Journal of Pharmacognosy and Phytochemistry
Available online at www.phytojournal.com

E-ISSN: 2278-4136
P-ISSN: 2349-8234
www.phytojournal.com
JPP 2024; 13(4): 512-524
Received: 01-05-2024
Accepted: 07-06-2024

Salman Ahmed
Department of Pharmacognosy, Faculty of Pharmacy and Pharmaceutical Sciences, University of Karachi, Karachi, Pakistan

Haseeb ur Rehman
Department of Pharmacognosy, Faculty of Pharmacy and Pharmaceutical Sciences, University of Karachi, Karachi, Pakistan

Nabeel Ahmed
Department of Pharmacognosy, Faculty of Pharmacy and Pharmaceutical Sciences, University of Karachi, Karachi, Pakistan

Corresponding Author:
Salman Ahmed
Department of Pharmacognosy, Faculty of Pharmacy and Pharmaceutical Sciences, University of Karachi, Karachi, Pakistan

Potato starch extraction: Techniques, challenges, and future opportunities

Salman Ahmed, Haseeb ur Rehman and Nabeel Ahmed

DOI: https://doi.org/10.22271/phyto.2024.v13.i4f.15046

Abstract

Potato starch extraction is a critical process with implications across various industries, including food, pharmaceuticals, and bioplastics. This review explores current techniques, challenges, and future opportunities in potato starch extraction. Traditional methods such as compression or wet grinding, enzymatic processes, and microwave-assisted extraction are examined for their efficiency, advantages, and limitations. The paper emphasizes the importance of quality control measures to ensure the purity and safety of the extracted starch. Critical quality control aspects include raw material inspection, monitoring during processing, purity and composition analysis, and adherence to national and international standards. Innovations in extraction methods, including enzymatic and green solvent extraction, ultrasonic and microwave-assisted techniques, and advancements in nanotechnology and biotechnological approaches, are highlighted as trends driving the industry towards greater sustainability and efficiency. The clean label movement also reflects a consumer-driven shift towards natural, minimally processed ingredients, influencing industry practices and regulatory compliance. The future of potato starch extraction holds significant promise, with the integration of sustainable practices and technological innovations to meet evolving market demands and regulatory standards, underscoring the need for continuous research and development in the field.

Keywords: Potato starch, extraction methods, quality control, enzymatic method, microwave-assisted extraction, starch yield

Introduction

Starch, a polysaccharide composed of numerous glucose units joined by glycosidic linkages, has a rich historical significance. Most green plants produce it for energy storage. The most economically essential crops that contain starch are cereal, legumes, tubers, and roots [1]. Table– 1 shows common crops along with their starch content. Microscopically, starch granules appear as particles with concentric layers and are made up of two glucose polymers: amylose (20-25%), which is linear and helical, and amylopectin (75-80%), which is branched. The historical roots of starch production extend back 100,000 years, with early uses such as grinding sorghum into flour. Egyptians utilized starch to create an adhesive from wheat to bind strips of papyrus. Starchy foods have been derived from seeds, roots, and tubers, with Cato detailing starch production in his Roman treatise. By 700 CE, rice starch was used in paper production in China. During the middle Ages, the manufacture of wheat starch became a crucial industry in Holland, renowned for its high quality. This period also saw the early modification of starch through mild hydrolysis with vinegar. Leeuwenhoek's microscopic observations of starch granules in 1716 and Kirchhoff's discovery of sugar production from potato starch through acid hydrolysis further advanced the understanding of starch. Although wheat was the primary starch source in Europe until the 18th century, potatoes and maize have become significant sources, with Europe currently leading in potato starch production and the 19th century marked a significant expansion in the starch industry, driven by the demands of textiles, color printing, and paper, as well as the discovery of dextrin, a gum-like starch derivative. Since the 1930s, advancements by carbohydrate chemists have led to numerous innovations, including waxy corn starch, high-amylose corn starch, and various chemically and naturally modified starches. The industry has also seen the introduction of banana starch and amaranth starch. This rich history of starch production underscores its enduring importance and potential for future innovation [2, 3].

Starch is widely used in pharmaceuticals due to its non-toxic, non-irritant nature, low cost, and versatility as a pharmaceutical excipient. It plays multiple roles in pharmaceutical production, serving as a binder, disintegrant, diluent, glidant, absorbent, and lubricant. For instance, it is a binder in tablet production, where starch mucilage provides binding force and ensures uniform distribution of active pharmaceutical ingredients (APIs). It functions as a disintegrant, promoting the rapid release of drugs from tablets and capsules, with maize and potato starches being commonly used. Starch is also a diluent in low-dose formulations, enhancing weight, mixing, and content uniformity without risky interactions with APIs. Understanding the properties and extraction methods of potato starch is therefore crucial for professionals in the pharmaceutical industry to ensure the quality and effectiveness of their products [4]. Modified starches, having undergone physical, chemical, or enzymatic alteration, are pivotal in the pharmaceutical industry as they serve as crucial coating agents. These modifications significantly enhance the starch's film-forming properties, creating robust protective barriers around sensitive drug components. This protection shields active ingredients from environmental factors such as moisture, light, and air, thereby improving the medication's stability and shelf life. Moreover, these coatings enhance the handling and mechanical properties of the final pharmaceutical products, ensuring their long-term effectiveness [5, 6]. The potential of starch modification in creating matrices for controlled drug release is a promising and significant avenue in pharmaceutical research. This approach, which ensures a sustained release of drugs over time, is particularly beneficial for developing long-acting medications and improving patient compliance. Techniques like microwave-assisted modification of starches, including arrowroot starch, have shown to enhance their properties as hydrophilic matrix excipients, paving the way for the development of more effective sustained-release tablets [7].

