processes

MDPI

Review

A Review on Sweet Potato Syrup Production Process: Effective Parameters and Syrup Properties

Kowsar Rezvanian [1], Shahryar Jafarinejad [1,*] and Adelia C. Bovell-Benjamin [2]

[1] Department of Chemical Engineering, College of Engineering, Tuskegee University, Tuskegee, AL 36088, USA; krezvanian8358@tuskegee.edu
[2] Department of Food and Nutritional Sciences, College of Agriculture, Environment and Nutrition Sciences (CAENS), Tuskegee University, Tuskegee, AL 36088, USA; abovellbenjamin@tuskegee.edu
* Correspondence: sjafarinejad@tuskegee.edu

Abstract: Sweet potato is always considered a food item that gives a sufficient stock of calories, nutrients, and minerals, and its syrup has numerous applications in the food industry. There is a need to review sweet potato syrup production processes in order to develop cost-effective and reliable designs for its production. The overall objective of this study is to update the current knowledge of the sweet potato syrup production processes and factors affecting its production. This study briefly reviews the sweet potato (its varieties, cultivation, and chemical composition/nutritional values), syrup production processes (acidic hydrolysis, enzymatic hydrolysis, acid–enzyme hydrolysis, and other processes to improve the quality of syrup), and effective parameters (e.g., enzyme type, enzyme dosage, temperature, pH, the role of water, and the role of starch and starch pretreatment) on the syrup production process. Finally, based on the gaps identified in the area, it discusses the conclusions and future outlook.

Keywords: sweet potato; starch; syrup; enzyme; hydrolysis

Citation: Rezvanian, K.; Jafarinejad, S.; Bovell-Benjamin, A.C. A Review on Sweet Potato Syrup Production Process: Effective Parameters and Syrup Properties. *Processes* **2023**, *11*, 3280. https://doi.org/10.3390/pr11123280

Academic Editor: Bing-Huei Chen

Received: 24 October 2023
Revised: 13 November 2023
Accepted: 19 November 2023
Published: 23 November 2023

1. Introduction

Sweet potato (*Ipomoea batatas* (L.) Lam) has unique features and nutritional values compared with other root crops. It can be considered a natural source of calories in the human diet due to its unique agronomic features, high calories, energy, dietary fiber, vitamins, mineral content, and high dry matter yield per unit area of land under proper cultivation [1–3]. Therefore, compared with any other food resource, not only can it provide food and nutritional products for more people per unit hectare but it can also help reduce food shortages in developing and developed countries [4,5].

Generally, features such as high drought tolerance, adaptability to various climates and farming systems, high yielding, and nutritional values can make a crop play an important role in people's diet and producers' cash income [6]. Large amounts of roots are destroyed, especially in developing countries, due to challenges such as poor storage management, food insecurity issues, limited transport infrastructure existence, droughts, and limited agricultural technologies. Hence, processing these roots into other useful and value-added products is imperative [7].

Depending on both genetic and environmental factors (e.g., soil type, light, etc.), the nutrient and chemical compositions of sweet potato roots vary [7]. Among the various nutrients present in sweet potatoes, protein content is notably diverse [7–9]. Carbohydrates contribute 80–90% of the dry matter content of sweet potato storage roots or 24–27% of the fresh weight. Starch and sugar contribute over 60% of dry matter [10]. Glucose, fructose, and sucrose are the sugars found in the raw sweet potato. However, sucrose is the major sugar in sweet potato roots [11–13]. Hence, based on its chemical composition, the bulk ingredients from the sweet potato can be processed into value-added and ready-to-use

products like sweeteners and syrups, with wide applications in industries such as food, pharmaceutical, space (for long-term space missions), and on-earth consumers [5,14–16].

Studies have reported that sweet potato's low glycemic index [1] has anti-diabetic properties, which makes it an appropriate food for people living with diabetes [1,17–20]. Nowadays, due to improved public health and food nutritional values awareness, consumers try to reduce their consumption of products with chemical treatments, additives, or preservatives as much as possible [6]. On the other hand, sweet potato has a high vulnerability to spoilage [21,22], with a shelf life of no longer than a few weeks [22]. Therefore, it is necessary to develop novel industrial methods to reduce its moisture content and to process it into value-added food products with longer shelf life such as starch, noodles, sugar, syrup, etc. [22,23].

Processing sweet potato into alternative products such as glucose and high fructose syrup (HFS), which are valuable sweeteners for the food and beverage industries, should be considered a solution for the increasing demand for sugar and the slight increase in sugar prices worldwide [24–26]. Starch processing has been extensively studied/discussed [27–34]. Processes used to hydrolyze starch are generally simple and relatively clean. They can be carried out either by acidic (hydrolyzed at low pH) or enzymatic processes. In the enzymatic hydrolysis process [27,28], investigating the effects of different factors such as type of enzyme and enzyme dosage and physical parameters such as temperature, pH, and time is important.

Bovell-Benjamin [7] reviewed the role of sweet potato in human nutrition [7]. Also, Zhu and Wang [35] reviewed physicochemical properties, molecular structure, and applications of sweet potato starch [35]. Furthermore, Wang et al. [9] thoroughly examined the chemical components and health benefits of sweet potatoes [9]. Sweet potato syrup has emerged as a promising ingredient in the food industry, with various potential uses such as sweeteners, pancake syrup, jams, etc. Thus, there is a need to conduct a review of the production processes involved in making sweet potato syrup in order to develop cost-effective and reliable methods for its production. This review aims to provide insights into the current knowledge of sweet potato syrup production. The study briefly reviews the sweet potato (its varieties, cultivation, and chemical composition/nutritional values), syrup production processes (acidic hydrolysis, enzymatic hydrolysis, acid–enzyme hydrolysis, and other processes to improve the quality of syrup), and effective parameters (e.g., enzyme type, enzyme dosage, temperature, pH, the role of water, and the role of starch and starch pretreatment) on the syrup production process. In addition, based on the gaps identified in the area, the review discusses the conclusions, recommendations, and future perspectives.

2. Sweet Potato Origin and Production

The origin of the sweet potato was suggested to be between the Yucatan Peninsula of Mexico and the Orinoco River in Venezuela [36]. According to historical records, sweet potato was known as a major food source by various indigenous populations in southern Central America and South America [37]. Previous studies by Roullier et al. [38,39], using chloroplast DNA and molecular phylogenetics, supported the sweet potato's hypothesized origin. Huang and Sun [40] also suggested Central America as the likely region with the highest genetic diversity.

Sweet potato is a vital economic crop in numerous countries [41] and was amongst the 15 largest agricultural products globally [22]. Countries such as Taiwan, China, Korea, and Japan use sweet potato starch as a raw material for several industrialized products such as beverages, industrial alcohol, ethanol, and sweeteners. Based on the Food and Agriculture Organization (FAO) of the United Nations, as of 2021, China was the largest sweet potato producer in the world. Tanzania and Nigeria followed China in sweet potato production [42]. Previous studies by Hijmans et al. [43], da Silva [44], and Mu and Li [45] had supported Africa's position as one of the largest sweet potato producers [43–46].

Between 2000 and 2014, sweet potato consumption in the United States was enhanced [47], possibly due to the widespread commercial availability of frozen "French-

fried" sweet potatoes. Among European countries, Portugal and Spain grow sweet potatoes, with 22,591 and 13,550 metric tons produced in 2014, respectively [48]. Despite the lack of significant growth in production over the past four decades, which has been attributed to limited public knowledge about the nutritional value of sweet potatoes and a decline in public consumption [49,50], sweet potatoes remain a vital protein source for a substantial proportion of the world's population [4,51].

2.1. Sweet Potato Varieties

Sweet potatoes are produced in different ranges of sizes, formats, and internal colors [7,52–54]. There are sweet potato varieties in different colors of skin and flesh. The sweet potato's nutritional profile varies depending on flesh color, offering β-carotene, anthocyanins, dietary fiber, vitamins, minerals, and other compounds [7,52]. The most commonly grown sweet potatoes are white and yellow/orange flesh varieties [7,53]. Some of the sweet potato varieties available in the United States include the Yellow Jersey, CA Oriental type, Japanese type, White type, One Beauregard, Okinawan type, and Beauregard White type [54]. Generally, each variety has its own characteristics, making it suitable for different culinary applications.

2.2. Sweet Potato Cultivation

Environmental and biophysical factors can affect sweet potato growth. Requirements for sweet potato growth have been discussed in the literature [55–58]. With growing in tropical and sub-tropical climates and in mild temperate regions [57], sweet potato growth is negatively impacted by heavy clay soils [54]. The soil should be rich in organic matter; to maximize sweet potato production, it is important to cultivate them in well-draining sandy loams with adequate moisture to effectively facilitate water drainage. The required pH should be between 5.6 and 6.6, and a temperature of at least 20 °C is needed and growth is negligible below 10 °C [57]. To grow and develop storage roots, it is necessary to maintain water supply during the first 40 days after planting and during the tuber formation stage (7 to 9 weeks after planting) [58].

2.3. Chemical Composition and Nutritional Values

Depending on the variety, soil type, and period of cultivation, the chemical composition of sweet potato may be different [22,59]. Sweet potatoes are rich in calories and nutrients, including protein [7,8]. In other words, they provide carbohydrates, minerals, carotenoids, dietary fiber, and vitamins. Sweet potato varieties typically contain high moisture [60–62]. The sweet potato vine's crude protein content is 18–30% dry matter, which is comparable to leguminous forages [63]. Also, Bovell-Benjamin [7] reported ranges of 4–27% and 1–9% for protein contents of sweet potato leaves and roots, respectively [7]. Research regarding sweet potato chemical and mineral composition shows that not only the sweet potato roots but also its leaves are very nutritious and can be used as any leafy vegetable [22,64].

Mineral and centesimal compositions of conventional and organic cultivars of sweet potato were studied by dos Santos et al. [65]. The average concentrations (mg/100 g) of minerals in conventional and organic cultivars, respectively, were reported as 23.5 and 40.7 (calcium); 0.082 and 0.159 (copper); 0.303 and 0.481 (iron); 197 and 381 (potassium); 166 and 35.7 (magnesium); 0.183 and 1.15 (manganese); 68.6 and 0.433 (sodium); 54.1 and 62.2 (phosphorus); and 0.197 and 0.261 (zinc). There were no significant differences between the centesimal compositions of conventional and organic cultivars, meaning that centesimal concentrations were reported to be 72 and 72% (moisture); 0.87 and 0.90% (ashes); 1.5 and 1.4% (proteins); 0.63 and 0.54% (lipids); 24.8 and 23.9% (carbohydrates) for conventional and organic cultivars, respectively [65].

