sustainability

MDPI

Review

Starch Valorisation as Biorefinery Concept Integrated by an Agro-Industry Case Study to Improve Sustainability

Maider Gomez Palmero [1,*], Ana Carrasco [2], Paula de la Sen [1], María Dolores Mainar-Toledo [1], Sonia Ascaso Malo [3] and Francisco Javier Royo Herrer [3]

1 Fundación CIRCE, Parque Empresarial Dinamiza, Avda. Ranillas 3D, 1ª Planta, 50018 Zaragoza, Spain; pdelasen@fcirce.es (P.d.l.S.)
2 PATURPAT, Arriurdina, 6, Polígono Industrial de Júndiz, 01015 Vitoria-Gasteiz, Spain
3 Energaia Institute (University Institute for Energy and Resource Efficiency Research of Aragon), University of Zaragoza, Mariano Esquillor Gómez, 15, 50018 Zaragoza, Spain
* Correspondence: mgomez@fcirce.es

Abstract

The production of bio-based products for different purposes has become an increasingly common strategy over the last few decades, both in Europe and worldwide. This trend seeks to contribute to mitigating the impacts associated with climate change and to cope with the ambitious objectives established at European level. Over recent decades, agro-industries have shown significant potential as biomass suppliers, triggering the development of robust logistical supply chains and the valorization of by-products to obtain bio-based products that can be marketed at competitive prices. However, this transformation may, in some cases, involve restructuring traditional business model to incorporate the biorefinery concept. In this sense, the first step in developing a bio-based value chain involves assessing the resource's availability and characterizing the feedstock to select the valorization pathway and the bio-application with the greatest potential. The paper incorporates inputs from a case study on PATURPAT, a company commercializing a wide range of ready-prepared potato products, which has commissioned a starch extraction facility to process the rejected pieces of potatoes and water from the process to obtain starch that can be further valorized for different bio-applications. This study aims to comprehensively review current trends and frameworks for potatoes processing agro-industries and define the most suitable bio-applications to target, as well as identify opportunities and challenges.

Keywords: potato agro-industry; by-product; valorization; starch; bio-application; bio-based products

check for updates

Academic Editors: Adriana Gómez-Sanabria and Haniyeh Jalalipour

Received: 19 June 2025
Revised: 21 July 2025
Accepted: 23 July 2025
Published: 27 July 2025

Citation: Gomez Palmero, M.; Carrasco, A.; de la Sen, P.; Mainar-Toledo, M.D.; Ascaso Malo, S.; Royo Herrer, F.J. Starch Valorisation as Biorefinery Concept Integrated by an Agro-Industry Case Study to Improve Sustainability. *Sustainability* **2025**, *17*, 6808. https://doi.org/10.3390/su17156808

1. Introduction

The production of bio-based products has emerged as a key strategy to transition away from reliance on fossil fuels and toward more sustainable and environmentally friendly alternatives. Bio-based products, derived from renewable biological resources, offer a promising resource to contribute to greenhouse gas emissions reduction, resource depletion minimization, and the development of a more resilient and sustainable economy among other factors [1–4]. In this sense, exploiting the potential of by-products from agro-industries for instance for the production of bio-based products can significantly contribute to decarbonization and support the transition towards a more circular and resource-efficient economy.

In Europe, there has been a joint effort to promote the production and consumption of bio-based products as part of a broader strategy to transition towards low-carbon and climate-resilient alternatives. Through initiatives such as the European Green Deal and the Circular Economy Action Plan, the European Union has set ambitious targets for reducing greenhouse gas emissions, increasing the share of renewable energies, and promoting sustainable resource management practices. In this context, bio-based products play a key role in achieving these ambitious objectives, offering innovative solutions across various sectors.

More specifically for the agrifood sector, the valorization of side streams and by-products is crucial to increase the sustainability of the related production processes [5]. Moreover, this approach contributes to diversifying the product portfolio and income of primary producers, enabling them to reduce the risk while creating new jobs in rural areas. These waste/by-product materials are often discarded due to not reaching the required standards or characteristics for further processing or commercialization. Nonetheless, they have high intrinsic value and can be used to generate high value-added products [5]. Various industries, such as the vegetable processing industry [6], woody manufacture, and the seafood industry [7], generate large amounts of by-products that can be recovered and used to create bio-products with a high potential to replace fossil-based alternatives. These by-products contain valuable compounds such as fiber, essential oils, proteins, lipids, carbohydrates, and bioactive compounds, which have interesting properties for different applications such as fertilizers, biostimulants, bioplastics, cosmetics, animal feed, biolubricants, and bioadhesives, among others. The present paper specifically addressesthe potato processing agro-industry focusing on the PATURPAT company as a case study. This company commercializes a wide range of ready-prepared potato products and obtains side streams (potato rejections and water used in processing) that can be valorized to obtain starch for different bio-application, such as bioplastic.

Using a comprehensive review of current trends and a framework for potato agro-industry' side streams, this paper seeks to explore relevant potential bio-applications and identify opportunities and challenges. The literature review is combined with and supported by information collected from PATURPAT.

2. Current Status of Potato Production and Cultivation

The potato is recognized as one of the most significant food crops worldwide, cultivated across different climates and geographical areas. It ranks as the fourth most relevant crop for human dietary needs and has been key in enhancing food security. According to potato production statistics in FAO's FAOSTAT database, in 2022, approximately 375 million tons of potatoes were produced globally, with China (95.5 million tons) and India (56 million tons) being the main producers. In Europe, Germany produced 10.6 million tons, France 8 million tons, the Netherlands 6.9 million tons, the UK 4.8 million tons and Belgium 3.6 million tons [8].

In 2023, the total potato harvested area in EU27 was 1304 thousand hectares according to EUROSTAT [6]. Most of the area devoted to potato cultivation in the EU is located in Germany, France, Poland, the Netherlands, Belgium and Spain. The percentage of farmland in Europe occupied by potato crops is depicted in Figure 1 [9].

Farms engaged in potato production within the EU are typically characterized by their dimensions, which are notably reduced compared to the one occupied for this aim in India and China. Nearly 90% of these farms devoted their efforts to cultivating potatoes on plots of land spanning less than 1 hectare. In contrast, certain Member States focused on the cultivation of potatoes on a larger scale. Consequently, although they represent a relatively small percentage in terms of quantity, these larger-scale potato farms contributed significantly to the total potato production area within the EU [6].