Resistant starch (RS) emerges as a key player in promoting gut health, particularly for patients with gastrointestinal disorders, due to its unique role as a prebiotic. It resists digestion in the small intestine and reaches the colon, where beneficial bacteria (*Bifidobacterium* and *Lactobacillus*) ferment it, *a* significant *discovery*. This fermentation process, which produces short-chain fatty acids (SCFAs) like butyrate, is crucial for maintaining gut health. The potential of butyrate to support the health of the colon lining and reduce inflammation is a promising development for individuals with conditions like irritable bowel syndrome (IBS), obesity and weight management and lowering the risk of Coronary Heart Disease[8, 9]. The consumption of RS has shown promising results in improving glucose tolerance, enhancing insulin sensitivity, and increasing satiety in healthy individuals. These effects suggest that RS could play a beneficial role in glycemic control for those at risk of or already living with type 2 diabetes. The potential of RS in managing blood glucose levels is encouraging, making it a promising dietary component for diabetes prevention and treatment strategies [10]. Starch-based dressings are a cornerstone of wound care thanks to their unique ability to absorb wound exudate and maintain a moist environment, which is crucial for optimal healing. These dressings often utilize polysaccharide-based hydrogels that can absorb significant amounts of exudate while keeping the wound bed moist. This moisture retention is essential because it promotes cellular activities critical for healing, reduces pain, and minimizes scarring. Moreover, the absorptive nature of these dressings helps manage wound exudate, preventing maceration of the surrounding tissue, which can otherwise lead to further complications, providing reassurance and confidence in their use [11, 12]. Starch plays a crucial role in diagnostic tests like the starch tolerance test, which assesses carbohydrate metabolism and can aid in diagnosing conditions such as diabetes mellitus. This test evaluates the body's ability to process starch, providing insights into a patient's glucose metabolism. The test measures the blood glucose levels before and after consuming a starch-rich meal, and abnormalities in the test results can indicate issues like insulin resistance or impaired glucose tolerance, which are critical factors in the development of diabetes [13, 14].

Beyond pharmaceuticals, starch has a wide range of uses in food and non-food industries, demonstrating its versatility. In the food industry, it is crucial for confectionery moulding, producing puddings, jellies, and other products, and enhancing fibre content in baked goods. Modified starches, created through reactions like hydrolysis and esterification, are used in various food products. Starches are vital for papermaking, corrugated board adhesives, and clothing starch in non-food sectors. Modified starches are also used as textile printing thickeners and in biodegradable plastics like polylactic acid. This broad impact of starch in these industries is a testament to its versatility and importance, showing the audience the significant role their work plays in various sectors. Additionally, powdered corn starch substitutes talcum powder in health and beauty products. Starches also serve as viscosifiers, emulsifiers, defoaming agents, and sizing agents in various industrial processes. The wide-ranging impact of starch in these industries is a testament to its versatility and importance [15, 16].

Potatoes, ranked as the fourth most crucial food crop globally, following wheat, rice, and maize, with an estimated annual production of 300 million tons, hold significant importance. Potatoes' nutrient composition and chemical profile vary significantly based on the cultivar and various environmental and agricultural factors, such as soil quality, fertilization practices, climatic conditions, and cultivation methods. These variables influence potatoes' nutritional value, texture, and suitability for culinary and industrial applications. This underlines the importance of the work of professionals in the potato starch extraction industry, as it directly impacts the global food supply and nutrition [17].

Why potato starch extraction?

Pretreatment extraction is not required for potato starch extraction: Potato starch typically contains fewer impurities than other starches like corn or wheat. It has low levels of protein and fat, making it easier to obtain a pure starch product. Steeping softens hard plant materials, especially grains, and facilitates wet grinding. Steeping is preferred for hard starch sources, and softer plant sources, like potatoes, don't require any treatment before extraction. It is essential to know that the dry milling hard plant materials grains (i.e., barley, oat, rice, corn, legumes) can result in substantial starch granule damage. A high percentage of damaged starch granules may alter the physicochemical properties of starch. Steeping or dry grinding are unnecessary steps in potato starch isolation. Thus, it can be Peeled, sliced into small pieces, and directly slurried in water [1].

The slurry formation of starch is more accessible than that of other sources: The water requirement for slurrying differs from the source of plant material. Cereal grains contain water-soluble non-starch polysaccharides such as β-glucan and hemicellulose, referred to as gums. These gums show high water-binding capacity, which substantially increases the viscosity of the slurry, making the filtration process difficult. They also slow down the sedimentation of plant components during centrifugation. A large amount of water (1:>25, w/w) is necessary for starch isolation from plant materials containing these gums. Legume seeds contain insoluble flocculent proteins, which decrease starch sedimentation and settle with starch to give a brownish deposit. Potato contains relatively low amounts of non-starch polysaccharides or flocculent proteins, requiring less water during starch extraction [1].

Absence of the need for Mechanical blenders: Potato starch extraction doesn't need mechanical blenders. This simplifies the equipment requirements for the extraction process, making it more accessible and cost-effective**.** For grain flours (e.g., oat, barley, corn), water slurrying can be done in a beaker using an overhead stirrer at high speed. Controlling the temperature during blending is essential, as heat can damage starch granules. The blending process generates heat, so care must be taken (Crushed ice can be added to the slurry) to avoid heat-induced damage to starch granules [1].

Starch granules from potatoes separate easily due to their large size: Starch granules usually exist in various sizes. Water-insoluble starch granules typically range between 1 and 100 µm in size. Small-granule starches from plant materials are complex to recover because they usually co-sediment with the protein, fiber, and mucilage layer (Dark or brown layer) during centrifugation [1]. Table 2 presents the shapes and sizes of starch granules derived from various natural sources.

Centrifugation is not necessary for Potato starch isolation: Centrifugation is an essential step in isolation that separates starch from fine fibers, insoluble or soluble protein, and gum or mucilage compounds. Centrifugation settles the starch (a white layer) at the bottom of the centrifuge tube. The water-insoluble contaminants (e.g., protein and fine fiber) form a dark or brown layer on the starch layer. This contaminant layer is usually removed manually by scraping with a spatula, careful not to scrape away any starch layers [1].

Low Protein and Fat Content: Potato starch has low protein and fat levels, simplifying the purification process. This results in a starch product that is purer and has fewer impurities. Tubers, roots, and yams contain very little protein (<3.0%, w/w, dry weight) and lipid (<1%, w/w, dry weight) compared to legume and cereal grains, which minimizes the contamination of starch by these components during isolation. Several washings with water or washing once with toluene or aqueous alkali (0.05 N NaOH or KOH) are adequate[1].