Several studies reported that sweet potato components can have beneficial effects on human metabolisms, including but not limited to anti-inflammatory [66], anti-cancer [67], anti-diabetic [68,69], and anti-obesity [70] effects.

3. Syrup Production Processes

Syrup has been produced by direct and indirect methods [71–75]. Most research studies have emphasized the indirect method of sweet potato syrup production (converting sweet potato to starch and then utilizing the starch for syrup production) [5,15,16,71]. Only a few studies have reported the direct method of sweet potato syrup production or direct conversion of roots to syrup [10,75]. The aim of the direct use of tuber roots for producing glucose syrup was to overcome the cost related to starch production and to reduce production time [75]. However, it has been reported that the final product had an unacceptable dark color and a bitter taste [5].

Starch is the main component of the sweet potato root (6.9–30.7%) [76] and it is the main carbohydrate in roots [77]. One of the applications of starch is to produce products such as glucose, maltose, and coupling sugars using hydrolysis processes [78,79].

The procedures for starch production from roots share many common steps. The combination of the following steps is required for starch production: grinding the washed and peeled roots, homogenization with water, centrifugation for several times (the starch granules will sediment in water due to their higher density), dehydration, and milling [5,7].

Sweet potato syrup is made by heating a mixture of water and sweet potato/sweet potato starch, treating the slurry with acid and/or different types of enzymes at different stages and operating conditions until obtaining a desired product followed by cooling, clarifying, decolorizing, and concentrating the final syrup. In other words, the hydrolysis process is used to produce syrup [5,10,15,80]. The starch to syrup conversion can be achieved with the following techniques: (i) enzymatic hydrolysis (involving the treatment of a starch–water mixture with either a single enzyme or a combination of enzymes) [5,81–84]; (ii) acid hydrolysis [83,85] (employing a pH around 2 and temperatures exceeding 100 °C); and (iii) acid–enzyme hydrolysis [86], where an acid-converted hydrolysate undergoes further treatment with one or more starch-hydrolyzing enzyme.

3.1. Acidic Hydrolysis

Acidic hydrolysis is the original method of starch hydrolysis. Corrosion resistant materials are needed to carry out this process [83]. In this method, a starch slurry is subjected to treatment with an acid such as hydrochloric acid (HCl) at high temperatures and a low pH (around 2) for a specified duration [86]. The acid breaks down the glycosidic bond between monosaccharides, allowing water molecules to penetrate the starch granules and cause expansion [87,88]. Parameters including acid solution, concentration, and treatment time can affect the efficiency of acid treatment [85,89,90].

Numerous advantages that acid hydrolysis presents include relatively simple installation, inexpensive acid catalyst or low prices for the materials, and short hydrolysis time [91]. Disadvantages of this method include but are not limited to the need for corrosion resistant materials, more energy usage for heating, and difficulty controlling the reaction [83]. To avoid these constraints and to reduce the energy consumed, enzymatic hydrolysis [92] has been used/introduced. Also, as the enzymatic hydrolysis process has the potential to generate high yields of desired products and less unwanted materials, it is usually preferred [93].

3.2. Enzymatic Hydrolysis

In 1833, Payen and Persoz [94] published the first scientific article on the enzymatic conversion of starch, a method that utilizes amylases to degrade raw starch. Since then, researchers have focused on optimizing the enzymatic hydrolysis process by considering various effective factors such as enzyme selection, immobilization, and genetic modifications and physical parameters such as temperature, pH, time, and concentration. These factors greatly influence the efficiency and effectiveness of the hydrolysis process. Enzymatic hydrolysis generally needs a longer processing time compared with other methods [95]. This prolonged period allows the enzymes sufficient time to fully break down the starch molecules into their constituent sugars. The enzymatic hydrolysis of sweet potato starch to glucose syrup involves a series of steps. Firstly, gelatinization of the starch takes

place. This is followed by dextrinization or liquefaction, which occurs after gelatinization through the action of α-amylase. Finally, saccharification takes place, leading to the further conversion of maltodextrins into glucose [7,15,96].

In order to convert raw starch to other processed products, gelatinization should be applied [92]. Gelatinization or destruction of the crystalline structure of starch can significantly increase the digestibility of the starch due to diffused amylose chains [97]. In this step, starch with excess water is heated (the temperature for gelatinization of sweet potato starch is reported to be in the range of 58 to 90 °C) [76].

The liquefaction process is an enzymatic method that uses heat-stable enzymes (commonly α-amylase enzymes from various sources) to treat a starch slurry and produce a soluble dextrin called amylodextrin [81]. This stage decreases the viscosity of the slurry and typically requires high temperatures. α-amylase enzymes fall under the category of endo-enzymes, signifying their action on glycosidic bonds and leading to the formation of dextrins with varying molecular weights. This process involves the cleavage of α,1,4-glycosidic bonds, resulting in the production of shorter chains of soluble dextrins [98,99].

The formation of some insoluble components in liquefaction is also expected. Their formation can be limited by using diatomite, and remaining insoluble compounds can be liquified by α-amylase, followed by fungal glucoamylase [81,100,101] or both enzymes jointly [81,102,103] may be helpful.

In order to produce sugar syrups with varying degrees of dextrose equivalent (DE) and disaccharides such as maltose and other lower saccharides, it is necessary to undergo saccharification, which completely converts maltodextrins into glucose and other saccharides [81]. Saccharification is a crucial step in the manufacturing process of sugar syrups, enabling the production of a wide range of products with varying compositions. Different factors, including the enzyme type, concentration, and reaction time, can impact the saccharification efficiency [81,104]. The saccharification of starch usually needs a combination of hydrolyzing enzymes such as α- and β-amylases, pullulanase, and glucoamylase [81,105]. It has been observed that the enzyme glucoamylase can effectively cleave 1,4 terminal bonds present in the degraded molecules to release a single glucose unit at a time [72,106]. Although the saccharification process is slower than the liquefaction process, it can be expedited by more than 50% with the use of fresh substrates and enzymes [81].

Overall, enzymatic hydrolysis can represent some advantages over acid hydrolysis [107].

3.3. Acid-Enzyme Hydrolysiss

The acid–enzyme hydrolysis of starch is applied in some industries [108], such as the conversion of starch to sweetener. In other words, the other method of syrup production is the acid–enzyme process. In this method, acid hydrolysis (e.g., using hydrochloric acid) is combined with the second stage of hydrolysis, which is an enzymatic hydrolysis (e.g., using appropriate enzymes like α-amylase and glucoamylase), to produce glucose syrup [86,109,110].

3.4. Other Processes to Improve the Quality of Syrup

In addition to the main steps for syrup production, other processes such as filtration, decolorization, and concentration/evaporation can be applied to improve the quality of the final product. After hydrolysis, the dilute syrup can be passed through a column to remove impurities, thus improving its color. Silayo et al. [10] studied the ash content and color of the produced sweet potato syrup using a system comprising filtration, deionization, and concentration. The filtration process consisted of vacuum filtration alone and combined with centrifuging. The vacuum filtration method resulted in a product with reduced pigmentation, albeit at a slow rate [10].

Ion exchange is used in the sweetener industry for demineralization, specifically for the production of high purity products. Ion exchange can be used to produce syrup with

low ash content [10]. It plays an important role in the production of desired sweeteners, as it improves the color of the syrup while substantially reducing the ash level and improving the flavor [86]. Depending on the specific needs of the final product, the ion exchange process can be used alone or in combination with other techniques, such as filtration [10] or activated carbon treatment.

In order to enhance the profitability of glucose syrup, it is crucial to minimize the dark color and make it more amber- or light-colored. One possible approach to achieve this goal is to use activated carbon, which has been demonstrated to be effective in reducing color precursors and off-flavors. This method has been explored in the work of Aït-Aissa et al. [111] and has been shown to be effective in improving the quality of glucose syrup by removing unwanted compounds [111].

Evaporation is a key process in the production of syrup due to its significant impact on raising the solids' concentration of the syrup, which is typically measured in degrees Brix. The evaporation process involves heating the solution to a controlled temperature and pressure, usually in a vacuum evaporator, to remove water and concentrate the solids [10].

4. Sweet Potato Syrup Production

Historically, several engineering methods [112–118] have been used to enhance the starch hydrolysis process. These methods may include the use of fluidized-bed reactors and fixed-bed reactors among others. For instance, fluidized-bed reactors offer higher enzyme activity and operational stability in the enzymatic reaction [112,113]. Also, continuous recycling membrane reactors can help address the issue of enzyme activity loss during starch hydrolysis [115].

The hydrolysis of starch has extensively been discussed in the literature [119–134]. A summary of different methods for sweet potato starch hydrolysis and/or sweet potato syrup production is listed in Table 1.

Lee and Kim [92] examined the optimal conditions for gelatinization and liquefaction of starch slurry. A single-step liquefaction and saccharification process, which utilized a heat-stable α-amylase, was used. The DE value for the saccharification of liquefied starch was selected to be 10. The study demonstrated that the percentage of gelatinization of sweet potato and corn starches was in the range of 80.4–89.8% at 110 °C, without considering starch moisture content [92]. Miller et al. [5] prepared sweet potato starch syrup with acceptable physicochemical and viscometric properties (refractive index (RI), color, and viscometric values). The sweet potato syrup's viscosity increased gradually during its storage [5]. In another work, Bovell-Benjamin et al. [15] examined the effect of α-amylase concentration, effect of storage (room and refrigerate) on the syrup stability, and consumer acceptance of the syrup. They concluded that 4.5 mL α-amylase had a higher syrup yield, higher RI, °Brix, and shorter filtration than the 3 mL α-amylase. The storage examination showed that °Brix increased in the refrigerated sweet potato starch syrup, which led to crystallization after 12 weeks [15].

Johnson et al. [135] studied the potential use of cassava/sweet potato flours and blends with rice or wheat for HFS production. The study revealed that the cassava–rice flour blend yielded a saccharified slurry with 70–72 g reducing sugars/100 g, which was greater than that of native cassava flour (69%). In contrast, when sweet potato was combined with rice or wheat, the resulting saccharified mash exhibited a reduced content of reducing sugars, typically ranging from 60% to 66% [135]. Meanwhile, Johnson et al. [75] achieved the direct production of fructose syrup from sweet potato and cassava roots. They concluded that the direct hydrolysis of root slurry using Stargen can potentially decrease the production cost of HFS [75].

Table 1. Summary of sweet potato starch hydrolysis and/or sweet potato syrup production studies reported in the literature.