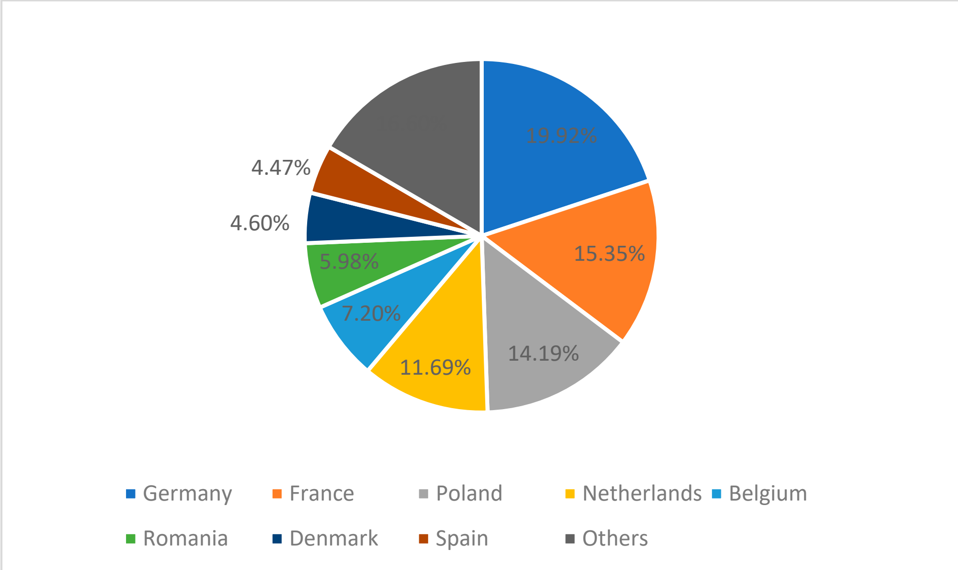

Figure 1. Share of EU potato area cultivated (Source: Eurostat [9]).

In addition to being consumed directly or traded, potatoes are transformed into four primary product categories: frozen potatoes, dried potatoes, prepared or preserved potatoes, and potato starch. The total value of processed potato production in the European Union achieved EUR 9.1 billion in 2019, which represents up to 1.6% of the overall value of food production in the European food industry. Of these products, frozen chips and crisps are the most relevant in terms of production value.

Potato loss during processing can vary significantly depending on the desired end product, processing method and initial quality of the potato [10–12]. Generally, losses are linked to the peeling, cutting, cooking processes, and the amount of rejected potatoes when they do not comply with the required quality standards. Table 1 depicts the average losses expected in the potato processing industry and the average losses measured in PATURPAT.

Table 1. Average losses according to the potato processing stage in the agro-industry.

Processing Stage	Average Loss (%)	Average Losses Considered in the Case of PATURPAT (%)
Peeling	15–25%	5%
Cutting	5%	neglectable
Discarding	5%	0–30%
Cooking	2–5%	5%
Overall losses	20–40%	15%

As shown in Table 1, the larger losses at a general bases are linked to the peeling system and depend on the final product targeted (pre-fried frozen potato, chips or pasteurized potato for instance). Therefore, the overall average loss when processing potatoes to produce elaborated products can range from 20 to 40%.

In the case of PATURPAT, losses associated with the peeling process is significantly lower due to the steam peeler used. During the sieving process after cutting, losses can ranges from practically zero in the case of the omelet products to almost 30% in the case of potato cubes. The discarded portion is also linked to the quality of the potato. During cooking, a 5% loss can be estimated due to it the steaming process, but this figure increases when the potatoes are fried instead. PATURPAT has estimated losses of 15%.

In Europe, more than 2000 companies are active in the potato products sector [13]. This market includes a variety of players, from companies involved in the production and processing of potatoes to those focusing on marketing and export. In Spain, around 1444 companies are involved in the commercialization of potato products [14]. This sector includes companies operating in different areas, from the production of fresh potatoes and processed products to the distribution and export of potatoes to other European markets. Moreover, this sector has experienced an increase in the production of value-added products, including pre-cooked and seasoned potatoes, which better aligns with current consumers' preferences.

3. Starch Valorization

Starch is a key polysaccharide due to its high abundance, lowcost, and absence of toxic properties. In principle two types of starch exist, storage starch and transitory starch [15], which are synthesized in differently and under different conditions. In general, there is a higher content of storage starch.

When analyzing the starch obtained from potato to evaluate its potential as raw material for different applications, several factors can influence the quantity of starch as well as its characteristics. Some of the characteristics that can differ are the Amylose (AMS)/Amylopectin (AMP) ratio, starch granule size or phosphorus content.

Firstly, the quantity of starch can be influenced by the potato variety used, growth conditions, meteorological conditions during the growing season, location characteristics, and fertilization applied [16]. Different studies have analysed different varieties and conditions, obtaining a wide range of results [17–19]. Table 2 presents the variation in starch content across different potato varieties, along with the average starch content of the varieties used by PATURPAT [20].

Table 2. Variation in starch content across different potato varieties [20].

Potato Variety	Starch Content (%)
Red Lady	14.5–16.8%
Bellarosa	12.6–15.7%
Arizona	13–16%
Santé	10–12.5%
Varieties processed in PATURPAT: Jazzy, Monalisa, Lucinda, Colomba, Soprano and Agria	13–20% Average considering the amount of each variety: 13–15%

Some studies have concluded that significant differences are derived from from differences between potato varieties [21]. It can be estimated that the effect can be as high as 66% [22], while others have concluded that the variety does not have a significant effect on the starch content of potatoes. The harvest moment also affects the starch content in fresh tuber, reaching the highest content at 2 months of growth [16]. Other aspects such as the temperature during the tuber growth, the latitude where the potato is cultivated and the conditions during the production season also impact the starch quality [22]. With respect to additional attributes, the size of starch granules, climatic and cultivar or field conditions contribute to variability in granule size [16]. Nonetheless, a research investigation assessing the influence of the cultivar, geographical location, and annual variations on the physico-chemical properties of starch revealed that amylose content, phosphorus levels, and granule size are parameters differ according to the variety. Additionally, this study concluded that these parameters are influenced by the location as well [22]. Furthermore, the growth moment is another factor that affects the granular size, which increases as the growth time increases and after reaching the largest size, the size decreases [21]. Phosphorous content is influenced by growth time [21]. Variety also affects this parameter [21]. Moreover, a correlation between levels of amylose and phosphorous has also been established showing higher content of phosphorous content alongside lower amylose content [22]. Finally, studies have concluded that location has an effect on the total starch, amylose, phosphorus content and starch granular size [22].

Furthermore, logistics aspects are also relevant and can significantly impact on the overall suitability of the value chain as well as the quality of the product marketed. In this sense, for starch obtained in PATURPAT, the most relevant parameters to consider are inked to the storage of this by-product. Some parameters that can be controlled at the storage site greatly impact the stability, quality and properties of the starch include the surrounding temperature which can cause degradation and the humidity of the environment which can contribute to reduce the moisture content of the material or increase it. Additionally, exposure to light can cause oxidation and degradation. Furthermore, the type of packaging used can help to preserve the starch properties over time, facilitate handling and contribute to avoid the microbial contamination associated with the hygienic conditions in which the starch might be stored (Figure 2).