Seasonal Variations in the Starch Yield of Potatoes

The starch yield in potatoes varies significantly with the season due to differences in growth conditions, temperature, and the maturity of the potato tubers.

a) **Spring**: Potatoes harvested in the spring often have lower starch content. The tubers usually do not fully mature during this time as the growing season has just begun. Immature potatoes have less accumulated starch.
b) **Summer**: Potatoes harvested in the summer can also have lower starch yields, particularly in regions with high temperatures. Elevated temperatures increase the plants' respiration rate, leading to greater consumption of stored carbohydrates and reducing the tubers' starch content.
c) Autumn is typically the peak season for potato starch yield. By this time, the potatoes are fully mature, having had the entire growing season to develop. Cooler temperatures in autumn also help preserve the starch content in the tubers. This is the most common time for harvesting potatoes destined for starch production, as the starch concentration in the tubers is at its highest.
d) **Winter**: In some regions, winter-harvested potatoes can also have high starch content, mainly if left in the ground until late in the season. However, in colder climates, potatoes may not be harvested in winter due to the risk of frost damage, which can negatively impact yield and starch quality. Potatoes stored over winter can undergo starch-to-sugar conversion, especially if storage conditions are not optimal (too warm or cold), decreasing starch content [18].

Comparative Analysis of Starch Extraction from Green, Red, and White Potatoes

Green potatoes are unsuitable for starch extraction due to the presence of a toxin called solanine, which develops when potatoes are exposed to light. This toxin is concentrated in the green parts of the potato and can cause bitterness, making the starch extracted from it undesirable for consumption. Additionally, the green color indicates that the potato is in an early sprouting stage, reducing the extracted starch content and quality. Therefore, using green potatoes in starch production can result in a product that is unsafe and of lower quality [19]. Red potatoes contain anthocyanins, a red pigment with antioxidant properties. The extraction process can be less efficient due to the lower starch content. A waxy texture with more fibrous cell walls can make the extraction process slightly more challenging and lower efficiency. White potatoes have a higher starch content compared to red potatoes. This makes them more suitable for extraction as they yield more starch per potato. Have a mealy texture due to higher starch content, making it easier to break down the cell walls and release starch granules during extraction. The higher starch content can lead to quicker sedimentation during the purification process, and the overall drying process can be simpler [17, 20].

The Role of pH in Starch Extraction

During starch extraction, a low pH environment can lead to the hydrolysis of starch. Hydrolysis is a chemical reaction where water molecules break down starch into smaller molecules. In an acidic medium (low pH), the hydrogen ions (H^+) present can catalyze the breaking of glycosidic bonds, which are the links between the glucose units in the starch polymer. This results in the breakdown of starch into smaller molecules such as dextrins, maltose, and even glucose, depending on the extent of hydrolysis. Hydrolysis of starch decreases its molecular weight by breaking it into smaller units, reducing viscosity and changing its gelatinization properties. This breakdown alters the functional properties of the starch, such as its thickening ability, texture, and stability, which are crucial in food and industrial applications. The starch's ability to form gels or maintain a stable structure may be compromised, affecting its performance in various products [21]. Similar to the effect of low pH, high pH can also cause hydrolysis. For instance, alkali treatment could decrease starch gelatinization temperature, which is the temperature at which starch granules swell and burst, indicating a decrease in the stability of starch granules. This decrease in gelatinization temperature clearly shows the effect of high pH on starch, providing a better understanding of its impact [22]. When starch is extracted in a neutral pH medium (Around pH 7), the process requires a delicate balance to preserve the structural integrity of the starch granules while allowing for efficient extraction. At neutral pH, the glycosidic bonds in the starch are not broken down, maintaining the starch's molecular weight and functional properties. This results in starch that retains its natural gelatinization temperature, viscosity, and ability to form stable gels. This preservation of the starch's natural properties is more than just promising. It has the potential to revolutionize various uses in food, pharmaceuticals, and other industries, inspiring new applications and demonstrating the broad applicability and potential of the product [21].

Potential for Starch Loss during Potato Cutting

During the cutting or slicing of potatoes, starch can be lost as cell walls rupture and release starch granules onto the chopping board. This white, sticky residue can be easily lost if not properly collected. Key factors contributing to starch loss include surface adhesion to the board, where uncollected starch can remain; juice absorption, where starch mixes with potato juices and is absorbed by cloth or towels; and washing away, where rinsing or washing potato pieces directly on the board can wash away surface starch. To minimize starch loss, it's crucial to collect surface starch by rinsing the board with minimal water and to avoid excessive washing of potato slices immediately after cutting. These are not just helpful but essential practices that can significantly reduce starch loss and ensure the quality of the final product [23].

Enhanced Efficiency of Mortar and Pestle over Mechanical Grinders in Potato Starch Extraction

For several reasons, grinding potatoes in a mortar and pestle can result in better starch extraction than using a mechanical grinder. While mechanical grinders are faster and more suitable for large-scale operations, using a mortar and pestle provides better control, less contamination, and a gentler process that can yield higher-quality starch with fewer impurities. This method is precious when extracting starch with minimal damage to the granules and maintaining the highest possible purity. Here is the explanation. Grinding in a mortar and pestle is a manual, low-speed process that gently breaks down the potato cells without generating excessive heat or friction. This helps preserve the integrity of starch granules, preventing them from being damaged during the extraction process. Mechanical grinders, especially high-speed ones, can generate significant heat due to friction. This heat can partially gelatinize the starch, making extracting pure, intact granules more difficult. Additionally, the forceful grinding can lead to the breakdown of the starch structure, which might reduce the overall yield. Since the process is manual and slow, there is less chance of contamination from the grinding equipment. The mortar and pestle are typically made of materials like stone or ceramic that do not react with the potato or introduce impurities. Mechanical grinders, especially those made of metal, can sometimes introduce small amounts of metal particles or rust, especially if the equipment needs to be well-maintained. This contamination can affect the purity of the extracted starch. The gentle nature of grinding with a mortar and pestle often requires less water to create a slurry, making separating starch easier and more efficient. The high-speed grinding process often requires more water to manage the heat and friction, diluting the slurry and making the subsequent starch extraction and purification steps more challenging [24].

Overview of the Extraction Process

The three processes of enzymatic, compression or wet grinding, and microwave-assisted extraction are used to separate and extract starch.