Objectives	Enzymes/Acids	Production Process Steps	Operating Conditions/Method	Major Findings	Reference
Single step gelatinization and liquefaction of sweet potato and corn starch	α-amylase	Single step gelatinization and liquefaction	A single-step process was used to gelatinize and liquefy a 20% (*w*/*w*) starch slurry containing 1% (*w*/*w*) α-amylase solution by heating it at 95 °C and a pH of 6.5 in a steam-jacketed kettle. Starch powder was fed into an extrusion cooker at a rate of 10 kg/hr, with added water at rates of 2–6 kg/hr to achieve moisture contents of 20%, 30%, 40%, 50%, and 55% (*w*/*w*). The slurry was stirred at a rate of 180 rpm, while the temperature was varied at 110 °C, 120 °C, 130 °C, and 135 °C; the concentration of added α-amylase ranged from 1% to 4% (*w*/*w*).	❖ Gelatinization and liquefaction time for 20% starch slurries in a kettle at 95 °C was 45 to 50 s. ❖ The gelatinization rates of sweet potato and corn starches were found to be in the range of 80.4–89.8% when heated to 110 °C, regardless of the moisture content of the starches. ❖ Sweet potato starch could be easily gelatinized and liquefied in an extruder when compared with corn starch. ❖ An increase in α-amylase added could enhance DE values of liquefied starch.	[92]
Designing a lab-scale system for conversion of sweet potato starch into glucose syrup	Diastase of malt Dextrozyme C	Gelatinization Liquefaction Saccharification Filtration Deionization Evaporation	The system consisted of several units, including a blender, a continuous stirred tank reactor (CSTR), centrifugal and vacuum filters, a deionization column, and an evaporator. An amount of 300 g sweet potato starch and water (ratio of 1:2) was homogenized; gelatinization took place at a temperature of 85 °C for 30 min, the mixture was hydrolyzed in the CSTR with 0.5 g $CaCl_2$ to enhance stability of the α-amylase enzyme. For liquefaction, the pH and temperature were 6.9 and 50 °C, respectively. Diastase of malt was added and incubated for 3 h. For saccharification, the conditions employed were a pH of 4.5 and a temperature of 60 °C. A volume of 2 mL of Dextrozyme was added and incubated for a period of 24 h. Slurry was centrifuged and vacuum filtered. Evaporation was at 100 °C bath and centrifuge filter was at 6600 rpm.	❖ Reducing sugar concentrations of 259 and 310 mg/mL in 150 mL syrups were reported in processing batches utilizing centrifuge and vacuum filter in series and vacuum filter alone, respectively. ❖ Through concentration trials, 100 mL and 70 mL volumes of syrup were produced with DEs of 281 and 213 mg/mL, respectively. ❖ The resulting syrups had a brownish color.	[10]
Production of syrup from sweet potato starch and evaluation of its physicochemical properties such as refractive index and color, as well as its viscometric properties during syrup storage	α-amylase Glucoamylase	Gelatinization Liquefaction Saccharification Filtration Evaporation	A mixture of 30 g sweet potato starch and 400 mL water was heated to 102 °C and treated with α-amylase at 90 °C for 5 h, then the mixture was cooled for saccharification. Glucoamylase was added at a temperature of 62.5 °C and incubated for 12 h. Storage temperatures were 21 ± 4 °C (room temperature) and 4 °C.	❖ Sweet potato syrup had a higher refractive index (1.4 ± 0.02) than the previously reported literature value of 0.7. ❖ The sweet potato syrup had mean L* (representing lightness/darkness), a* (representing redness/greenness), and b* (representing yellowness/blueness) values of 68.8 ± 0.6, 0.7 ± 0.1, and 18.7 ± 0.6, respectively. ❖ The sweet potato syrup's viscosity increased gradually during its storage.	[5]

Table 1. *Cont.*

Objectives	Enzymes/Acids	Production Process Steps	Operating Conditions/Method	Major Findings	Reference
Effect of different concentrations of α-amylase on syrup characteristics, shelf life, and consumer acceptance of the syrup	α-amylase Glucoamylase	Gelatinization Liquefaction Saccharification Filtration Evaporation	A mixture of 30 g sweet potato starch and 400 mL distilled water was heated to 102 °C, then it was cooled to 90 °C; α-amylase was added, the mixture was incubated in a water bath at 90 °C for 6 h and then it was cooled to 25 °C and the pH was adjusted to 6.4 to stop the hydrolysis process. Glucoamylase was added and the mixture was incubated at 62.5 °C for 12 h, then the mixture was filtered and evaporated.	❖ In the 4.5 and 3.0 α-amylase-treated syrups, the refractive index was measured at 1.5 and 1.4, respectively. ❖ The 4.5 mL α-amylase-treated syrup had a higher moisture content (16.7 vs. 12.5) and °Brix (65.0 vs. 57.0) in comparison with 3.0 mL α-amylase-treated syrup. ❖ During storage, the °Brix and L* color values of refrigerated syrup were observed to be higher ($p < 0.05$) than those stored at room temperature. ❖ In syrup tasted by children aged 12–13 years old, there was no significant difference between the sweet potato starch syrup and maple syrup.	[15]
Direct use of cassava and sweet potato root slurry for glucose production through six treatment systems. The treatment systems included Liquezyme-Dextrozyme (treatment1, T1), Stargen (treat-ment2, T2), Stargen in two split doses (treatment3, T3), Spezyme–Stargen (treatment4, T4), Stargen at 60 °C (treatment5, T5), and Spezyme–Stargen at 60 °C (treatment6, T6).	Liquezyme-X Dextrozyme-GA Spezyme® Stargen™	Gelatinization Liquefaction Saccharification Isomerization Filtration Evaporation	T1 involved Liquezyme-X for incubation at 90 °C for 1 h, followed by incubation with Dextrozyme-GA at 60 °C for 48 h. T2 involved gelatinization and Stargen for incubation at room temperature for 48 h. T3 involved two doses of Stargen for incubation at different temperatures and times. T4 involved Spezyme for incubation at 90 °C for 30 min, followed by Stargen for incubation at 30 ± 1 °C for 48 h. T5 involved gelatinization at 95 °C for 15 min, followed by Stargen for incubation at 60 °C for 48 h. T6 involved Spezyme for incubation at 90 °C for 30 min, followed by Stargen for incubation at 60 °C.	❖ The conversion rate to glucose was greater in T1–T4 (95–98%) than in T5 and T6 (88–92%). ❖ The production cost of HFS could be lowered through a direct hydrolysis of root slurry utilizing Stargen. ❖ The yields of glucose and fructose were more from cassava than sweet potato due to the high initial starch content. ❖ Starch from sweet potato or cassava root slurry could be directly hydrolyzed to glucose at temperature (30 ± 1 °C) and pH 4.5 using enzyme Stargen™ 001, which could then be effectively isomerized to fructose.	[75]
Investigation of the use of native cassava and sweet potato flours and their mix with rice and wheat flours for HFS production to tackle the production costs related to starch preparation.	Liquezyme-X (thermostable α-amylase) Dextrozyme-GA (glucoamylase) Sweetzyme-T (immobilized glucose isomerase)	Gelatinization Liquefaction Saccharification Isomerization	After preparation of a 25% (w/v) suspension of the native cassava or sweet potato and their blends (pH 6.5) and equilibrating at temperature of 90 °C for 10 min, Liquezyme was added and incubated at temperature of 90 °C for 1 h. Then, the solution was cooled to 60 °C at a pH of 4.0 and Dextrozyme-GA was added. The slurry was incubated for 48 h. For isomerization, immobilized glucose isomerase was used at a pH of 7 and incubated at temperature of 60 °C for 48 h.	❖ Cassava/rice flour blends produced saccharified slurry with higher reducing sugar content (70–72 g/100 g) than native cassava flour (69%), while sweet potato blends had lower reducing sugar content (60–66%). ❖ Fructose conversion rates were similar (42–43%) for cassava/sweet potato blends and blends with cereal flours, which higher fructose yields observed in native cassava flour and cassava/rice mixtures (28–29 g/100 g).	[135]

Table 1. *Cont.*

Objectives	Enzymes/Acids	Production Process Steps	Operating Conditions/Method	Major Findings	Reference
Improving the quality and storage stability of an isomerized sweet potato starch syrup.	α-amylase Glucoamylase Glucose isomerase Pullulanase	Gelatinization Liquefaction Saccharification Isomerization	A blend of sweet potato starch (30 g) with 400 mL distilled water was heated to 100 °C. For liquefaction, the pH was adjusted to 4.5 and α-amylase was added and incubation took place at 90 °C for 2 h. Saccharification was conducted using pullulanase and glucoamylase at 62 °C and a pH of 7.5 for 48 h. Isomerization took place using glucose isomerase at 60 °C for 5 h. Then, vacuum-filtered and concentrated to 63–73.9 °Brix.	❖ Mean fructose content was 7.6 ± 0.4%. ❖ The sweet potato starch syrup had significantly higher ($p < 0.05$) mineral content compared with ginger and pancake syrups. ❖ Increasing the shear rate caused the sweet potato starch syrup, pancake syrup, and ginger syrup to exhibit a shear-thinning behavior due to the decrease in their apparent viscosity. ❖ Viscosity of syrup during 70 days of storage decreased as shear stress increased.	[16]
Assessing the potential of arrowroot, cassava, Curcuma, dioscorea, and sweet potato starches relative to corn starch to produce high fructose syrup.	Liquezyme-X Dextrozyme-GA Sweetzyme-T	Liquefaction Saccharification Isomerization	A mixture of 20% (w/v) of starch was prepared. For liquefaction, 0.1% (v/w) α-amylase was added at a pH of 7 and incubated at temperature of 90 °C for 1 h. For saccharification, (0.2% v/w) Dextrozyme was added (pH 4.0) and incubated at 60 °C for 48 h. Glucose syrup was filtered and concentrated to 40% (w/v) solids. For isomerization, 50 mg of Sweetzyme T/g glucose and $MgSO_4 \cdot 7H_2O$ (16 mg) were added at a pH of 7.5 and incubated at temperature of 60 °C for 24 h.	❖ The conversion of starch to glucose was either equivalent or superior for arrowroot, Curcuma, and cassava starches compared with corn starch. ❖ The sugar profile of the saccharified slurry for arrowroot, Curcuma, and cassava starches contained a high proportion of glucose (98.28–98.84%) and lower amounts of maltose and maltotriose (1.03–1.69% and 0.03–0.10%, respectively), whereas other starches had a lower range of glucose (94.76–97.28%) and higher levels of maltose and maltotriose (2.0–4.3% and 0.49–0.75%, respectively).	[71]
Exploring the impact of time, enzyme dosage, and temperature on glucose levels during a two-step optimized enzymatic hydrolysis of sweet potato peel.	α-amylase Glucoamylase	Gelatinization Liquefaction Saccharification	A 27.5% (w/v) starch slurry was prepared (10 g of flour was added into 20 mL of a 26 ppm $CaCl_2$ solution) at a pH of 6.5; gelatinization took place at 97 °C. A Box–Behnken experimental design was used to optimize liquefaction and saccharification processes with 17 experiments. The variables included time (20, 40, 60 min for liquefaction and 10, 35, 60 min for saccharification), enzyme doses % (v/v) of glucoamylase and α-amylase (0.5, 0.75, 1), and temperatures of 50, 60, 70 for liquefaction and 40, 50, 60 for saccharification.	❖ The statistical model demonstrated the highest glucose concentration as 126.66 g/L by setting the temperature at 56.4 °C, α-amylase dose at 1% (v/v), and time for 60 min for the liquefaction step. ❖ The statistical model for the second step showed that the highest glucose concentration was 178.39 g/L, at a temperature of 45 °C, glucoamylase dose at 1% (v/v), and time of 60 min.	[72]
Investigating particle size and solid-to-liquid ratio effects on the hydrolysis of sweet potato starch with endogenous enzymes.	Sweet potato endogenous enzymes	Liquefaction Saccharification	Liquefaction was conducted at 71.5 °C and a pH of 6 for 25 min. For saccharification, temperature, pH, and time were 53 °C, 5.5, and 72 h, respectively.	❖ Smaller tubers enhance enzyme mobility but lower sugar concentration. ❖ Utilizing the endogenous enzymes of sweet potatoes for pre-hydrolysis can lead to a significant reduction in the amount of enzymes required for the conventional hydrolysis process, up to nearly 50%.	[34]