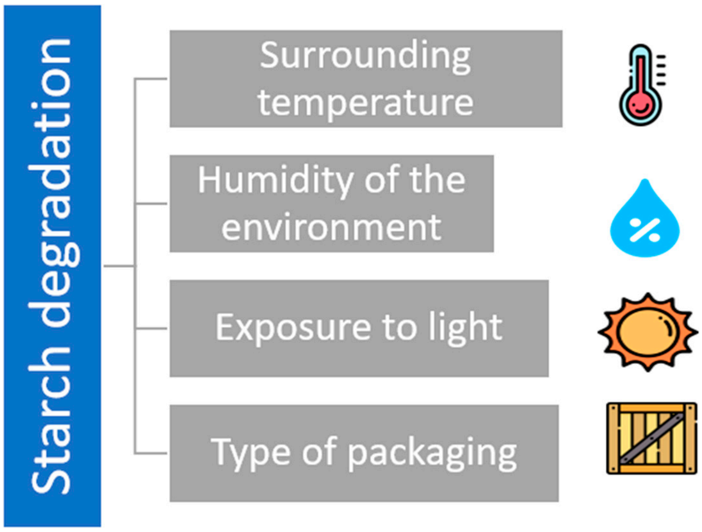

Figure 2. Parameters influencing potato degradation associated with the feedstock logistic.

Apart from the starch that can be extracted from potato rejections, it is also relevant to consider potential starch recovery from the wastewater generated by potato industries. The amount of water required in the washing process is quite significant. But water is also used in other processes such as peeling, cutting or slicing. The wastewater generated during the processing contains high concentrations of starch, present in the form of free suspended solids as well as high content of gelling or bioactive fractions [23,24].

In the case of PATURPAT the water required in the process is around 80,000 m^3 per year. Due to the high Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) the water must be treated before disposal or even recirculated in the process. The Chemical Oxygen Demand (COD) refers to the total amount of oxygen required to chemically oxidize all organic and inorganic matter present in a water sample. It is a measure of the potential for water to consume oxygen through chemical reactions captures both biodegradable and non-biodegradable substances. The Biological Oxygen Demand (BOD), on the other hand, measures the amount of oxygen required by aerobic microorganisms to biologically decompose the organic matter in water over a specified period, usually 5 days at 20 °C (BOD_5). Both COD and BOD are critical for assessing the organic pollution load in water used or discharged by industrial operations. High levels of COD or BOD indicate significant presence of organic matter, which, if untreated, can deplete dissolved oxygen in receiving water bodies, leading to environmental degradation such as eutrophication and harm to aquatic life. For agro-industries monitoring these parameters it is key to ensure compliance with environmental discharge regulations, select the most suitable wastewater treatment systems (e.g., biological reactors or anaerobic digesters for example) and evaluate the efficiency of resource recovery. In the case of PATURPAT the strategy to reduce these parameters has focused on the installation of a starch extraction plant. The data depicted in Table 3 shows recent data analyzed by PATURPAT from the water at different points of the processing line and downstream the extraction plant. The values will likely be improved once the operation of the extraction plant is optimized.

Table 3. DBO, DQO and suspended solids determined by analysising of the water used in the process at PATURPAT.

	BOD5 (mg/L)	COD (mg/L)	SS * (mg/L)
Measure of the BOD and CDO parameters after the cutting process in production line 1	3.730	7.190	10.623
After cutting process in the production line 2	2.950	5.060	3.212
After starch recovery system	1.256	1.296	451
Overall BOD and COD reduction achieved in line 1 (%)	−66.33	−81.97	−95.75
Overall DBO and DQO reduction achieved in line 2 (%)	−57.42	−74.39	−85.96

* In the context of water quality, total solids include all the solid materials, suspended and dissolved, present in a water sample. SS refers to suspended solids.

4. Potato Processing Side-Streams and the Starch Biorefinery Concept

The substantial quantity of waste biomass generated has been recognized as a potentially valuable and environmentally friendly alternative to producing energy, materials and biofuel [25]. In line with existing regulations, some countries are adopting good practices to mitigate food waste; nevertheless, challenges to achieve this goal remain [5]. In addition to food loss and waste, there is also a loss of nutrient density as food progresses through the supply chain [5]. Effective food supply chain management plays a pivotal role in achieving food waste decrease. The adoption of new technologies can have a significant impact in this regard [26]. In this sense, stakeholders engaged in the potato value chain are developing different strategies seeking to reduce food waste; however, significant challenges must still be overcome [5].

In many cases, the by-products generated by food-industries have been mainly valorized as animal-feed; however, there are other valorization pathways that should be explored when considering the biorefinery concept, which in fact, could be associated with higher value-added products [27]. Indeed, the biorefinery approach facilitate residues valorization while increasing their value and transitioning towards a circular economy. In this regard, several pathways could be considered such as biofuel, fertilizer, cosmetics or biomaterial production [28]. In particular, the potato industry generates a significant amount of waste and by-products during the production process, such as pulp, processed water, peels, and mash [29].

In PATURPAT, the potatoes are chopped and washed generating water with high starch content that must be treated due to their high COD and BOD content as well as potato pieces rejected. In Spain, discharging this process water is not possible above the BOD and COD values set in the relevant regulations [30,31]. Alternatives include the installation of a water treatment plant or other type of treatment to reduce these BOD and COD parameters below the stated requirements. This latter option would allow the recovery of the starch which can then be valorized for different bio-applications as previously mentioned.

The extraction facility installed in the case study company includes two flume system for transporting slurry and pieces of potato from the potato processing lines to the starch recovery system. This system includes one parabolic screen, screw press, one refining sieve, one recirculation water tank, two hydro cyclone units, two pumps, one vacuum filter, two screw conveyor and one tank for feeding the hydro cyclone units (Figure 3).