Compression or Wet grinding method (traditional method)

This method of starch extraction was developed by Watson *et al.,* 1955 [25]. The wet grinding method of starch extraction is a mechanical method that involves using water and physical crushing (Compression) and grinding (Reduction to small pieces) techniques to release starch granules from the potato tissues. In this traditional method, mortar and pestle are used for grinding. Figure 1 provides a summarized overview of the compression or wet grinding process. Here's a step-by-step explanation of the wet grinding process:

Step – 01: Raw Material Selection and Preparation: The selection and preparation of raw materials are critical steps in extracting potato starch. These steps should be considered, as they ensure that the starting material is of high quality, directly impacting the extraction process's efficiency and the quality of the final starch product. Proper handling at this stage also helps to minimize waste and optimize the overall yield of the starch extraction process.

a) **Weight of raw material:** The weight of plant or raw material that should be taken for starch extraction will depend on the starch requirement, the plant material's starch content, and the extraction procedure's usually 85% to 90% recovery. For example, 100 g of freshly peeled potato tuber, corn grains, and barley grains generally yield 15 to 16, 55 to 60, and 40 to 45 g of starch, respectively.
b) **Raw Material Selection encompasses Choosing the Right Potato:** Larger potatoes are favored for their ability to produce more starch, and the quality of the potatoes is crucial; they should be free from defects, diseases, or damage, which can impact the quantity and quality of the extracted starch. Additionally, fully mature potatoes are ideal as they typically contain more starch.
c) **Preparation of Raw Material and Washing:** The starch extraction process from potatoes begins with thorough water washing to remove dirt and impurities. Potatoes may be peeled to eliminate the skin, which contains pigments, Solanine alkaloids and other non-starch materials. The cleaned and optionally peeled potatoes are then chopped into smaller pieces or slices for easier grinding [1].

Step – 02: Separation of Starch: The slices are crushed and ground with water using a mortar and pestle, creating a slurry. The grinding breaks open the potato cells, releasing the starch granules into the water, resulting in a mixture containing water, starch, fibers, and other potato components. Water is essential in forming slurry for starch isolation from plant materials because starch granules are insoluble and dense. The process typically involves using excess water to slurry or wash the starch or to separate it from other components. The plant material and water are blended until a smooth slurry forms, typically within 5 to 10 minutes. Sliced potatoes into mortar and pestle, add 5 ml of water and crush with pestle to form slurry, add 100 ml distilled water and filter. To prevent microbial growth and amylose enzyme (A commonly occurring plant enzyme that hydrolyzes starch) activity that can degrade starch, adding 0.01% sodium metabisulfite or 0.01 M mercuric chloride during slurrying is recommended. The slurry from the potato starch extraction process is treated to separate the starch granules by sedimentation [1].

Step – 03: Purification (Sedimentation, decantation): To purify potato starch, the slurry undergoes multiple washing stages with fresh water to remove fine fibers and other insoluble impurities. After washing, the slurry is allowed to settle, and the supernatant liquid containing impurities is decanted [1].

Step – 04: Drying of Potato Starch: Various drying methods convert purified wet starch into a dry form suitable for handling and storage to reduce its moisture content. According to European Pharmacopoeia "The moisture content of extracted starch should not exceed 20% to ensure quality and usability". Exceeding this limit can cause spoilage, reduced shelf life, and altered properties, compromising its effectiveness in food and industrial applications. Maintaining this moisture level ensures the starch remains stable, safe, and functional [26]. The drying methods include air drying, which is slower and energy-efficient; oven drying at temperatures between 30° and 40 °C; drum drying, where the starch is spread onto a heated drum and then scraped off as it dries; and spray drying, which is commonly used for high-quality starch production in food and pharmaceutical applications. Spray drying involves spraying the starch slurry into a chamber with hot air, quickly evaporating the water and leaving fine starch particles. Care is taken to avoid high temperatures during drying to prevent altering the starch's properties [1].

Step – 05: Observation: Calculating the percentage yield of dried starch from potatoes begins by recording the weight of the potatoes (A) as 100 g. Measure the weight of an empty china dish (B), then weigh the dish with the dried starch (C). The weight of the dried starch is determined by subtracting the weight of the empty dish (B) from the combined weight (C). Finally, the percentage yield is calculated using the formula: $(C-B)/A\times100$.

Common Pitfalls to Avoid in Potato Starch Extraction

To extract pure starch from potatoes effectively, follow these critical steps:

a) **Peeling:** Thoroughly peel the potatoes to eliminate impurities, as the peel can introduce unwanted materials.
b) **Cutting:** Cut the potatoes into small cubes or slice using a stainless-steel knife. This knife is essential to avoid rust, which can contaminate the starch.
c) **Crushing and Slurry Formation:** Crush the potato slices thoroughly until a complete slurry forms. Adding water prematurely can dilute the mixture and impede proper slurry formation.
d) **Straining:** Use a muslin cloth to filter the slurry gently, ensuring the cloth is undamaged and avoiding excessive pressure to prevent tearing or pulp contamination.
e) **Sedimentation:** Glass beakers are ideal for observing starch sedimentation, allowing for better control of the purification process. Improper sedimentation results in reduced purity of the final starch product, leading to potential contamination with non-starch components and decreased overall yield.
f) **Drying:** Dry the starch at controlled temperatures to prevent degradation or denaturation. Avoid using temperatures that are too high or too low, and ensure the appropriate drying duration.
g) **Storage:** Store the dried starch in a moisture-free environment to prevent fungal growth and degradation[1].

Advantages

The wet grinding method is highly efficient for breaking down cell structures and releasing starch granules, resulting in high-purity starch due to multiple washing steps that remove non-starch components [1].

Disadvantages

While effective, this method is not suitable for high-throughput industrial operations due to its multiple washing and sedimentation steps, which can lengthen the overall processing time. The process also requires a significant amount of water for the grinding and washing stages, which can be a drawback in areas where water conservation is a priority. The process often requires careful monitoring and manual intervention, making it labor-intensive compared to more automated methods. Hence, it is only suitable for small-scale production [1].