Table 1. *Cont.*

Objectives	Enzymes/Acids	Production Process Steps	Operating Conditions/Method	Major Findings	Reference
Producing glucose from potato tuber by acid hydrolysis	Sulphonated salicylic acid A/B HCl		Starch solutions were prepared using HCl or solid acid. Then, the solutions were stirred for 6 h at 50 °C. The resulting solutions were filtered. Dinitrosalicylic acid solution was added to the filtrate and the solution was boiled in water bath for 5 min and cooled.	❖ The use of mineral acid (HCl) for hydrolysis results in a greater yield of glucose compared with solid acid. ❖ The solid acid can be conveniently filtered and reused multiple times. ❖ Hydrolysis of starch using distilled water does not yield glucose, and solid acid B proves more effective than acid A due to the presence of more or bulkier acidic groups.	[93]

5. Effective Parameters on the Syrup Production Process

Operating parameters play a crucial role in the syrup production process. The effects of operating factors, including enzyme type, enzyme dosage, temperature, pH, the role of water, and the role of starch and starch pretreatment on syrup production, are discussed in this section.

5.1. Enzyme Type

Starch is composed of amylose and amylopectin. Amylose is a linear polymer containing α-1,4-linked glucose units, whereas amylopectin contains branched chains including α-1,4 and α-1,6 linkages [136–138]. Amylase refers to a group of enzymes that facilitate the hydrolysis of starch, breaking down the polymer into individual glucose molecules. In other words, these enzymes can be applied in the industry for the hydrolysis of starch [137]. Dunn [136] developed a model for the breakdown of starch granules by mixtures of α-amylase and β-amylase [136].

Starch hydrolyzing enzymes have extensively been explored and discussed in the literature [137–154]. α-amylase, β-amylase, glucoamylase, and pullulanase are the major amylolytic enzymes typically used in the industrial processes of starch enzymatic hydrolysis [138]. α-amylase can cleave both amylose and amylopectin molecules [137] and release glucose monomers by acting on all the α-1,4 glycosidic bonds except those near the branch points [23], whereas β-amylase can release maltose from the non-reducing ends of amylose and amylopectin molecules [23,137]. Debranching enzymes, including pullulanase and isoamylase, can only catalyze the hydrolysis of α-1,6 glycosidic bonds at the branch point of amylopectin [23]. D-glucose (dextrose) syrups and crystalline D-glucose can be produced using a combination of α-amylase and glucoamylase [137]. Glucose isomerase, also known as xylose isomerase, can catalyze isomerization of D-glucose to D-fructose and is utilized for high fructose syrup production [137,150,151].

Norman [140] reported that the optimal temperature and pH of the pullulanase (60 °C and pH 5.0) could be similar to those of Aspergillus niger glucoamylase and soybean β-amylase [140]. Hesam et al. [3] stated that sweet potato's β-amylase enzyme is active in a wide range of pH levels (3.5 to 7.5), making it beneficial in processes that need a wide range of pH alterations [3].

Enzymes that have been utilized in the sweet potato syrup production process have been listed in Table 1. Utilizing the endogenous enzymes of sweet potatoes for pre-hydrolysis can result in a substantial reduction in the amount of enzyme required for the conventional hydrolysis process [34].

5.2. Enzyme Quantity

The quantity of enzymes can significantly affect the hydrolyzing and converting of starch into glucose syrup. Bovell-Benjamin et al. [15] used three levels of thermo-stable bacterial α-amylases (1.5, 3.0, and 4.5 mL) for the conversion of sweet potato starch into glucose syrup. Results indicated that 4.5-mL α-amylase-treated starch had a significantly higher conversion ($p < 0.05$) compared with 1.5- and 3.0-mL levels [15]. Lee and Kim [92] reported that an increase in α-amylase added could enhance DE values of liquefied sweet potato starch [92].

5.3. Temperature

Enzymes have optimal performance temperatures, and understanding the temperature effects is essential for various industrial and biological processes. Temperature can affect the reaction during starch degradation. Kim et al. [155] reported that increasing the reaction temperature from 50 °C to 60 °C could enhance the degradation rate of potato raw starch granules because of effective enzyme attacks on these granules at 60 °C [155]. The optimal temperatures of α-amylase and β-amylase were reported as 71 °C and below 75 °C, respectively [156].

5.4. pH

The pH level is an important factor in starch hydrolysis as it can influence the activity of enzymes involved in the process, thus impacting the extent of hydrolysis [29]. Purwadi et al. [34] performed liquefaction (at 71.5 °C and pH 6 for 25 min) and saccharification (at 53 °C and pH 5.5 for 72 h) processes in the hydrolysis of sweet potato starch using endogenous enzymes [34]. Lee and Kim [92] carried out gelatinization and liquefaction of sweet potato and corn starches at 95 °C and pH 6.5 in a steam-jacketed kettle with α-amylase (a single step process) [92]. Johnson et al. [75] reported the direct conversion of cassava or sweet potato root slurry to glucose using the improved enzyme, Stargen™ 001, at 30 ± 1 °C and pH 4.5 [75].

5.5. Role of Water

The presence of water plays a key role in hydrolysis, particularly in the enzymatic hydrolysis of starch. Heating starch molecules in excess water can result in disrupting the crystalline structure and linking water molecules to the hydroxyl groups of amylose and amylopectin that can enhance granule swelling and solubility [157]. In a solution with an initial starch concentration of 35%, about 5% of the initial water content is needed for theoretical complete conversion of starch into glucose via hydrolysis. Van der Veen et al. [158] have discussed starch hydrolysis under low water conditions [158].

5.6. Role of Starch and Starch Pretreatment

Form, functionality, and hydrolysis of starch have been discussed in detail in the literature [159,160]. The digestibility of starch can be influenced by several factors, including granule size and shape, crystallinity, amylose to amylopectin ratio, and phosphate and lipid content on the surface of starch granules [159–163]. In other words, the size of starch granules, along with their surface characteristics and degree of crystallinity, can play an important role in determining their rate of digestion. Smaller granules with increased surface area are more digestible [164]. Kumakura and Kaetsu [165] reported that pretreated starch raw materials with mill could be effectively hydrolyzed using immobilized glucoamylase. Mechanical crushing treatments may affect enzymatic hydrolysis [165]. Generally, starch crystallography is divided into A, B, C, and V types, depending on their crystallographic characteristics, with amylose content affecting their crystalline structure. Cereal starches exhibit A-type (monoclinic); tubers and high amylose starches display B-type (hexagonal); legumes, certain fruits, and stems demonstrate C-type; and V-type is observed when amylose is complexed with lipids [166–170]. Enhanced levels of A-type crystalline structure and amylopectin side chains in the range of DP 6–24 contribute to an accelerated digestion rate [171]. Amylose content and amylopectin architecture can affect thermal properties and gel formation [159]. Wickramasinghe et al. [162] reported that high amylose can decrease starch gelatinization enthalpy and its effect is stronger than that of phosphate. Also, amylose contributes to the decreased swelling power [162]. Lipids in starch limit the accessibility of digestive enzymes to the starch granules, which can reduce the rate of starch digestion [172–174]. As phosphate content affects the physicochemical properties of starch, it can also influence starch digestibility [175]. Noda and Sarker [176] studied the enzymatic digestibility of various raw and gelatinized starches (e.g., potato, sweet potato, cassava, and yam starches) and reported that higher values of phosphorus content are typically associated with lower digestibility in raw and gelatinized starches [176].

6. Conclusions and Future Perspectives

This study provided an overview of sweet potato properties, syrup production processes, and effective parameters on syrup production. Sweet potato glucose syrup production can be a promising and viable alternative to traditional corn-based glucose syrup production. The use of sweet potato as a raw material can provide several benefits, including a more sustainable production process, as well as a potential for increased nutritional

value in the final product. Additionally, the use of enzyme technology can allow for more precise control over the hydrolysis process, resulting in a suitable yield of glucose syrup.

Two approaches can be applied for syrup production: (1) direct use of sweet potato root and (2) use of extracted starch for syrup production. Sweet potato starch extraction is processed through the following steps: grinding the washed and peeled roots, homogenization with water, centrifuging several times, dehydration, and milling. Different methods can be applied to convert the starch into syrup, e.g., acidic conversion, enzymatic conversion, and acid–enzyme conversion. Acid hydrolysis is a simple method. However, disadvantages such as the need for corrosion resistant materials, more energy usage for heating, and difficulty controlling the reaction have shifted the option to enzymatic hydrolysis. Enzymatic hydrolysis of sweet potato starch consists of gelatinization, liquefaction, and saccharification. To improve the quality of syrup, the process can be followed by filtration and concentration.

Further investigations are still desirable to focus on optimizing the production process to improve the efficiency and cost-effectiveness of sweet potato glucose syrup production. This can include improving sweet potato syrup production and its storage, determining the key physical and chemical factors modulating the acceptance of sweet potato sweetener syrup by consumers, low-cost and appropriate sweet potato processing technologies and methods, exploring new enzymes or enzyme combinations that may be more effective in hydrolyzing sweet potato starch, and investigating new methods for pretreatment or refining of the raw material. In addition, continued efforts can be made to develop new applications for sweet potato glucose syrup in various industries, such as food, pharmaceuticals, etc. Improvement in these areas can contribute data and knowledge to the food industry.