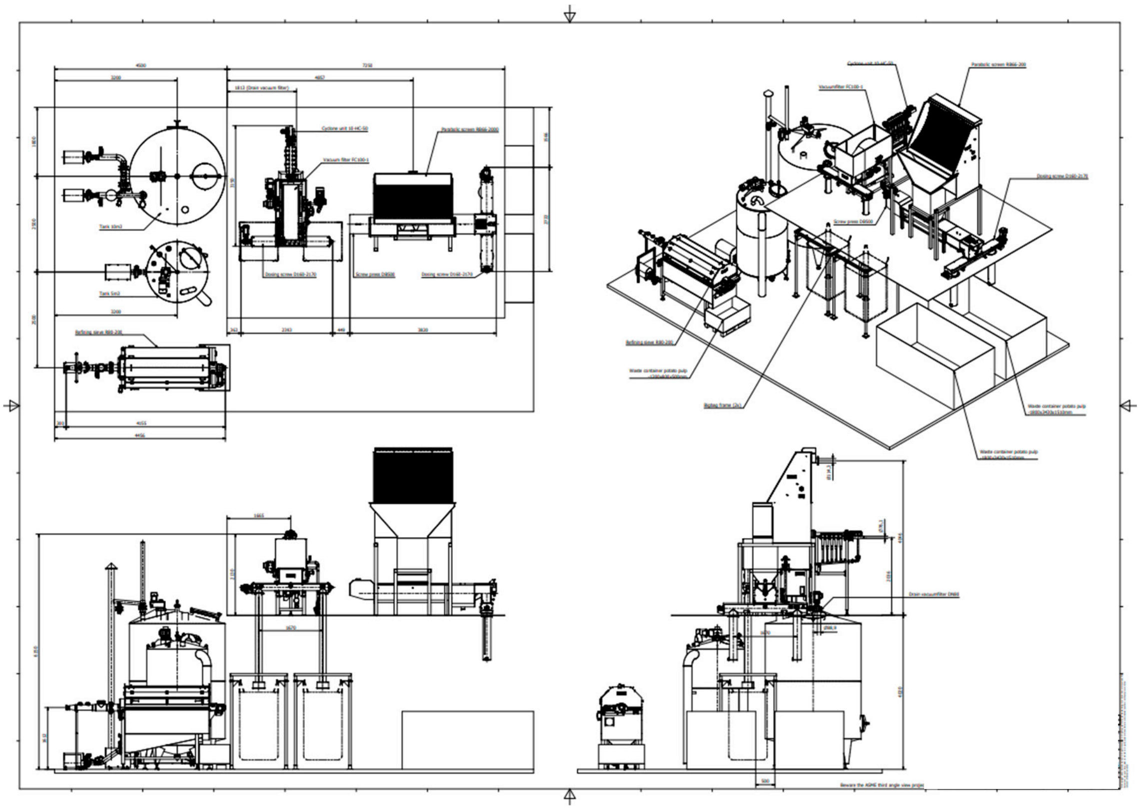

Figure 3. Layout of the starch recovery system installed in PATURPAT company.

As previously mentioned, the starch is extracted from the rejected fragments and water used in the potato processing lines to produce pasteurized potatoes. These lines include peeling, cutting, packaging, and cooking processes. The rejected pieces of potato will be transported by recirculating flumes to the starch recovery system.

5. Starch Valorization Funded Research

To improve the functional characteristics of extracted starch, modifications can be carried, thereby making the starchsuitable for many foods and industrial applications. During the modification treatment, starch properties can be altered, including the solution viscosity, gelatinization properties, pasting properties, retrogradation behaviour, association behaviour, and shelf-life stability in the final products [32]. In general, modifications can be categorized into two groups. The first group encompasses in planta modifications, which can be carried out through genetic manipulation via breeding and molecular biology technologies. The second group encompasses all modifications that occur outside the plant or facility system and can be obtained through physical, chemical, and/or enzymatic methods [15]. Physical methods such as heat-moisture treatment, extrusion, and microwave or ultrasound application could help to improve stability and processability. Additionally, these methods are suitable for biodegradable applications since they do not leave chemical residues, something which is very relevant for certain bio-applications. However, their effectiveness in improving certain performance parameters may be limited compared to that of chemical approaches. Chemical treatments contribute to improving parameters such as flexibility, strength and compatibility with other polymers, for example, which is key for the production of bioplastics production for example. Lastly, enzymatic methods can help reduce crystallinity or produce linear chains, which are relevant for gelling and film formation. The valorization of starch waste from the food processing industry has already been investigated to generate value-added products, platform chemicals, and biofuels, thereby contributing to sustainability and reducing waste management costs [33–36]. Overall, the valorization of starch presents opportunities for the deployment of innovative and sustainable materials and products that will be described in the following sections [37].

5.1. Food Systems

Starch is widely used in the food industry, accounting for around 60% of global production. Starch used as a thickening agent, stabilizer, and texturizer in various food products [38] in the manufacture of snack foods [25]. Additionally, incorporating modified starch enables the production of high-quality snack foods fortified with fiber [39]. The quality of baked products can also be enhanced by the significant properties of starch, including gelatinization, water absorption, and retrogradation [40,41]. The food industry has also explored the use of starch as thickener and stabilizer for gravies, soups and sauces as well as mayonnaise and salad dressing [39]. Additionally, the food industry has shown an increasing interest in finding materials suitable for three-dimensional (3D) printing due to this technology's potential capacity to fabricate tailored products in accordance with customer needs or nutritional requirements. Nonetheless, this application requires edible bio-inks possessing which in turn requires appropriate physicochemical and sensory characteristics of the material. Starch is among the substances that have undergone experimentation to developing food-grade bio-inks [42].

5.2. Textile Industry

Starch has also been employed as a conventional finishing agent for cotton and other textiles despite its lack of durability. Here, the primary purpose of starch is to enhance fabric appearance. Moreover, starch can act as a binding agent for various fillers and helps to increase fabric rigidity [43]. Although synthetic alternatives with superior durability and resistance to washing have been developed, starch remains the preferred choice in some cases due to its biodegradability, low cost, non-toxicity, and compatibility with natural fibers. Starch is especially relevant in eco-friendly textile processing or fabric samples, fashion prototypes, or recyclable garments. Potato starch is especially valued in warp sizing due to its high viscosity, good film-forming ability, and excellent adhesive properties which helps reduce yarn breakage, improve weaving efficiency, and enhances the surface smoothness of fabrics. It is also used in fabric finishing to create a stiffening effect thereby enhancing the overall appearance of the fabric [43,44].

5.3. Pharmaceutical Industry

Starch is employed in the pharmaceutical sector as a binder in tablet formulations, thereby facilitating the bonding of active ingredients. In this sense, tablets continue to be one of the most commonly prescribed forms of medicines due to their stability and ease of handling [45,46]. Currently, starch is listed as one of the most commonly used excipients in tablet formulation. Starches are used for this application due to their versatility and multifunctional characteristics such as their inert nature and cost-effectiveness among others [32,47]. Potato starch, however, can present significant limitations that restrict its widespread use for tablet formulation [45,48]. One of the primary concerns is the variable quality and composition of the starch, which can lead to inconsistencies in tablet performance and drug release. Additionally, its relatively high moisture content makes potato starch susceptible to microbial contamination and reduces the stability of moisture-sensitive active pharmaceutical ingredients. Furthermore, potato starch may may suffer from compatibility issues with certain excipients leading to undesirable chemical interactions. Overall, compared to synthetic or chemically modified binders, potato starch generally provides weaker binding strength, which can compromise tablet hardness and increase friability. Regulatory limitations may also constrain its use depending on the therapeutic application. In conclusion, considering the quality of the starch required for medical, this application does not seem adequate for the starch currently produced by PATURPAT.

5.4. Paper Industry

Due to its aforementioned binding property, starch can also be used in papermaking and paper coating as surface sizing agent and binder contributing to improve the strength and printability of the paper [32]. Its natural film-forming properties make it useful for coating applications, particularly in packaging papers, to enhance ink adhesion and reduce porosity. However, the amount of starch absorbed is limited by the absorption of cellulose substrates. Other problems might can arise at the operational level due to the high viscosity of the starch paste after cooking. Additionally, its cost variability can make it less suitable compared to corn or tapioca starches that are also used for this aim depending on local availability. Moreover, as previously mentioned, the storage of potato starch can be challenging as it can affect the quality of this raw material for the paper production application. Furthermore, its viscosity and gelatinization behavior would require careful control during application. Therefore, this application does not show a significant potential for the product obtained in the case study.