Enzymatic method

The enzymatic process of starch extraction involves using enzymes to break down the structural components of the potato, specifically the cell walls, to release starch. Cellulase is used because it helps break down the cellulose in the cell walls, releasing the starch granules. This process provides better yields and requires less mechanical effort and energy than traditional methods. This method enables more efficient starch extraction from cell wall components, enhancing overall recovery rates [27, 28]. Figure 2 presents a concise summary of the enzymatic process. Here's a step-by-step overview of the process:

Step – 01: Preparation of Raw Material: Potatoes are first washed to remove dirt and impurities. They are then cut into smaller pieces without peeling to prepare them for grinding. The cut potatoes are ground into a fine meal using a grinder. This step is crucial for exposing more surface area for enzymatic action.

Step – 02: Enzyme Preparation and Application: A solution of cellulase enzyme, a key player in the enzymatic process, is prepared by mixing a specific amount of the enzyme in water (0.5gm cellulase for 100gm of potato + 10-20 ml of water). This enzyme is crucial as it aids in the breakdown of the potato cell walls, releasing the starch for extraction.

Step – 03: Mixing of enzyme solution with Potato Meal: The cellulase enzyme solution was added to the potato meal for 5 hours. The mixture was then thoroughly mixed to ensure the enzyme contacted as much potato meal as possible.

Step – 04: Filtration, washing and settling: After the enzymatic reaction, the mixture is filtered to separate the solid residues (Pomace) from the starch liquid. A fine mesh strainer catches the solid residues, thoroughly separating the liquid and starch. The filtered liquid may be washed with additional water to recover any remaining starch. The starch, being heavier, settles at the bottom, and the liquid above it is removed.

Step – 05: Drying and Recovery: The recovered starch is then dried, often using methods like oven drying, to reduce its moisture content to a stable level for storage or further processing.

Controlled Conditions for Enzyme Activity

The enzyme-potato meal mixture is meticulously kept under precise conditions, often involving specific temperatures

(45ºC) and 5-hour periods. This meticulous control allows the enzyme to catalyze the breakdown of cell walls and release the starch. The mixture's pH is adjusted to optimal (pH 5) to ensure the enzyme works effectively [27, 28].

Advantages

The enzymatic process can achieve a higher starch yield than mechanical methods, as enzymes break down cell walls and release more starch. This potential for increased productivity is a significant advantage of the enzymatic process. Furthermore, this process requires less mechanical grinding, saving energy and importantly, reducing equipment wear. It can produce starch with fewer impurities and a more consistent quality. The enzymatic process, therefore, offers a more efficient and potentially higher-quality method of starch extraction suitable for various industrial applications [27, 28].

Disadvantages

The enzymatic method for potato starch extraction, while offering several advantages, also has some notable disadvantages:

a) **Cost:** Enzymes can be expensive to produce and purchase, making the enzymatic method more costly than traditional mechanical or chemical extraction processes.
b) **Enzyme Inactivation:** Enzymes are sensitive to environmental conditions such as temperature and pH. The enzymes can become inactive if these conditions are not optimal, leading to inefficient starch extraction. Therefore, maintaining optimal conditions is crucial to prevent this and may require additional monitoring and control systems.
c) **Processing Time:** Enzymatic reactions can be slower than mechanical methods. The time required for enzymes to break down the cell walls and release starch granules can be longer, potentially reducing the throughput of the extraction process.
d) **Complexity:** Enzymatic methods can be more complex than traditional methods. They require precise control of reaction conditions, including temperature, pH, and enzyme concentration. This complexity increases the need for skilled personnel and necessitates sophisticated equipment, making it a significant consideration for those planning to adopt this method.
e) **Potential Contamination:** Using enzymes introduces the risk of microbial contamination, especially if the enzymes are not pure or if the reaction conditions favor the growth of unwanted microorganisms. This can compromise the quality and safety of the extracted starch, making it essential to use pure enzymes and maintain sterile conditions. Strict quality control is crucial to ensure the extracted starch's safety and quality, emphasizing the importance of maintaining high standards in the enzymatic process.
f) **Residual Enzymes:** Residual enzymes can remain in the starch product if not adequately inactivated or removed. These enzymes can affect the properties and stability of the starch, limiting its use in specific applications [27, 28].

Microwave-assisted extraction

The efficiency of extracting potato starch using microwave-assisted techniques was analyzed by examining the effects of microwave power, treatment duration, particle size, and material-to-liquid ratio on starch yield. Optimal conditions-500W power, 4 minutes, 30 mesh size particles, and a 1:1 g/mL ratio (300g peeled potato in 300 mL of water)-achieved a 93.85% extraction rate, outperforming traditional methods. This method offers a more efficient, sustainable, and high-quality approach to industrial potato starch extraction [29].

Critical Aspects of Quality control

Quality control measures are implemented throughout the extraction process to ensure that the starch meets specific standards for purity, moisture content, and other relevant characteristics. Failure to meet these standards can result in compromised product quality, safety issues, and loss of market access. For instance, if the starch does not meet the required purity standards, it may not be suitable for use in food or pharmaceuticals. This could lead to potential health risks for consumers, loss of market share, and even legal implications. Similarly, if the moisture content is not within the acceptable range, the starch may degrade faster, reducing its shelf life and market value. Quality Control and Standards ensure that the product meets the same high standards in every batch, crucial for customer satisfaction and product performance. Adherence to regulatory standards is necessary for legal compliance and market acceptance. High-quality control standards are not just about meeting standards; they are about maintaining a positive reputation and trust with customers and stakeholders, which is crucial in the food and pharmaceutical industry. These potential consequences underscore the critical role of quality control in the starch extraction process are as follows.

Raw Material Inspection: The quality control process commences with a meticulous selection and inspection of raw potatoes. Critical factors such as starch content, absence of defects, and overall quality are assessed with the utmost care. This thorough inspection ensures that only high-quality potatoes are used, guaranteeing the purity and yield of the starch and providing you with a product of the highest standard [30].

Monitoring During Processing

Continuous monitoring is conducted throughout the extraction, separation, purification, and drying processes to ensure the production parameters are within the desired range. Monitoring the pH during washing and purification helps control the removal of impurities. It also determines the acidity or alkalinity of the starch, which can affect its stability and application in food products. A starch slurry is prepared in distilled water, and the pH is measured using a pH meter. Temperature and Moisture are critical during drying to achieve the desired moisture content and avoid starch degradation. Regular calibration of equipment like centrifuges, filters, and dryers ensures accurate operation and consistent product quality, providing reliable and high-quality starch products [31].