Author Contributions: Conceptualization, K.R., S.J. and A.C.B.-B.; methodology, K.R., S.J. and A.C.B.-B.; investigation, K.R., S.J. and A.C.B.-B.; writing—original draft preparation, K.R.; writing—review and editing, K.R., S.J. and A.C.B.-B.; supervision, S.J. and A.C.B.-B.; project administration, A.C.B.-B. and S.J. All authors have read and agreed to the published version of the manuscript.

Funding: The authors acknowledge support from the USDA-NIFA under grant number 2019-38821-29157. Any opinions, findings, conclusions, or recommendations expressed in this paper are those of the authors and do not reflect the views of the USDA-NIFA.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funder had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Padmaja, G.; Sheriff, J.T.; Sajeev, M.S. Food uses and nutritional benefits of sweet potato. In *Fruit, Vegetable and Cereal Science and Biotechnology*; Nedunchezhiyan, M., Byju, G., Eds.; Global Science Books, 2012; Volume 6 (Special Issue 1), pp. 115–123. Available online: http://www.globalsciencebooks.info/Journals/FVCSB.html (accessed on 23 October 2023).
2. Ruiz, M.E.; Lozano, E.; Ruiz, A. Utilization of sweet potatoes (*Ipomoea batatas* (L.) Lam) in animal feeding. III. Addition of various levels of roots and urea to sweet potato forage silage. *Trop. Anim. Prod.* **1981**, *6*, 234–244.
3. Hesam, F.; Taheri Tehrani, R.; Balali, G.R. Evaluation of beta-amylase activity of sweet potato (*Ipomoea batatas*) cultivated in Iran. *J. Food Biosci. Technol.* **2015**, *5*, 41–48.
4. Woolfe, J.A. *Sweetpotato: An Untapped Food Resource*, 1st ed.; Cambridge University Press: New York, NY, USA, 1992.
5. Miller, S.A.; Dean, D.; Ganguli, S.; Abdalla, M.; Bovell-Benjamin, A.C. *Physicochemical and Viscometric Properties of a Sweetpotato Syrup*; SAE Technical Paper 2003-01-2620; SAE International: Warrendale, PA, USA, 2003.
6. Scott, G.J.; Rosegrant, M.W.; Ringler, C. Global projections for root and tuber crops to the year 2020. *Food Policy* **2000**, *25*, 561–597. [CrossRef]
7. Bovell-Benjamin, A.C. Sweet potato: A review of its past, present, and future role in human nutrition. *Adv. Food Nutr. Res.* **2007**, *52*, 1–59.
8. Purcell, A.E.; Walter, W.M., Jr.; Giesbrecht, F.G. Root, hill, and field variance in protein content of North Carolina sweet potatoes. *J. Agric. Food Chem.* **1978**, *26*, 362–364. [CrossRef]
9. Wang, S.; Nie, S.; Zhu, F. Chemical constituents and health effects of sweet potato. *Food Res. Int.* **2016**, *89*, 90–116. [CrossRef] [PubMed]

10. Silayo, V.C.K.; Lu, J.Y.; Aglan, H.A. Development of a pilot system for converting sweet potato starch into glucose syrup. *Habitation* **2003**, *9*, 9–15. [CrossRef]
11. Martin, F.W.; Deshpande, S.N. Sugars and starches in a non-sweet sweetpotato compared to those of conventional cultivars. *J. Agric. Univ. Puerto Rico* **1985**, *69*, 401–406.
12. Picha, D.H. HPLC determination of sugars in raw and baked sweetpotatoes. *J. Food Sci.* **1985**, *50*, 1189–1190. [CrossRef]
13. Tamate, J.; Bradbury, J.H. Determination of sugars in tropical root crops using ^{13}C N.m.r. spectroscopy: Comparison with HPLC method. *J. Sci. Food Agric.* **1985**, *36*, 1291–1302. [CrossRef]
14. Sarikaya, E.; Higasa, T.; Adachi, M.; Mikami, B. Comparison of degradation abilities of α- and β-amylases on raw starch granules. *Process Biochem.* **2000**, *35*, 711–715. [CrossRef]
15. Bovell-Benjamin, A.C.; Yousif-Ibrahim, S.; Gichuhi, P.; Bromfield, E. *Influence of α-Amylase on the Physical Properties and Consumer Acceptability of Sweetpotato Starch Syrup*; SAE Technical Paper 2005-01-3113; SAE International: Warrendale, PA, USA, 2005.
16. Dominque, B.; Gichuhi, P.N.; Rangari, V.; Bovell-Benjamin, A.C. Sugar profile, mineral content, and rheological and thermal properties of an isomerized sweet potato starch syrup. *Int. J. Food Sci.* **2013**, *2013*, 243412. [CrossRef]
17. Kusano, S.; Abe, H. Anti-diabetic activity of white skinned sweet potato (*Ipomoea batatas* L.) in obese zucker fatty rats. *Biol. Pharm. Bull.* **2000**, *23*, 23–26. [CrossRef] [PubMed]
18. Ludvik, B.; Waldhäusl, W.; Prager, R.; Kautzky-Willer, A.; Pacini, G. Mode of action of *Ipomoea batatas* (caiapo) in type 2 diabetic patients. *Metabolism* **2003**, *52*, 875–880. [CrossRef]
19. Björck, I.; Liljeberg, H.; Ostman, E. Low glycaemic-index foods. *Br. J. Nutr.* **2000**, *83* (Suppl. S1), S149–S155. [CrossRef]
20. Jenkins, D.J.; Kendall, C.W.; Augustin, L.S.; Franceschi, S.; Hamidi, M.; Marchie, A.; Jenkins, A.L.; Axelsen, M. Glycemic index: Overview of implications in health and disease. *Am. J. Clin. Nutr.* **2002**, *76*, 266S–273S. [CrossRef]
21. Hathorn, C.S.; Biswas, M.A.; Gichuhi, P.N.; Bovell-Benjamin, A.C. Comparison of chemical, physical, micro-structural, and microbial properties of breads supplemented with sweetpotato flour and high-gluten dough enhancers. *LWT-Food Sci. Technol.* **2008**, *41*, 803–815. [CrossRef]
22. Antonio, G.C.; Takeiti, C.Y.; De Oliveira, R.A.; Park, K.J. Sweet potato: Production, morphological and physicochemical characteristics, and technological process. *Fruit Veg. Cereal Sci. Biotechnol.* **2011**, *5*, 1–18.
23. Raigond, P.; Singh, B.; Dutt, S.; Joshi, A.; Ezekiel, R. Resistant starch production technologies—A review. *Potato J.* **2015**, *42*, 81–94.
24. Hanover, L.M.; White, J.S. Manufacturing, composition and applications of fructose. *Am. J. Clin. Nutr.* **1993**, *58*, 724S–732S. [CrossRef]
25. Khalid, N.M. Cassava starch for high fructose syrup production. In Proceedings of the 2nd International Symposium on Sweet Potato and Cassava, Kuala Lumpur, Malaysia, 14–17 June 2005.
26. White, J.S. Sucrose, HFCS, and fructose: History, manufacture, composition, applications, and production. In *Fructose, High Fructose Corn Syrup, Sucrose and Health. Nutrition and Health*; Rippe, J., Ed.; Humana Press: New York, NY, USA, 2014; pp. 13–33.
27. Singh, R.S.; Chauhan, K.; Singh, R.P. Enzymatic approaches for the synthesis of high fructose syrup. In *Plant Biotechnology: Recent Advancements and Developments*; Gahlawat, S., Salar, R., Siwach, P., Duhan, J., Kumar, S., Kaur, P., Eds.; Springer: Singapore, 2017; pp. 189–211.
28. Power, R.F. Enzymatic conversion of starch to fermentable sugars. In *The Alcohol Textbook*, 4th ed.; Jacques, K.A., Ed.; Nottingham University Press: Nottingham, UK, 2003; pp. 23–32.
29. Mishra, A.; Debnath, M. Effect of pH on simultaneous saccharification and isomerization by glucoamylase and glucose isomerase. *Appl. Biochem. Biotechnol.* **2002**, *102*, 193–199. [CrossRef] [PubMed]
30. White, J.S. Straight talk about high-fructose corn syrup: What it is and what it ain't. *Am. J. Clin. Nutr.* **2008**, *88*, 1716S–1721S. [CrossRef] [PubMed]
31. Synowiecki, J. The use of starch processing enzymes in the food industry. In *Industrial Enzymes*; Polaina, J., MacCabe, A.P., Eds.; Springer: Dordrecht, The Netherlands, 2007; pp. 19–34.
32. Pereira, C.R.; Resende, J.T.V.; Guerra, E.P.; Lima, V.A.; Martins, M.D.; Knob, A. Enzymatic conversion of sweet potato granular starch into fermentable sugars: Feasibility of sweet potato peels alternative substrate for α-amylase production. *Biocatal. Agric. Biotechnol.* **2017**, *11*, 231–238. [CrossRef]
33. Nakamura, K.; Ohto, M.A.; Yoshida, N.; Nakamura, K. Sucrose-induced accumulation of β-amylase occurs concomitant with the accumulation of starch and sporamin in leaf-petiole cuttings of sweet potato. *Plant Physiol.* **1991**, *96*, 902–909. [CrossRef] [PubMed]
34. Purwadi, R.; Lestari, D.; Lohoo, C.A.; Tirtaadji, J.L. The effect of size and solid content in hydrolysis of sweet potato starch using endogenous beta-amylase enzyme. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1143*, 012043. [CrossRef]
35. Zhu, F.; Wang, S. Physicochemical properties, molecular structure, and uses of sweet potato starch. *Trends Food Sci. Technol.* **2014**, *36*, 68–78. [CrossRef]
36. Austin, D.F. The taxonomy, evolution and genetic diversity of sweet potatoes and related wild species. In *Exploration, Maintenance, and Utilization of Sweet Potato Genetic Resources*; Gregory, P., Ed.; International Potato Center: Lima, Peru, 1988; pp. 27–59.
37. Sauer, J.D. Cultivated plants of South and Central America. In *Handbook of South American Indians, Bureau of American Ethnology Bulletin 143*; Steward, J., Ed.; Government Printing Office: Washington, DC, USA, 1950; Volume 6, pp. 487–543.
38. Roullier, C.; Benoit, L.; McKey, D.B.; Lebot, V. Historical collections reveal patterns of diffusion of sweetpotato in Oceania obscured by modern plant movements and recombination. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 2205–2210. [CrossRef]

