maize starch, kraft paper, etc.

The market for starch-based bioplastics was valued at $424 million in 2016 by Allied Market Research, with a CAGR of 3.7% (Roy, 2017).  The European Bioplastics Association calculated that starch blends accounted for 840 million pounds, or 18.8%, of the global bioplastics capacity in 2017.

(Plant-based materials and transitioning to a circular economy Randal Shogren a , Delilah Wood b , William Orts b , Gregory Glenn b,∗ <https://doi.org/10.1016/j.spc.2019.04.007>)

**Conclusion**

As a result of placing a higher priority on health, well-being, and social & environmental consciousness, the health-conscious buyer market has recently turned to eating more sustainably and naturally, which has raised awareness of "clean-label food". In this context, this review provided an overview of native starches from a range of non-conventional and underutilised sources and their modification using environmentally safe physical, enzymatic, and other approaches. Physical and enzymatic modification processes can significantly enhance the characteristics of native starch by changing its physicochemical properties, functionalities and structural attributes and increasing its technical value as a clean label starch because they are free from artificial and synthetic ingredients. Furthermore, it discusses innovative uses of clean-label starch, such as the production of biodegradable and nano-composite films, starch-protein-lipid complexes, and plant-based alternatives in the food industry.

It is important to look for research possibilities to more fully comprehend and utilise uncommon and underused starches. It is crucial to emphasise the genetic variety of starch characteristics and to conduct comparisons between unconventional and industrially important starches. Such starches should be examined for modifications and uses, and a life-cycle analysis of their manufacturing should be conducted for environmentally friendly production. Relationships between an individual starch's structure, function, and utilisation are crucial for expanding applications. Moreover, Starch-based materials have a lot of potential and demand for usage in applications including fertiliser and water treatment. Therefore, it is necessary for academics and researchers to investigate this direction.