5.5. Feed for Animal

The organic by-products of potato processing are usually valorized as feedstock, especially in cattle and dairy farms. Such by-product can also be used to feed pigs, but only if cooked; otherwise the material is indigestible. Thus, by-products include on the one hand, potato rejections (potato pieces rejected from the production process or unable to meet the commercialization standards) as well as by-products from the starch extraction plant. This type of valorization is feasible but the by-product logistics play a key role as the moisture content of these materials is very high (around 50%). Therefore, this value chain will most likely be economically feasible only when the farm and the agro-industry are close to each other (less than 30–50 km) [49].

5.6. Starch for Ethanol Production

Starch is awidely utilized primary substance to produce ethanol [50,51]. Consequently, several techniques and technologies have been developed to transform starch into ethanol [52]. Among them, the method that entails the pretreatment of starch to break down larger starch molecules into smaller ones prior to fermentation is one of the more attractive [53]. Investigations have also been conducted on the creation of yeast capable of converting raw starch into ethanol without the need for external enzymes, which highly contributes to reducing the investment required [54]. Nevertheless, the use of potato starch for ethanol production faces several constraints that hinder its large-scale deployment such as the high production cost compared to corn or sugarcane for instance, as mentioned for other applications. Additionally, the initial steps of the process in some cases (gelatinization and enzymatic hydrolysis) are energy-intensive and require specialized enzymes which hinder the economic feasibility of the process. Additionally, as presented in Section 3, the composition of potato rejections can significantly vary which makes challenging the process optimization. Finally, the same constraint as previously mentioned for other bio-applications linked to logistics in terms of storage of the feedstock apply in this case. Therefore, logistics needs to be carefully considered to avoid the deterioration of the potato starch.

5.7. Packaging Applications

Over the past few decades, there has been growing interest in utilizing biodegradable polymers derived from renewable resources for specific agricultural purposes such as mulching. This interest is the outcome of the very challenging and ambitious environmental objectives established at the European and national levels seeking to reduce the use of fossil-based materials. In this sense, starch is characterized by its availability worldwide, competitive price but also biodegradability as a key characteristic for this specific application. Furthermore, the starch also possesses thermoplastic characteristics essential for this application [55]. Moreover, starch has the potential to serve as a versatile additive that can play different roles as a filler, a constituent in composites, a plasticizer, or an effective carrier for the targeted delivery of biocides, among others [56]. Furthermore, the overall framework foresees that the global production capacity for bioplastics by 2026 is expected to grow to 7.6 million tons, with Europe accounting for a substantial share of the market at 43.5% [57–59].

Considering the above factors, the characteristics of the starch produced by PATURPAT and the market potential of this product, efforts should focus on determining the potential for stretching film and mulching bio-applications. This last bio-application is especially interesting due to the potential use that the agro-industry could make of this bio-products at field sites. The mulching film produced with the potato starch obtained could be used as mulching at field sites therefore increasing the circularity of the value chain and expanding the company's current business model. The valorization scheme of the PATURPAT case study is summarized in Figure 4.

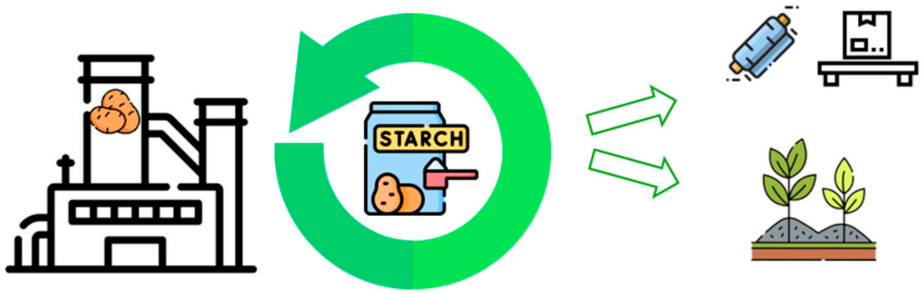

Figure 4. Valorization scheme of PATURPAT case study.

Furthermore, produced biomaterialsmust comply with existing regulations and certification standards, which vary depending on the intended use and market. In the European Union, biomaterials used in packaging or agriculture must adhere to regulations such as REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) [60]. Additionally, certification schemes such EN 13432 [61] for compostability and the OK Bio-based label seek to ensure compliance and market acceptance [62]. The process to comply with the regulatory framework can be challenging for agro-industries as it can be time-consuming and resource-intensive process, especially for small or medium-sized agro-processors not familiar with these regulations. Additionally, extensive laboratory testing and documentation is required for certification which can be financially and technically demanding. Lastly, many clients and retailers now require eco-labels to prove the renewable origin of materials and the traceability of the value chain which again requires additional expertise (collaboration with external entities) and consumes resources. Therefore, resources and actions necessary to comply with these regulations should be considered from the preliminary stage.

6. Commercialization of Starch for Targeted Bio-Applications

The current environmental context of natural resources depletion, excessive plastic pollution and climate change has led to thesignificant development of bioplastics in recent decades. Different directives and regulations have contributed to this aim focusing on reducing the impact of certain plastic products [63]. Recent years have witnessed increasing pressure to seek alternatives to single-use plastics. In this sense, challenging objectives have been established to replace to a certain extent single-use plastics and regular plastic with bioplastics and biodegradable plastics. However, in 2021, 90.2% of global plastics production was of fossil origin while recycled plastics and bio-based plastics accounted for 8.3% and 1.5% of global plastics production, respectively [64].

Nevertheless, in recent years these types of plastic have increased from 0.8 tons in 2018 to 1.3 million tons in 2022. It is expected that the production of bioplastics will reach 7.43 million tons in 2028 [65]. Ultimately, bioplastics are used in an increasing number of applications such as packaging, consumers goods, automative and transport materials, agriculture, electronic, coating and adhesives and construction.

Mulching films are made from plastics that offer durability, flexibility, and resistance to UV degradation, mainly low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polypropylene (PP) as the ones currently used in the agro-industry targeted but also oxo degradable plastics and biodegradable plastics (PLA or Starch-Based). The choice of plastic depends on the type of crop, climate and environmental conditions, duration required by the application but also the availability and price. Figure 5 presents the increasing capacity of PP and PLA over the short-term given that the global production capacity of bioplastics reached 2.18 million tons in 2023 and is expected to increase to 7.43 million tonnes in 2028.