39. Roullier, C.; Duputié, A.; Wennekes, P.; Benoit, L.; Fernández Bringas, V.M.; Rossel, G.; Tay, D.; McKey, D.; Lebot, V. Disentangling the origins of cultivated sweet potato (*Ipomoea batatas* (L.) Lam.). *PLoS ONE* **2013**, *8*, e62707. [CrossRef]
40. Huang, J.C.; Sun, M. Genetic diversity and relationships of sweetpotato and its wild relatives in Ipomoea series batatas (Convolvulaceae) as revealed by inter-simple sequence repeat (ISSR) and restriction analysis of chloroplast DNA. *Theor. Appl. Genet.* **2000**, *100*, 1050–1060. [CrossRef]
41. Food and Agriculture Organization (FAO). FAOSTAT, Crops and Livestock Products. 2016. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 23 October 2023).
42. Food and Agriculture Organization (FAO). FAOSTAT, Crops and Livestock Products. 2021. Available online: https://www.fao.org/faostat/en/#data/QCL (accessed on 23 October 2023).
43. Hijmans, R.J.L.; Huaccho, L.; Zhang, D. Description and analysis of a geo-referenced database of the global distribution of sweetpotato area. *Acta Hortic.* **2001**, *583*, 41–49. [CrossRef]
44. da Silva, J.B.C.; Lopes, C.A.; Magalhães, J.S. *Cultura da Batata Doce*; Embrapa: Brasília, Brazil, 2004.
45. Mu, T.H.; Li, P.G. Sweet potato: Origin and production. In *Sweet Potato, Chemistry, Processing and Nutrition*; Mu, T.H., Singh, J., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 5–25.
46. Food and Agriculture Organization (FAO). *Production Yearbook 1999*; FAO: Rome, Italy, 2001.
47. Food and Agriculture Organization (FAO). *FAO Statistical Yearbook 2015*; FAO: Rome, Italy, 2015.
48. Truong, V.D.; Avula, R.Y.; Pecota, K.V.; Yencho, G.C. Sweetpotato production, processing, and nutritional quality. In *Handbook of Vegetables and Vegetable Processing*, 2nd ed.; Siddiq, M., Uebersax, M.A., Eds.; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2018; Volume II, pp. 811–838.
49. Yamakawa, O.; Yoshimoto, M. Sweetpotato as food material with physiological functions. In *ISHS Acta Horticulturae 583: I International Conference on Sweetpotato. Food and Health for the Future*; ISHS: Leuven, Belgium, 2002; pp. 179–185.
50. Kays, S.J. Sweetpotato production worldwide: Assessment, trends and the future. *Acta Hortic.* **2005**, *670*, 19–25. [CrossRef]
51. Walter, W.M.; Collins, W.W.; Purcell, A.E. Sweet potato protein: A review. *J. Agric. Food Chem.* **1984**, *32*, 695–699. [CrossRef]
52. Bradbury, J.H.; Holloway, W.D. *Chemistry of Tropical Root Crops: Significance for Nutrition and Agriculture in the Pacific*; Australian Centre for International Agricultural Research: Canberra, Australia, 1988.
53. Onwueme, I.C. *The Tropical Root Crops: Yam, Cassava, Sweetpotato and Cocoyam*; John Wiley & Sons: New York, NY, USA, 1978.
54. Maity, T.; Saxena, A.; Raju, S.P. Processing of root crops and functionality of their biocomponents. In *Vegetable Processing and Bioactive Compounds*; CRC Press: Boca Raton, FL, USA, 2017; pp. 195–237.
55. Martin, F.W. Sweet Potato, Echo Technical Note. 1988. Available online: https://s3-us-west-2.amazonaws.com/resilience-exchange/attachments/uploads/3206/original/Sweet_Potato.pdf (accessed on 23 October 2023).
56. Onwueme, I.C.; Charles, W.B. *Tropical Root and Tuber Crops: Production, Perspectives and Future Prospects*; FAO Plant Production and Protection Paper 126; Food and Agriculture Organization of the United Nations: Rome, Italy, 1994.
57. Mukhopadhyay, S.K.; Chattopadhyay, A.; Chakraborty, I.; Bhattacharya, I. Crops that feed the world 5. Sweetpotato. Sweetpotatoes for income and food security. *Food Secur.* **2011**, *3*, 283–305. [CrossRef]
58. Valenzuela, H.; Fukuda, S.; Arakaki, A. Sweet Potato Production Guidelines for Hawaii. 2000. Available online: http://www.extento.hawaii.edu/kbase/reports/sweetpot_prod.htm (accessed on 23 October 2023).
59. Ruiz, F.S. Estudo das Variáveis Envolvidas no Processo de Obtenção de Farinhas Pregelatinizadas, de Batata Doce, por Desidratação com Rolos Aquecidos (Double Drum-Dryer) [Study of Variables Involved in the Process of Obtaining Pregelatinized Flour, Sweet Potato, for Dehydration with Hot Rolls (Double Drum-Dryer)]. Master's Thesis, State University of Campinas, Campinas, Brazil, 1984; p. 106.
60. Rose, I.M.; Vasanthakaalam, H. Comparison of the nutrient composition of four sweet potato varieties cultivated in Rwanda. *Am. J. Food Nutr.* **2011**, *1*, 34–38. [CrossRef]
61. Leite, C.E.C.; Souza, B.K.F.; Manfio, C.E.; Wamser, G.H.; Alves, D.P.; de Francisco, A. Sweet potato new varieties screening based on morphology, pulp color, proximal composition, and total dietary fiber content via factor analysis and principal component analysis. *Front. Plant Sci.* **2022**, *13*, 852709. [CrossRef] [PubMed]
62. Heo, S.; Choi, J.Y.; Kim, J.; Moon, K.D. Prediction of moisture content in steamed and dried purple sweet potato using hyperspectral imaging analysis. *Food Sci. Biotechnol.* **2021**, *30*, 783–791. [CrossRef]
63. Olorunnisomo, O.A. Yield and quality of sweet potato forage pruned at different intervals for West African dwarf sheep. *Livest. Res. Rural Dev.* **2007**, *19*, 32–41.
64. Ishida, H.; Suzuno, H.; Sugiyama, N.; Innami, S.; Tadokoro, T.; Maekawa, A. Nutritive evaluation on chemical components of leaves, stalks and stems of sweet potatoes (*Ipomoea batatas* poir). *Food Chem.* **2000**, *68*, 359–367. [CrossRef]
65. dos Santos, A.M.P.; Lima, J.S.; dos Santos, I.F.; Silva, E.F.R.; de Santana, F.A.; de Araujo, D.G.G.; dos Santos, L.O. Mineral and centesimal composition evaluation of conventional and organic cultivars sweet potato (*Ipomoea batatas* (L.) Lam) using chemometric tools. *Food Chem.* **2019**, *273*, 166–171. [CrossRef]
66. Chen, H.; Sun, J.; Liu, J.; Gou, Y.; Zhang, X.; Wu, X.; Sun, R.; Tang, S.; Kan, J.; Qian, C.; et al. Structural characterization and anti-inflammatory activity of alkali-soluble polysaccharides from purple sweet potato. *Int. J. Biol. Macromol.* **2019**, *131*, 484–494. [CrossRef]
67. Sugata, M.; Lin, C.Y.; Shih, Y.C. Anti-inflammatory and anticancer activities of Taiwanese purple-fleshed sweet potatoes (*Ipomoea batatas* L. Lam) extracts. *BioMed Res. Int.* **2015**, *2015*, 768093. [CrossRef] [PubMed]