Purity and Composition Analysis

The third point underscores the crucial role of purity and composition analysis in ensuring the quality of the extracted starch. This analysis is conducted to verify that the starch meets the required standards for various impurities, including:

a) Starch Purity ensures the starch is free from other carbohydrates like sugars and fibers. Purity is often measured by enzymatic or chemical methods that quantify the percentage of starch in the sample.
b) Residual Proteins and Fats can significantly alter the starch's taste, appearance, and functionality, underscoring the importance of comprehensive testing.

c) Fiber Content: Excessive fiber can affect the texture and clarity of the starch, especially in food applications.
d) Ash Content represents the total mineral content, which should be minimal in high-purity starch. Measures the inorganic residue remaining after the starch is burned, indicating the presence of minerals or impurities. The starch sample is incinerated at 550-600°C, and the weight of the residue (ash) is measured as a percentage of the original sample weight.
e) Heavy Metal Contamination ensures the starch is free from toxic heavy metals like lead, mercury, or cadmium. Atomic Absorption Spectroscopy (AAS) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is used to detect and quantify heavy metals.

Physical and Chemical Properties

The fourth point highlights the pivotal role of testing the physical and chemical properties of the starch in determining its suitability for various applications. These properties include:

- **Color and Odor:** Starch should be white and odorless, indicating the absence of impurities and proper processing. Ensures that the starch has an acceptable appearance for its intended use. Colorimeters or visual inspection against standard color charts are commonly used.
- Moisture content determines the amount of water present in the starch. High moisture content can affect the starch's storage stability and quality. It is typically measured by drying a sample at 105 °C until a constant weight is achieved and calculating the moisture loss as a percentage of the original sample weight.
- Particle Size Analysis is important for ensuring uniformity in texture and behavior in various applications. Laser diffraction or sieving methods are used to measure particle size distribution.
- Water Absorption Capacity measures the ability of starch to absorb and retain water, which is essential for its application in food products. Starch is mixed with water and centrifuged, and the water absorbed is calculated.
- **Viscosity:** A critical parameter for applications where the starch is used as a thickening agent. Assesses the thickening ability of the starch, which is essential for applications in food, pharmaceuticals, and other industries. A viscometer measures the viscosity of a starch paste under controlled temperature.
- Gelatinization Temperature indicates the temperature at which starch granules swell and burst, affecting their behavior in cooking and processing. Differential Scanning Calorimetry (DSC) is often used to measure the gelatinization temperature.
- **Amylose and Amylopectin Content:** Determines the ratio of amylose to amylopectin, which affects the gelatinization, retro gradation, and textural properties of starch. Iodine binding assays are commonly used, where the amylose-iodine complex is measured spectrophotometrically [32-34].

Microbiological Testing

Microbiological testing is not just a routine task in food and pharmaceutical applications. It is a critical element that ensures the starch is devoid of harmful microorganisms, making it safe for consumption. This process is crucial, as it directly impacts the safety and quality of the final product. Total Viable Count (TVC) refers to the total number of viable bacteria present in a given sample. It is a key indicator of the overall microbial load and can provide insights into the potential spoilage or safety risks associated with the product. The absence of yeast and mold at levels below detectable limits is a testament to the stringent standards for safety and quality that professionals are responsible for maintaining [35].

Compliance with Standards

The sixth point underscores the necessity of ensuring compliance with national and international standards. These standards are not just rules to follow, but tools to ensure the safety and quality of the products. FDA (Food and Drug Administration) in the United States, EFSA (European Food Safety Authority) in Europe are crucial in the food industry, while adherence to Good Manufacturing Practice guidelines is essential in the pharmaceutical sector. ISO Standards such as ISO 9001 for quality management systems, ISO 22000 for food safety management, and ISO 14001 for environmental management. Compliance with these standards ensure that the extracted starch meets the requirements for its intended applications, whether in food, pharmaceuticals, paper, textiles, or other industries [36, 37].

In summary, quality control and adherence to standards in potato starch production are vital for delivering a safe, consistent, and high-quality product that meets the needs of various industries [38].

Innovations and Future Trends

Potato starch extraction is evolving with a focus on sustainability, efficiency, and innovation, driven by the demands of industries ranging from food to bioplastics. Traditional methods of starch extraction, often reliant on chemical and mechanical processes, are being enhanced or replaced by advanced techniques that promise higher yields, better quality, and reduced environmental impact. One of the most significant trends is the adoption of enzymatic extraction, where enzymes help release starch granules from potato cells without damaging them. This method improves the starch quality and reduces reliance on harsh chemicals, making the process more sustainable [39].

Another area of interest is green solvent extraction, utilizing ionic liquids and deep eutectic solvents. These solvents are more environmentally friendly than traditional solvents, effectively disrupting cell walls to release starch with minimal chemical impact. Ultrasonic and microwave-assisted extraction methods are also gaining traction. Ultrasound waves can break down cell walls, facilitating starch release, while microwaves rapidly heat and disintegrate cells, making the extraction process quicker and more energy-efficient[40, 41].

Nanotechnology is a game-changer in the evolution of starch extraction. It can revolutionize the industry by enhancing separation and purification processes, leading to higher-quality starch with improved functional properties. Nanomaterials can create controlled release systems for enzymes and other agents during extraction, thereby optimizing the process. Additionally, biotechnological approaches, including genetic engineering and microbial fermentation, offer promising avenues for developing potato varieties with starches that are easier to extract or tailored for specific industrial uses. Microbial fermentation, in particular, could provide innovative, sustainable methods for starch extraction, leveraging engineered microorganisms to process potato biomass [42].

Sustainability is at the forefront of future extraction trends, emphasizing zero-waste processes and circular economy principles. The industry can reduce its environmental footprint by minimizing waste and maximizing the use of by-products, such as converting potato peel into bioenergy or feedstock. Automation and smart technologies, integral to the Industry, are set to optimize extraction processes further. Sensors, data analytics, and artificial intelligence can monitor and adjust conditions in real-time, ensuring consistent product quality and maximizing yield while reducing costs [43-45].