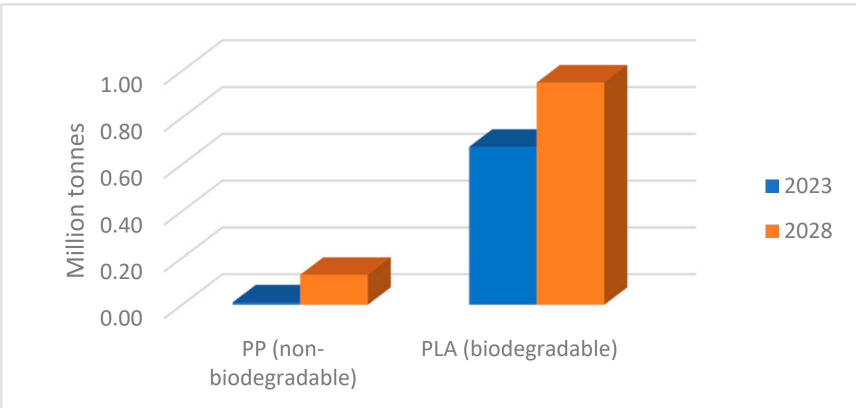

Figure 5. Evolution of the global production capacities of bioplastics.

Similarly, bioplastics produced from by-products generated in agriculture or the agro-industry could represent a sustainable option to increase the rate of bio-based plastics adoption. Here, consumer preferences play a key role as alongside existing regulation. Despite these encouraging trends and supporting measures, there remain issues to be resolved, including cost-effectiveness, technological constraints, and the scalability of biomaterial production [66].

Starch based materials are being widely used in the development of food packaging due to their lower environmental impacts. This type of packaging must also comply with the standards of sustainability and food safety regulations to be considered suitable for commercial applications [66]. Some studies have explored various modifications to improve relevant properties such as modifying native starch in resistant starch to improves the film-forming capacity and extends the feasible applications [67], and improving the water resistance of starch [68]. Starch-based films can also be modified or blended with other polymers to improve their mechanical strength [69]. Other improvements analyzed are related to including antioxidant or antibacterial substances, extending food shelf-life [5]. It is worth highlighting that more research is needed to create starch-based films with mechanical and barrier properties similar to those of traditional plastic packaging [69].

7. Challenges and Future Perspectives

Starch can be used as raw material for different bio-applications in key markets. However, in many countries the current agricultural systems is increasingly deteriorating due to environmental impacts and depletion of arable land for instance. Investigating and documenting of alternative sources of starch, beyond conventional sources such as maize, potato, rice, and wheat, are key to decreasing the pressure over biomaterials development and better pursue the environmental objectives established at the European level. The price fluctuation due to the high demand for these crops in the production of starch for industrial purposes could hinder the deployment of bio-based value chains to exploit starch's potential [70].

As reported in Section 2, the demand for processed meals has also experienced a significant increase due to the new patterns of consumption linked with a reduced time allocated to food preparation which in turn is associated with risen prosperity level in some countries. On the other hand, the telematic work has also helped to balance this trend. Notably, consumer trends can vary greatly over a short period of time, but existing information indeed reveals an increasing demand for such products. Nevertheless, potential changes in consumption trends entails a significant risk when considering potential investments that could hinder the implementation of potential value chains in agro-industries based on side streams valorization like starch which could help expand the existing production of bioplastics.

Within food preparation enterprises, the most common source of environmental pollution arises from the decomposition of organic waste [71]. As previously mentioned, the handling of starch is key to preserving the quality of the product when considering potential application requirements but must be balanced with the economic costs associated with improving the storage conditions.

Additionally, each agro-industry and therefore each potato processing company has a different business model and thus produce different kinds of products and obtain different by-products and side steams. This variety represents a challenge to overcome when designing the most suitable strategy for managing the by-products obtained in a sustainable and cost-effective way. Potato waste management using different techniques has been reported, but the effectiveness of such techniques is limited and depends on the selecting appropriate valorization schemes [72]. Nevertheless, the valorization scheme presented in PATURPAT case study is highly replicable considering on the one hand the maturity of the technology used (starch extraction technology that is already widely commercialized and proven in industrial settings). On the other hand, the targeted agro-industries across Europe typically have well-developed processing lines, facilitating integration of these complementary processes. Furthermore, the agro-industry sector is generally open to innovation and actively seeks to improve environmental sustainability of their processes which is a growing priority in many sectors. Finally, the replication of this valorization initiative would be particularly interesting in countries such as Germany, France, the

Netherlands, Poland, and Belgium which are major potato producers with well-developed processing sectors.

As previously mentioned, there is a considerable demand for biodegradable materials. Unfortunately, while some bio-products have gained commercial acceptance, natural bio-based materials are still slowly transitioning from the laboratory to industrial application [73].

Forthcoming regulation could also play a crucial role in enhancing the path towards the valorization of by-products obtained in agro-industries, such as the use of starch in the targeted agro-industry. Indeed, a provisional agreement regarding the Packaging and Packaging Waste Regulation (PPWR) was adopted in April 2024. The text of this regulation is expected to enter into force in the coming year. This regulation could affect potato commercialization. Therefore, the associated impacts will need to be considered to update potential business models as needed thus addressing the valorization of potato rejections and process water by such companies.

8. Conclusions

The use of potato starch to produce biomaterials is strongly aligned with the European Union's overarching sustainability goals and legislative frameworks which support the transition to a circular economy (Bioeconomy Strategy, Circular Economy Action Plan, EU 2019/904 [63], related to the single use of plastics and the broader Green Deal). The valorization of potato starch also supports the Waste Framework Directive which aligns with the recovery and reuse of organic materials. To reach the ambitious environmental objectives established at European level, the pursuit of suitable materials should seek to enhance the production of alternatives to fossil-based goods and support measures designed to boost replication of valorization schemes with improved sustainability and competitive prices.

Considering the current scenario alongside the short and medium-term forecasts for the potato industry, assessing valorization alternatives to recover the by-products generated in the industrial process, such as starch, have an important role. The constant evolution of consumer trends or regulations, among others, requires the adaptation of current business models in the coming years. These business models will necessarily should consider aspects such as the process' environmental sustainability and the social innovation based on the economic feasibility. Enlarging the agro-industries' current business model to valorize by-products such as the starch can significantly help to boost bioeconomy and circularity in rural areas while contributing to explore additional the sources of incomes for agro-industries.

Based on the data provided, starch from the extraction plant that processes both potato rejections and processing water is suitable for various applications, but the manufacture of thermoplastics with agricultural applications is of particular relevance. On the one hand, it can contributes to enhancing the circularity of the process through its use as mulching material on site for crop cultivation. On the other hand, the quality standards required for this material's use in food applications would entail a more significant investment to further process the starch obtained. Thus, it is key to find a balance that allow companies to update their business model to improve the sustainability and circularity of the process while maintaining economic profitability.

Exploring the generated starch's potentialas mulching product for use in fields brings these circularity and sustainability objectives closer to the primary sector actors, farmers, who are key stakeholders involved in the value chain and to the rural environment. The involvement of these actors is fundamental and collaboration between these agents and the agro-industry is key to the successful deployment of the bioeconomy and the proposed valorization scheme.