68. Dutta, S. Sweet potatoes for diabetes mellitus: A systematic review. *Pharmacophore* **2015**, *6*, 60–72.
69. Yuan, B.; Yang, X.Q.; Kou, M.; Lu, C.Y.; Wang, Y.Y.; Peng, J.; Chen, P.; Jiang, J.H. Selenylation of polysaccharide from the sweet potato and evaluation of antioxidant, antitumor, and antidiabetic activities. *J. Agric. Food Chem.* **2017**, *65*, 605–617. [CrossRef] [PubMed]
70. Kim, H.J.; Koo, K.A.; Park, W.S.; Kang, D.M.; Kim, H.S.; Lee, B.Y.; Goo, Y.M.; Kim, J.H.; Lee, M.K.; Woo, D.K.; et al. Anti-obesity activity of anthocyanin and carotenoid extracts from color-fleshed sweet potatoes. *J. Food Biochem.* **2020**, *44*, e13438. [CrossRef] [PubMed]
71. Johnson, R.; Padmaja, G. Comparative studies on the production of glucose and high fructose syrup from tuber starches. *Int. Res. J. Biol. Sci.* **2013**, *2*, 68–75.
72. Betiku, E.; Akindolani, O.O.; Ismaila, A.R. Enzymatic hydrolysis optimization of sweet potato (*Ipomoea batatas*) peel using a statistical approach. *Braz. J. Chem. Eng.* **2013**, *30*, 467–476. [CrossRef]
73. Chavan, R.; Saxena, K.; Tigote, D. Optimization of acid hydrolysis process for free glucose recovery from starch. *Int. J. Innov. Sci. Eng. Technol.* **2015**, *2*, 55–58.
74. Lambri, M.; Dordoni, R.; Roda, A.; De Faveri, D.M. Process development for maltodextrins and glucose syrup from cassava. *Chem. Eng. Trans.* **2014**, *38*, 469–474.
75. Johnson, R.; Padmaja, G.; Moorthy, S.N. Comparative production of glucose and high fructose syrup from cassava and sweet potato roots by direct conversion techniques. *Innov. Food Sci. Emerg. Technol.* **2009**, *10*, 616–620. [CrossRef]
76. Tian, S.J.; Rickard, J.E.; Blanshard, J.M.V. Physicochemical properties of sweet potato starch. *J. Sci. Food Agric.* **1991**, *57*, 459–491. [CrossRef]
77. Zaidul, I.S.M.; Absar, N.; Kim, S.J.; Suzuki, T.; Karim, A.A.; Yamauchi, H.; Noda, T. DSC study of mixtures of wheat flour and potato, sweet potato, cassava, and yam starches. *J. Food Eng.* **2008**, *86*, 68–73. [CrossRef]
78. Solarek, D.B. Modified starches-Properties and uses. In *Modified Starches*; Wurzburg, O.B., Ed.; CRC Press: Boca Raton, FL, USA, 1987; pp. 1–30.
79. Zobel, H.F. Starch: Sources, production, and properties. In *Starch Hydrolysis Products*; Schenck, F.W., Hebeda, R.E., Eds.; VCH: New York, NY, USA, 1992; pp. 23–44.
80. Mironescu, M.; Mironescu, I.D.; Trifan, A.; Ignatova, M.; Mironescu, V. Influence of the liquefied starch composition and pH on the saccharification at the obtaining of maltose syrup. *Bull. UASVM Agric.* **2009**, *66*, 354–358. [CrossRef] [PubMed]
81. Tomasik, P.; Horton, D. Enzymatic conversions of starch. *Adv. Carbohydr. Chem. Biochem.* **2012**, *68*, 59–436. [PubMed]
82. Kolusheva, T.; Marinova, A. A study of the optimal conditions for starch hydrolysis through thermostable α-amylase. *J. Univ. Chem. Technol. Metall.* **2007**, *42*, 93–96.
83. Ezugwu, A.L.; Eze, S.O.O.; Chilaka, F.C. A study of the optimal conditions for glucoamylases obtained from Aspergillus niger using amylopectin from cassava starch as carbon source. *Afr. J. Biotechnol.* **2015**, *14*, 2593–2702. [CrossRef]
84. Wang, Y.J.; Wang, L. Structures and properties of commercial maltodextrins from corn, potato, and rice starches. *Starch-Stärke* **2000**, *52*, 296–304. [CrossRef]
85. Hoover, R. Acid-treated starches. *Food Rev. Int.* **2000**, *16*, 369–392. [CrossRef]
86. Hobbs, L. Sweeteners from starch: Production, properties and uses. In *Starch*, 3rd ed.; Chemistry and Technology, Food Science and Technology; Academic Press: San Diego, CA, USA, 2009; pp. 797–832.
87. Robyt, J.F.; Choe, J.Y.; Hahn, R.S.; Fuchs, E.B. Acid modification of starch granules in alcohols: Effects of temperature, acid concentration, and starch concentration. *Carbohydr. Res.* **1996**, *281*, 203–218. [CrossRef]
88. Yiu, P.H.; Loh, S.L.; Rajan, A.; Wong, S.C.; Bong, C.F.J. Physiochemical properties of sago starch modified by acid treatment in alcohol. *Am. J. Appl. Sci.* **2008**, *5*, 307–311. [CrossRef]
89. Espinosa-Solis, V.; Sánchez-Ambriz, S.L.; Hamaker, B.R.; Bello-Pérez, L.A. Fine structural characteristics related to digestion properties of acid-treated fruit starches. *Starch-Stärke* **2011**, *63*, 717–727. [CrossRef]
90. Utrilla-Coello, R.G.; Hernández-Jaimes, C.; Carrillo-Navas, H.; González, F.; Rodríguez, E.; Bello-Pérez, L.A.; Vernon-Carter, E.J.; Alvarez-Ramirez, J. Acid hydrolysis of native corn starch: Morphology, crystallinity, rheological and thermal properties. *Carbohydr. Polym.* **2014**, *103*, 596–602. [CrossRef] [PubMed]
91. Monica, M.; Vionel, M. Hygienic aspects at the production of glucose syrups through acid hydrolysis. *Acta Univ. Cibiniensis Ser. E Food Technol.* **2006**, *10*, 29–38.
92. Lee, Y.C.; Kim, K.T. Gelatinization and liquefaction of starch with a heat stable alpha-amylase. *J. Food Sci.* **1990**, *55*, 1365–1366. [CrossRef]
93. Tunde, A.A. Production of glucose from hydrolysis of potato starch. *World Sci. News* **2020**, *145*, 128–143.
94. Payen, A.; Persoz, J.F. Mémoire sur la diastase, les principaux produits de ses réactions, et leurs applications aux arts industriels. *Ann. Chim. Phys.* **1833**, *53*, 73–92.
95. Kimura, A.; Robyt, J.F. Reaction of enzymes with starch granules: Kinetics and products of the reaction with glucoamylase. *Carbohydr. Res.* **1995**, *277*, 87–107. [CrossRef]
96. Klimovskii, D.N.; Rodzevich, V.I. Hydrolysis of starch by amylase from different sources. *Biokhimiya* **1949**, *14*, 26–34. (In Russian)
97. Futch, J. Altering Sweet Potato Starch Functionality by Amino Acids and pH Treatments. Master's Thesis, Louisiana State University, Baton Rouge, LA, USA, 2009.

98. Guzman-Maldonado, H.; Paredes-Lopez, O. Amylolytic enzymes and products derived from starch: A review. *Crit. Rev. Food Sci. Nutr.* **1995**, *35*, 373–403. [CrossRef]
99. Van der Maarel, M.J.; Van der Veen, B.; Uitdehaag, J.C.; Leemhuis, H.; Dijkhuizen, L. Properties and applications of starch-converting enzymes of the α-amylase family. *J. Biotechnol.* **2002**, *94*, 137–155. [CrossRef]
100. Ludvig, L.; Varga, M. Semi-industrial starch degradation with Hungarian enzyme preparations. *Szeszipar* **1968**, *16*, 22–26. (In Hungarian)
101. Carr, M.E.; Black, L.T.; Bagby, M.O. Continuous enzymatic liquefaction of starch for saccharification. *Biotechnol. Bioeng.* **1982**, *24*, 2441–2449. [CrossRef] [PubMed]
102. Komaki, T.; Taji, N. Enzymic liquefaction and saccharification of starch. VIII. Liquefying conditions of corn starch by bacterial alpha amylase. *Agric. Biol. Chem.* **1968**, *32*, 860–872.
103. Leach, H.W.; Hebeda, R.E.; Holik, D.J. Enzymatic Hydrolysis of Granular Starch. U.S. Patent 3,922,196, 25 November 1975.
104. Bidrawn, J.L.; Ewing, F.G.; Landis, B.H.; Wheeler, H.R. Continuous enzyme conversion of corn starch. *Tappi* **1965**, *48*, 101A–104A.
105. Underkofler, L.A.; Denault, L.J.; Hou, E.F. Enzymes in the starch industry. *Starch/Stärke* **1965**, *17*, 179–184. [CrossRef]
106. Blanco, M.; Coello, J.; Iturriaga, H.; Maspoch, S.; González Bañó, R. Online monitoring of starch enzymatic hydrolysis by near infrared spectroscopy. *Analyst* **2000**, *125*, 749–752. [CrossRef]
107. Yankov, D.; Dobreva, V.; Beschkov, V.; Emanuilova, E. Study of optimum conditions and kinetics of starch hydrolysis by means of thermostable α-amylase. *J. Enzym. Microb. Technol.* **1986**, *8*, 665–667. [CrossRef]
108. Whistler, R.L.; BeMiller, J.N.; Paschall, E.F. *Starch: Chemistry and Technology*, 2nd ed.; Academic Press: San Diego, CA, USA, 1984.
109. Sroczynski, A.; Pierzgalski, T.; Nowakowska, K. Production of high saccharified syrups by two-stage enzymatic hydrolysis of potato starch. *Acta Aliment. Pol.* **1977**, *3*, 107–114.
110. Adejumo, A.L.; Agboola, F.K.; Layokun, S.K. Hydrolysis of maize starch using amylolytic enzymes extracted from sorghum malt. *Int. J. Biol. Chem. Sci.* **2009**, *3*, 1030–1041. [CrossRef]
111. Aït-Aissa, A.; Gerliani, N.; Orlova, T.; Sadeghi-Tabatabai, B.; Aïder, M. Development of a process for color improvement of low-grade dark maple syrup by adsorption on activated carbon. *ACS Omega* **2020**, *5*, 21084–21093. [CrossRef]
112. Emery, A.N.; Cardoso, J.P. Parameter evaluation and performance studies in a fluidized-bed immobilized enzyme reactor. *Biotechnol. Bioeng.* **1978**, *20*, 1903–1929. [CrossRef]
113. Novais, J.M.; Cabral, J.M.S.; Cardoso, J.P. Kinetic model and comparison of continuous reactor for starch hydrolysis by immobilized amyloglucosidase. *Actas 9th Simp. Iberoam. Catal.* **1984**, *1*, 397–406. (In Portuguese)
114. Nakajima, M.; Iwasaki, K.; Nabetani, H.; Watanabe, A. Continuous hydrolysis of soluble starch by free β-amylase and pullulanase using an ultrafiltration membrane reactor. *Agric. Biol. Chem.* **1990**, *54*, 2793–2799.
115. Woo, G.J.; McCord, J.D. Maltotetraose production using pseudomonas stutzeri exo-β-amylase in a membrane recycle bioreactor. *J. Food Sci.* **1991**, *56*, 1019–1023. [CrossRef]
116. Sims, K.A.; Cheryan, M. Hydrolysis of liquefied corn starch in a membrane reactor. *Biotechnol. Bioeng.* **1992**, *39*, 960–967. [CrossRef] [PubMed]
117. Darnoko, D.; Cheryan, M.; Artz, W.E. Saccharification of cassava starch in an ultrafiltration reactor. *Enzym. Microb. Technol.* **1989**, *11*, 154–159. [CrossRef]
118. Ohnishi, M.; Ishimoto, C.; Seto, J. The properties of the multistage bioreactor constructed by the LB technique. *Bull. Chem. Soc. Jpn.* **1991**, *64*, 3581–3584. [CrossRef]
119. Sato, T. Use of food enzymes. Theories and examples. *Shokuhin Kogyo* **1980**, *23*, 57–63. (In Japanese)
120. Tsujisaka, Y. Applications of microbial enzyme in starch production. *Denpun Kagaku* **1988**, *35*, 61–67.
121. Gupta, R.; Gigras, P.; Mohapatra, H.; Goswami, V.K.; Chauhan, B. Microbial α-amylases: A biotechnological perspective. *Process Biochem.* **2003**, *38*, 1599–1616. [CrossRef]
122. Reddy, N.S.; Nimmagadda, A.; Rao, K.R.S.S. An overview of the microbial α-amylase family. *Afr. J. Biotechnol.* **2003**, *2*, 645–648.
123. Frankova, L. Basic characteristics of enzymes involved in the amylolytic process. *Biologia* **2003**, *68*, 81–107. (In Slovak)
124. Kitano, T. Takaamylase. *Chem. Rev. Jpn.* **1937**, *3*, 433–444. (In Japanese)
125. Takasaki, Y.; Furutani, S.; Hayashi, S.; Imada, K. Acid-stable and thermostable α-amylase from *Bacillus licheniformis* α. *J. Ferment. Bioeng.* **1994**, *77*, 94–96. [CrossRef]
126. Farjon, B.; Targonski, Z.; Pielecki, J. Enzymes hydrolyzing bounds of alfa-1.6-D glucosides, their properties and application in the starch bioconversion [pullulanase EC 3.2. 1.41 and isoamylase EC 3.2. 1.68]. *Przem. Ferment. Owocowo-Warzywny (Pol.)* **1992**.
127. Ray, R.R. Microbial isoamylases: An overview. *Am. J. Food Technol.* **2011**, *6*, 1–18.
128. Goto, M. Digestion of raw starch by glucoamylase I from *Aspergillus awamori* var. *kawachi*. *Biosci. Ind.* **2001**, *59*, 183–184.
129. Saha, B.C.; Zeikus, J.G. Novel highly thermostable pullulanase from thermophiles. *Trends Biotechnol.* **1989**, *7*, 234–239. [CrossRef]
130. Ziegler, P. Cereal beta-amylases. *J. Cereal Sci.* **1999**, *29*, 195–204. [CrossRef]
131. Kaplan, F.; Dong, Y.; Guy, C.L. Roles of β-amylase and starch breakdown during temperature stress. *Physiol. Plant.* **2006**, *126*, 120–128. [CrossRef]
132. Hesse, A. Vervendung von enzymen in der industrie. 1. Abbau von Stärke und Eiweiss dem Malzen und Maischen. *Ergeb. Enzym.* **1934**, *3*, 95–134.
133. Tamura, T. Liquefaction of starch. *Denpun Kogyo Gakkaishi* **1963**, *10*, 93–97.
134. Ohya, T.; Yokoi, N.; Sakai, T. Enzymic saccharification of starch. *New Food Ind.* **1984**, *26*, 16–21. (In Japanese)