Technological advancements, market trends, and regulatory changes are shaping the future of potato starch extraction. A notable example of this influence is the increasing demand for "clean label" products. The "clean label" movement reflects a consumer-driven shift towards food products with simple, recognizable, and minimally processed ingredients. These products avoid artificial additives, preservatives, and synthetic chemicals in favor of natural ingredients, which are perceived as healthier and safer. Key aspects include transparency, clear ingredient lists, using natural ingredients like beet juice or turmeric, minimal processing to preserve ingredient integrity, and being free from undesirable components like artificial flavors and genetically modified organisms (GMOs) or gluten. This trend influences the food industry, including starch extraction, to adopt more natural production methods and simplify ingredient lists. It also drives stricter regulatory compliance to ensure clean label claims are accurate. Overall, the clean label movement is reshaping food production towards more natural, transparent, and minimally processed solutions, aligning with evolving consumer preferences and industry standards. This trend reflects a broader shift toward natural extraction methods as health-conscious consumers increasingly avoid modified starches due to concerns about food additives and chemical processes. Clean-label starches are characterized by their lack of chemical modifications, with their production relying on starch blending and various physical and enzymatic modification techniques. Physical changes include methods such as ultrasound, hydrothermal treatments (e.g., heat-moisture treatment and annealing), pre-gelatinization techniques (e.g., drum drying, roll drying, spray cooking, and extrusion cooking), high-pressure treatments (e.g., high hydrostatic pressure), and pulsed electric field treatments. The industry's commitment to aligning with consumer preferences and its focus on delivering high-quality products underscore its dedication to customer needs. Additionally, potential regulatory restrictions on specific chemicals or processes may spur innovation in alternative extraction methods, illustrating the industry's adaptability to market trends and regulatory requirements [46, 47].

In summary, the future of potato starch extraction is characterized by a shift towards more sustainable, efficient, and technologically advanced methods. Enzymatic and green solvent extractions, ultrasonic and microwave-assisted techniques, nanotechnology, and biotechnological approaches contribute to a more eco-friendly and efficient process. As automation and smart technologies further optimize production and as the industry adapts to changing consumer preferences and regulatory landscapes, potato starch extraction will continue to evolve, more sustainably meeting the needs of a wide range of sectors [48].

Table 1: Common crops along with their starch content

Category	Natural sources (raw)	Starch g/100 g
Cereals or grains	*Oryza sativa* (Rice, Chawal)	70 - 80 [49]
	Zea mays (Maize, Makai)	60-70 [50]
	Triticum aestivum (Wheat, Gandum)	60-75 [51]
	Secale cereal (Rye, Dio Gandum)	57-66 [52]
	Sorghum bicolor (Sorghum, Jawar)	56-75 [2, 53]
	Panicum miliaceum (Millet, Bajra)	50-70 [54, 55]
	Avena sativa (Oats, Jai)	50-60 [56, 57]
	Amaranthus caudatus (Amaranth grain)	48 – 62 [58]
	Hordeum vulgare (Barley, Jao)	47-67 [59, 60]
Roots	*Manihot esculenta* (Cassava, Aat Kaat)	50 – 70 [61]
Tubers	*Dioscorea* sp. (Yam)	63 - 66 [62]
	Solanum tuberosum (Potatoes, Aaloo)	15 - 20[63]
	Ipomoea batatas (Sweet Potato, Shakar kandi)	15 - 17 [64]
	Maranta arundinacea (Arrowroot)	12-24[65-67]
Nuts	*Anacardium occidentale* (Cashew Nuts, Kajoo)	23.5 [68]
	Pistacia vera (Pistachio, Pista)	1.67 [69]
	Macadamia integrifolia (Macadamia)	1.05 [70]
	Prunus amygdalus (Almonds, Badam)	0.72 [71]
	Carya illinoinensis (Pecans, Amreeki Akhrot)	0.46 [72, 73]
	Juglans regia (Walnut, Akhrot)	0.06 [74]
Legumes or beans	*Cicer arietinum* (Chickpeas, Chana)	50 - 60 [75]
	Lens culinaris (Lentils)	45-50 [76, 77]
	Phaseolus vulgaris (Kidney Beans, Lobia)	29 - 38 [78]
	Vigna unguiculata (Cow pea, Safaid Lobia)	27-43 [79]

Table 2: Shapes and sizes of starch granules from natural sources [80-82].

Source category	Sources	Shapes	Size of granules (diameter) µm
Cereal	*Hordeum vulgare* (Barley)	Spherical and flat circular (Lens)	2-5 (Spherical), 15-25 (Lens shape)
	Zea mays (Maize)	Angular (Polyhedral)	2–30
	Panicum miliaceum (Millet)		4–12
	Avena sativa (Oats)	Polyhedral	3–10
	Oryza sativa (Rice)	Angular (Polyhedral)	3-8
	Secale cereal (Rye)	Spherical and flat circular (LENS)	5-10 (Spherical), 10-40 (Lens shape)
	Metroxylon sagu (Sago or Sabu dana)	Oval	20-40
	Sorghum bicolor (Sorghum)	Spherical	5-20
	Triticosecale Wittmack (Triticale)		1–30
	Triticum aestivum (Wheat)	Spherical and flat circular (Lens)	2-10 (Spherical), 15-25 (Lens shape)
Tuber	*Solanum tuberosum* (Potato)	Oval	5–100
Triticale is a cereal, a product of crossbreeding between wheat and rye. Its name is formed from *Triticum* (wheat) and *Secale* (rye).			