Furthermore, business model for a potato processing agro-industry such as PATURPAT that integrates a starch extraction plant to valorize side streams has strong replication potential across Europe considering the significant number of agro-industrial facilities devoted to this aim and the large surface area used for potato cultivation. The benefits for agro-industries currently discarding the by-products obtained in their process include avoiding of disposal costs associated with waste management and could also contribute to minimizing the environmental impacts and enhancing resource efficiency. Additionally, starch represents a high-demand market due to its different bio applications. Overall, the model exemplifies the principles of circular economy and aligns with the objectives of the EU Green Deal, strategically aligning this concept with policy drivers and increasing its attractiveness for replication.

Author Contributions: M.G.P., A.C., P.d.l.S., M.D.M.-T., S.A.M. and F.J.R.H. contributed to the study conception and design. Material preparation and data collection were performed by M.G.P., P.d.l.S. and A.C. The analysis was performed by M.G.P. and P.d.l.S. The first draft of the manuscript was written by M.G.P., P.d.l.S., M.D.M.-T., S.A.M. and F.J.R.H. commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by European Union's Horizon Europe programme under grant agreements BIOLOC project with GA n° 101060558 and BRILIAN project with GA n° 101112436.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets generated during and/or analyzed during the current study are not publicly available due but are available from the corresponding author on reasonable request.

Conflicts of Interest: Author Ana Carrasco was employed by the company PATURPAT. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Sharma, P.; Gaur, V.K.; Sirohi, R.; Varjani, S.; Kim, S.H.; Wong, J.W.C. Sustainable Processing of Food Waste for Production of Bio-based Products for Circular Bioeconomy. *Bioresour. Technol.* **2021**, *325*, 124684. [CrossRef]
2. Yaashikaa, P.R.; Kumar, P.S.; Saravanan, A.; Varjani, S.; Ramamurthy, R. Bioconversion of municipal solid waste into bio-based products: A review on valorisation and sustainable approach for circular bioeconomy. *Sci. Total Environ.* **2020**, *748*, 141312. [CrossRef]
3. Beer, K.; Böcher, M.; Ganzer, C.; Blöbaum, A.; Engel, L.; Sieverding, T.D.P.; Sundmacher, K.; Matthies, E. Forest-based bioeconomy and bio-based chemical production in the European Union: Policy issues, institutions, actors, and instruments in a changing forest policy subsystem. *For. Policy Econ.* **2025**, *177*, 103521. [CrossRef]
4. Ding, Z.; Hamann, K.T.; Grundmann, P. Enhancing circular bioeconomy in Europe: Sustainable valorization of residual grassland biomass for emerging bio-based value chains. *Sustain. Prod. Consum.* **2024**, *45*, 265–280. [CrossRef]
5. Verni, M.; Casanova, F. The Potential of Food By-Products: Bioprocessing, Bioactive Compounds Extraction and Functional Ingredients Utilization. *Foods* **2022**, *11*, 4092. [CrossRef]
6. Fotschki, J.; Ogrodowczyk, A.M.; Wróblewska, B.; Juśkiewicz, J. Side Streams of Vegetable Processing and Its Bioactive Compounds Support Microbiota, Intestine Milieu, and Immune System. *Molecules* **2023**, *28*, 4340. [CrossRef]
7. Zou, Y.; Heyndrickx, M.; Debode, J.; Raes, K.; de Pascale, D.; Behan, P.; Giltrap, M.; O'cOnnor, C.; Solstad, R.G.; Lian, K.; et al. Valorisation of crustacean and bivalve processing side streams for industrial fast time-to-market products: A review from the European Union regulation perspective. *Front. Mar. Sci.* **2023**, *10*, 1068151. [CrossRef]
8. Food and Agriculture Organization (FAO). FAO Statistics. Available online: https://www.fao.org/statistics/en (accessed on 14 October 2024).