135. Johnson, R.; Moorthy, S.N.; Padmaja, G. Production of high fructose syrup from cassava and sweet potato flours and their blends with cereal flours. *Food Sci. Technol. Int.* **2010**, *16*, 251–258. [CrossRef] [PubMed]
136. Dunn, G. A model for starch breakdown in higher plants. *Phytochemistry* **1974**, *13*, 1341–1346. [CrossRef]
137. BeMiller, J.N. Starches: Conversions, modifications, and uses. In *Carbohydrate Chemistry for Food Scientists*, 3rd ed.; BeMiller, J.N., Ed.; Elsevier: Amsterdam, The Netherlands; AACC International: St. Paul, MN, USA, 2019; pp. 191–221.
138. Malakar, R.N.; Mandal, S.; Tiwari, A. Pullulanase: A potential enzyme for industrial application. *Int. J. Biomed. Res.* **2010**, *1*, 10–20.
139. Hii, S.L.; Tan, J.S.; Ling, T.C.; Ariff, A.B. Pullulanase: Role in starch hydrolysis and potential industrial applications. *Enzym. Res.* **2012**, *2012*, 921362. [CrossRef] [PubMed]
140. Norman, B.E. A novel *Bacillus* pullulanase. Its properties and application in the glucose syrups industry. *J. Jpn. Soc. Starch Sci.* **1983**, *30*, 200–211.
141. Sherwood, M.A. Enzymes in industry. *Process Biochem.* **1966**, *1*, 279–285.
142. Wurzburg, O.B.; Szymanski, C.D. Modified starches in the food industry. *J. Agric. Food Chem.* **1970**, *18*, 997–1003.
143. Allen, W.G.; Dawson, H.G. Technology and uses of debranching enzymes. *Food Technol.* **1975**, *29*, 70–80.
144. Gao, Q.; Suling, L.; Jian, H.; Liang, S. Preparation and properties of resistant starch from corn starch with enzymes. *Afr. J. Biotechnol.* **2011**, *10*, 1186–1193.
145. Kung, J.T.; Hanrahan, V.M.; Caldwell, M.L. A comparison of the action of several alpha amylases upon a linear fraction from corn starch. *J. Am. Chem. Soc.* **1953**, *75*, 5548–5554. [CrossRef]
146. Higashihara, M.; Miyoshi, S.; Okada, S. Action of β-amylase on raw starch. *J. Jpn. Soc. Starch Sci.* **1987**, *34*, 106–112. [CrossRef]
147. Norman, B.E. A novel debranching enzyme for application in the glucose syrup industry. *Starch-Stärke* **1982**, *34*, 340–346. [CrossRef]
148. Stenholm, K.; Home, S.; Lauro, M.; Perttula, M.; Suortti, T. Hydrolysis of barley starch by malt limit dextrinase. In *Proceedings of the 26th Congress Maastricht-European Brewery Convention*; Oxford University Press: Oxford, UK, 1997; Volume 26, pp. 283–290.
149. Hizukuri, S. Raw-starch-digesting activity and kinetic properties of glucoamylases. *J. Jpn. Soc. Starch Sci.* **1987**, *34*, 98–105. [CrossRef]
150. Singh, R.S.; Singh, T.; Pandey, A. Microbial enzymes—An overview. In *Advances in Enzyme Technology, A Volume in Biomass, Biofuels, Biochemicals*; Singh, R.S., Singhania, R.R., Pandey, A., Larroche, C., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; pp. 1–40.
151. Fatima, B.; Hussain, Z. Xylose isomerases from Thermotogales. *J. Anim. Plant Sci.* **2015**, *25*, 10–18.
152. Dai, C.; Miao, T.; Hai, J.; Xiao, Y.; Li, Y.; Zhao, J.; Qiu, H.; Xu, B. A novel glucose isomerase from *Caldicellulosiruptor bescii* with great potentials in the production of high-fructose corn syrup. *BioMed Res. Int.* **2020**, *2020*, 1871934. [CrossRef]
153. Tsumura, N.; Hagi, M.; Sato, T. Studies on glucose isomerase from *Pseudomonas saccharophila*. *Agric. Biol. Chem.* **1967**, *31*, 902–907.
154. Jia, D.X.; Zhou, L.; Zheng, Y.G. Properties of a novel thermostable glucose isomerase mined from Thermus oshimai and its application to preparation of high fructose corn syrup. *Enzym. Microb. Technol.* **2017**, *99*, 1–8. [CrossRef]
155. Kim, J.; Nanmori, T.; Shinike, R. Thermostable, raw-starch digesting amylase from *Bacillus stearothermophilus*. *Appl. Environ. Microbiol.* **1989**, *55*, 1638–1639. [CrossRef]
156. Mensah, E.O.; Ibok, O.; Ellis, W.O.; Carey, E.E. Thermal stability of β-amylase activity and sugar profile of sweet-potato varieties during processing. *J. Nutr. Food Sci.* **2016**, *6*, 515.
157. Singh, N.; Singh, J.; Kaur, L.; Sodhi, N.S.; Gill, B.S. Morphological, thermal and rheological properties of starches from different botanical sources. *Food Chem.* **2003**, *81*, 219–231. [CrossRef]
158. Van der Veen, E.; Veelaert, S.; Van der Goot, A.J.; Boom, R.M. Starch hydrolysis under low water conditions. A conceptual process design. *J. Food Eng.* **2006**, *75*, 178–186. [CrossRef]
159. Copeland, L.; Blazek, J.; Salman, H.; Tang, M.C. Form and functionality of starch. *Food Hydrocoll.* **2009**, *23*, 1527–1534. [CrossRef]
160. Wang, Y.; Ral, J.P.; Saulnier, L.; Kansou, K. How does starch structure impact amylolysis? Review of current strategies for starch digestibility study. *Foods* **2022**, *11*, 1223. [CrossRef]
161. Robertson, G.H.; Wong, D.W.; Lee, C.C.; Wagschal, K.; Smith, M.R.; Orts, W.J. Native or raw starch digestion: A key step in energy efficient biorefining of grain. *J. Agric. Food Chem.* **2006**, *54*, 353–365. [CrossRef]
162. Wickramasinghe, H.A.M.; Blennow, A.; Noda, T. Physico-chemical and degradative properties of in-planta re-structured potato starch. *Carbohydr. Polym.* **2009**, *77*, 118–124. [CrossRef]
163. Blazek, J.; Gilbert, E.P. Effect of enzymatic hydrolysis on native starch granule structure. *Biomacromolecules* **2010**, *11*, 3275–3289. [CrossRef]
164. Ramadoss, B.R.; Gangola, M.P.; Agasimani, S.; Jaiswal, S.; Venkatesan, T.; Sundaram, G.R.; Chibbar, R.N. Starch granule size and amylopectin chain length influence starch in vitro enzymatic digestibility in selected rice mutants with similar amylose concentration. *J. Food Sci. Technol.* **2019**, *56*, 391–400. [CrossRef]
165. Kumakura, M.; Kaetsu, I. Pretreatment of starch raw materials and their enzymic hydrolysis by immobilized glucoamylase. *Enzym. Microb. Technol.* **1983**, *5*, 199–203. [CrossRef]
166. Ngo, T.V.; Kusumawardani, S.; Kunyanee, K.; Luangsakul, N. Polyphenol modified starches and their applications in the food industry: Recent updates and future directions. *Foods* **2022**, *11*, 3384. [CrossRef] [PubMed]
167. Sevenou, O.; Hill, S.E.; Farhat, I.A.; Mitchell, J.R. Organisation of the external region of the starch granule as determined by infrared spectroscopy. *Int. J. Biol. Macromol.* **2002**, *31*, 79–85. [CrossRef] [PubMed]

168. Hsien-Chih, H.W.; Sarko, A. The double-helical molecular structure of crystalline α-amylose. *Carbohydr. Res.* **1978**, *61*, 27–40. [CrossRef]
169. Lebail, P.; Buleon, A.; Shiftan, D.; Marchessault, R.H. Mobility of lipid in complexes of amylose–fatty acids by deuterium and 13C solid state NMR. *Carbohydr. Polym.* **2000**, *43*, 317–326. [CrossRef]
170. Wang, S.; Chao, C.; Cai, J.; Niu, B.; Copeland, L.; Wang, S. Starch–lipid and starch–lipid–protein complexes: A comprehensive review. *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 1056–1079. [CrossRef] [PubMed]
171. Martens, B.M.; Gerrits, W.J.; Bruininx, E.M.; Schols, H.A. Amylopectin structure and crystallinity explains variation in digestion kinetics of starches across botanic sources in an in vitro pig model. *J. Anim. Sci. Biotechnol.* **2018**, *9*, 1–13. [CrossRef] [PubMed]
172. Ye, J.; Hu, X.; Luo, S.; McClements, D.J.; Liang, L.; Liu, C. Effect of endogenous proteins and lipids on starch digestibility in rice flour. *Food Res. Int.* **2018**, *106*, 404–409. [CrossRef]
173. Debet, M.R.; Gidley, M.J. Three classes of starch granule swelling: Influence of surface proteins and lipids. *Carbohydr. Polym.* **2006**, *64*, 452–465. [CrossRef]
174. Morrison, W.R. Starch lipids and how they relate to starch granule structure and functionality. *Cereal Foods World* **1995**, *40*, 437–446.
175. Compart, J.; Singh, A.; Fettke, J.; Apriyanto, A. Customizing starch properties: A review of starch modifications and their applications. *Polymers* **2023**, *15*, 3491. [CrossRef]
176. Noda, T.; Sarker, M.Z.I. Factors influencing starch digestibility. In *Proceedings of the International Conference on Science, Technology and Social Sciences (ICSTSS) 2012*; Kasim, A., Wan Omar, W., Abdul Razak, N., Wahidah Musa, N., Ab. Halim, R., Mohamed, S., Eds.; Springer: Singapore, 2014; pp. 449–453.