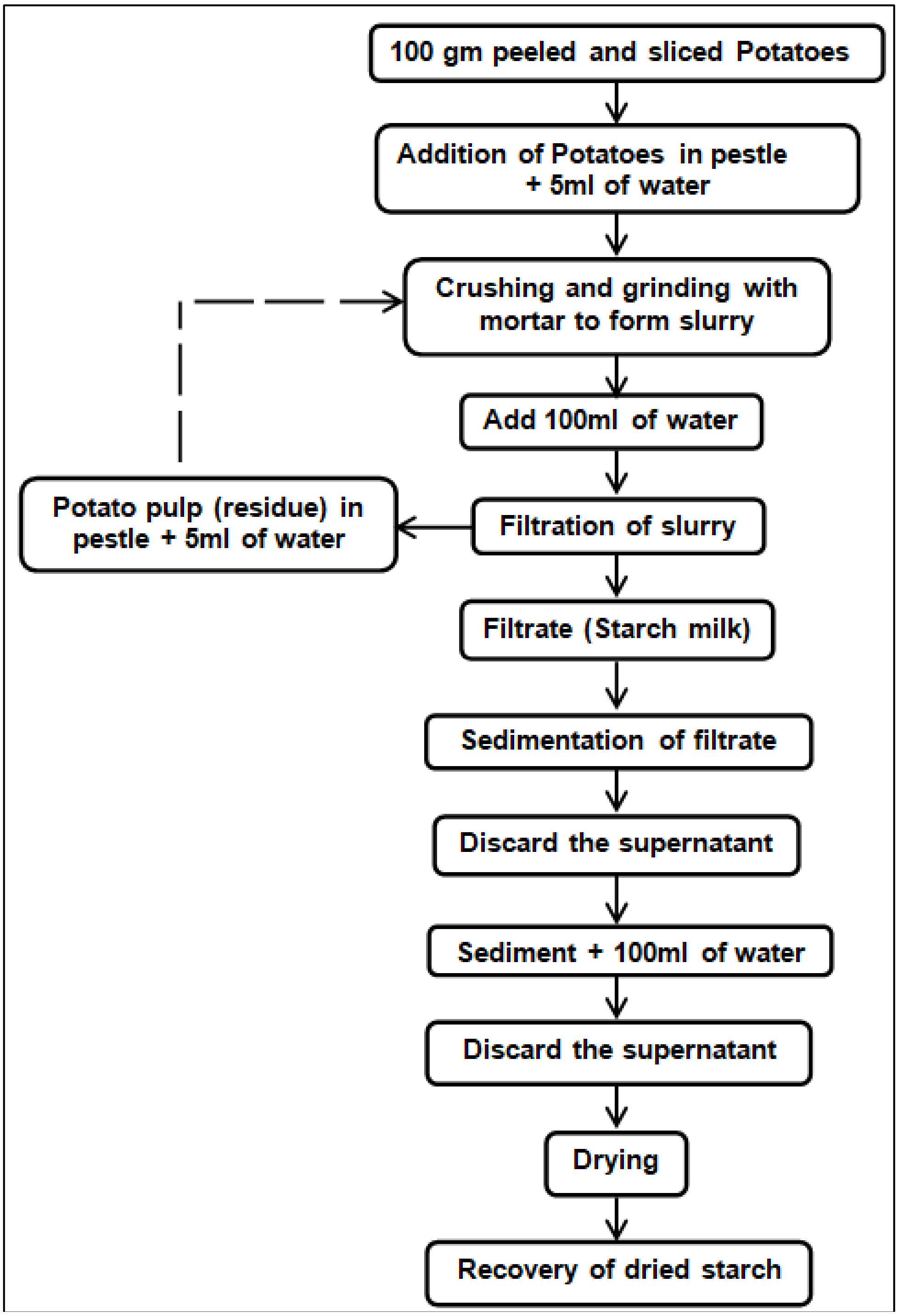

Fig 1: Compression or Wet grinding method for potato starch extraction.

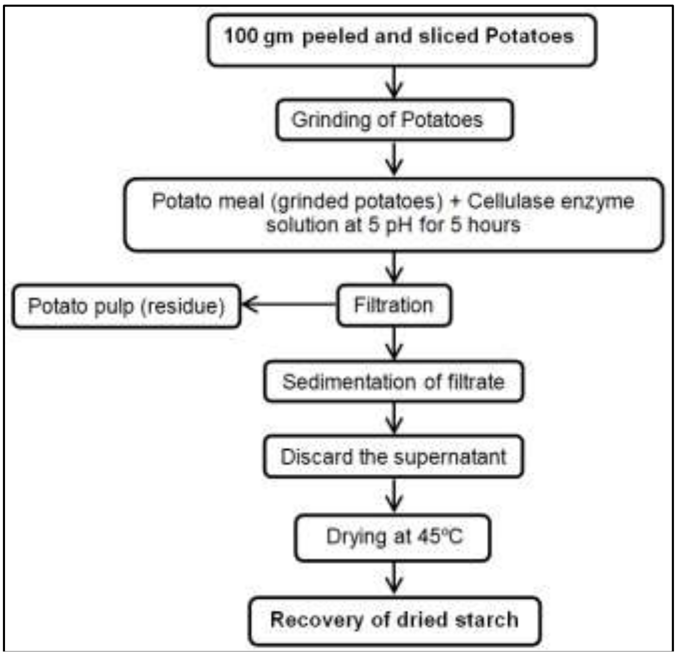

Fig 2: Enzymatic process for potato starch extraction

Conclusion

Potato starch extraction is a vital process with widespread applications in food, pharmaceuticals, bioplastics, and other industries. This review has explored three primary extraction methods: traditional wet grinding, enzymatic extraction, and microwave-assisted extraction. Each method offers distinct advantages and challenges. Conventional wet grinding is efficient and scalable but demands significant water and labor. The enzymatic method provides higher yields and superior quality but incurs higher costs and complexity. Microwave-assisted extraction stands out for its high efficiency, reduced water usage, and improved starch properties. The future of potato starch extraction is moving towards sustainability and technological advancement. Innovative methods like enzymatic and green solvent extractions enhance starch quality and reduce environmental impact. Techniques such as ultrasonic and microwave-assisted extraction, nanotechnology, and biotechnological approaches modernize traditional processes to yield higher-quality starches. This evolution aligns with sustainability goals and zero-waste practices, while the clean label movement pushes for natural, minimally processed products free from chemical additives. As automation and smart technologies enhance production, the industry is committed to meeting diverse needs more effectively and sustainably. The potato starch industry can achieve more efficient, high-quality, and environmentally sustainable production processes by addressing current challenges and leveraging technological advancements. This will enhance potato starch's value and applicability across various sectors, ensuring its continued importance in the global market.

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