9. EUROSTAT. Crop Production in EU Standard Humidity. Available online: https://ec.europa.eu/eurostat/databrowser/ (accessed on 11 July 2025).
10. Varns, J.L.; Schaper, L.A.; Preston, D.A. Potato losses during the first three months of storage for processing. *Am. Potato J.* **1985**, *62*, 91–99. [CrossRef]
11. Meyer, C.H.; Dominik, F.; Hamer, M.; Oertzen, G. Food Losses in Supply Chains for Fruits, Vegetables and Potatoes between Field and Retail Shelf in North-Rhine Westphalia, Germany. In Proceedings of the 11th International European Forum (Igls-Forum) (161st EAAE Seminar) on System Dynamics and Innovation in Food Networks, Innsbruck-Igls, Austria, 13–17 February 2017. [CrossRef]
12. Magdalena, G.; Dariusz, M. Losses during Storage of Potato Varieties in Relation to Weather Conditions during the Vegetation Period and Temperatures during Long-Term Storage. *Am. J. Potato Res.* **2018**, *95*, 130–138. [CrossRef]
13. The EU Potato Sector—Statistics on Production, Prices and Trade. 2024. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=The_EU_potato_sector_-_statistics_on_production,_prices_and_trade (accessed on 14 October 2024).
14. Euromonitor International. *Report Vegetable, Potato and Fruit Products in Spain*; Euromonitor International: London, UK, 2024.
15. Compart, J.; Singh, A.; Fettke, J.; Apriyanto, A. Customizing Starch Properties: A Review of Starch Modifications and Their Applications. *Polymers* **2023**, *15*, 3491. [CrossRef]
16. Yusuph, M.; Tester, R.F.; Ansell, R.; Snape, C.E. Composition and properties of starches extracted from tubers of different potato varieties grown under the same environmental conditions. *Food Chem.* **2003**, *82*, 283–289. [CrossRef]
17. Ngobese, N.Z.; Workneh, T.S.; Alimi, B.A.; Tesfay, S. Nutrient composition and starch characteristics of eight European potato cultivars cultivated in South Africa. *J. Food Compos. Anal.* **2017**, *55*, 1–11. [CrossRef]
18. Zaidul, I.; Yamauchi, H.; Takigawa, S.; Matsuuraendo, C.; Suzuki, T.; Noda, T. Correlation between the compositional and pasting properties of various potato starches. *Food Chem.* **2007**, *105*, 164–172. [CrossRef]
19. Ahmad, D.; Ying, Y.; Bao, J. Understanding Starch Biosynthesis in Potatoes for Metabolic Engineering to Improve Starch Quality: A Detailed Review. *Carbohydr. Polym.* **2024**, *346*, 122592. [CrossRef]
20. Agricopotatoes. Home Page. Available online: https://www.agricopotatoes.com (accessed on 21 July 2025).
21. Liu, Q.; Weber, E.; Currie, V.; Yada, R. Physicochemical properties of starches during potato growth. *Carbohydr. Polym.* **2003**, *51*, 213–221. [CrossRef]
22. Simkova, D.; Lachman, J.; Hamouz, K.; Vokal, B. Effect of cultivar, location and year on total starch, amylose, phosphorus content and starch grain size of high starch potato cultivars for food and industrial processing. *Food Chem.* **2013**, *141*, 3872–3880. [CrossRef]
23. Torres, M.D.; Fradinho, P.; Rodríguez, P.; Falqué, E.; Santos, V.; Domínguez, H. Biorefinery concept for discarded potatoes: Recovery of starch and bioactive compounds. *J. Food Eng.* **2020**, *275*, 109886. [CrossRef]
24. SDevereux; Shuttleworth, P.S.; Macquarrie, D.J.; Paradisi, F. Isolation and Characterization of Recovered Starch from Industrial Wastewater. *J. Polym. Environ.* **2011**, *19*, 971–979. [CrossRef]
25. Elgarahy, A.M.; Eloffy, M.; Alengebawy, A.; El-Sherif, D.M.; Gaballah, M.S.; Elwakeel, K.Z.; El-Qelish, M. Sustainable management of food waste; pre-treatment strategies, techno-economic assessment, bibliometric analysis, and potential utilizations: A systematic review. *Environ. Res.* **2023**, *225*, 115558. [CrossRef]
26. Raji, A.O. Utilization of Starch in Food and Allied Industries in Africa: Challenges and Prospects. In *Innovation in the Food Sector Through the Valorization of Food and Agro-Food By-Products*; IntechOpen: London, UK, 2021. [CrossRef]
27. PAlmeida, V.; Gando-Ferreira, L.M.; Quina, M.J. Biorefinery Perspective for Industrial Potato Peel Management: Technology Readiness Level and Economic Assessment. *J. Environ. Chem. Eng.* **2023**, *11*, 110049. [CrossRef]
28. Barampouti, E.M.; Christofi, A.; Malamis, D.; Mai, S. A sustainable approach to valorize potato peel waste towards biofuel production. *Biomass Convers. Biorefin* **2023**, *13*, 8197–8208. [CrossRef]
29. Suresh, T.; Sivarajasekar, N.; Balasubramani, K.; Ahamad, T.; Alam, M.; Naushad, M. Process intensification and comparison of bioethanol production from food industry waste (potatoes) by ultrasonic assisted acid hydrolysis and enzymatic hydrolysis: Statistical modelling and optimization. *Biomass Bioenergy* **2020**, *142*, 105752. [CrossRef]
30. Gobierno de España. Real Decreto 1085/2024, de 21 de marzo, por el que se regula la reutilización del agua. *Bol. Of. Estado* **2024**, *121*, 34567–34589.
31. Ayuntamiento de Vitoria-Gasteiz. Ordenanza municipal de vertidos no domésticos. In *BOP Álava*; Diputación Foral de Álava: Álava, Spain, 2023; Volume 215, pp. 22–35.
32. Özden, Ö.; Sönmez, S. Starch Usage in Paper Industry. In *Research & Reviews in Engineering*; Gece Publishing: New York, NY, USA, 2019.
33. BSaba; Bharathidasan, A.K.; Ezeji, T.C.; Cornish, K. Characterization and potential valorization of industrial food processing wastes. *Sci. Total Environ.* **2023**, *868*, 161550. [CrossRef]
34. Ben Amara, F.; Bouzid, M.; Sahnoun, M.; Ben Nasr, Y.; Jaouadi, B.; Bejar, S.; Jemli, S. Valorization of Potato Peels Starch for Efficient β-Cyclodextrin Production and Purification through an Eco-Friendly Process. *Starch—Stärke* **2022**, *74*, 2200037. [CrossRef]

35. Drosg, B.; Neubauer, M.; Marzynski, M.; Meixner, K. Valorisation of Starch Wastewater by Anaerobic Fermentation. *Appl. Sci.* **2021**, *11*, 10482. [CrossRef]
36. Vadivel, D.; Ferraro, F.; Dondi, D. Harnessing Biomass for a Sustainable Future: The Role of Starch and Lignin. *Catalysts* **2024**, *14*, 747. [CrossRef]
37. EU Potato Market Analysis, Forecast, Size, Trends and Insights. 2024. Available online: https://www.indexbox.io/blog/potato-european-union-market-overview-2024-2/ (accessed on 14 October 2024).
38. Ogori, A.F.; Taofeek, A. Starch source, modification and food application. *Res. J. Food Sci. Nutr.* **2022**, *7*, 85–91. [CrossRef]
39. Aprianita, A.; Vasiljevic, T.; Bannikova, A.; Kasapis, S. Physicochemical properties of flours and starches derived from traditional Indonesian tubers and roots. *J. Food Sci. Technol.* **2014**, *51*, 3669–3679. [CrossRef]
40. Woodbury, T.J.; Pitts, S.L.; Pilch, A.M.; Smith, P.; Mauer, L.J. Mechanisms of the different effects of sucrose, glucose, fructose, and a glucose–fructose mixture on wheat starch gelatinization, pasting, and retrogradation. *J. Food Sci.* **2023**, *88*, 293–314. [CrossRef]
41. Donmez, D.; Pinho, L.; Patel, B.; Desam, P.; Campanella, O.H. Characterization of starch–water interactions and their effects on two key functional properties: Starch gelatinization and retrogradation. *Curr. Opin. Food Sci.* **2021**, *39*, 103–109. [CrossRef]
42. Chen, Y.; McClements, D.J.; Peng, X.; Chen, L.; Xu, Z.; Meng, M.; Zhou, X.; Zhao, J.; Jin, Z. Starch as edible ink in 3D printing for food applications: A review. *Crit. Rev. Food Sci. Nutr.* **2024**, *64*, 456–471. [CrossRef]
43. Chowdhury, A.K.R. Starch Finishing. In *Principles of Textile Finishing*; Woodhead Publishing: Sawston, CA, USA, 2017; pp. 61–77. [CrossRef]
44. Chiu, C.; Solarek, D. Modification of Starches. In *Starch*; Elsevier: Amsterdam, The Netherlands, 2009; pp. 629–655. [CrossRef]
45. Apeji, Y.E.; Kaigama, R.T.; Ibrahim, S.H.; Anyebe, S.N.; Abdussalam, A.O.; Oyi, A.R. Tableting Performance of Maize and Potato Starches Used in Combination as Binder/Disintegrant in Metronidazole Tablet Formulation. *Turk. J. Pharm. Sci.* **2022**, *19*, 513–520. [CrossRef]
46. Patil, S.V.; Ghatage, S.L.; Navale, S.S.; Mujawar, N.K. Natural Binders in Tablet Formulation. *Int. J. PharmTech Res.* **2014**, *6*, 1070–1073.
47. Apeji, Y.E.; Ali, A.; Anyebe, S.N.; Orugun, O.A.; Olowosulu, A.K.; Oyi, A.R. Performance Evaluation of Maize Starch as a Multifunctional Excipient in Metronidazole Tablet Formulation. *Ars. Pharm.* **2019**, *60*, 161–167. [CrossRef]
48. Bharath, S.; Deveswaran, R. Extraction of polysaccharide polymer from *Dioscorea trifida* and evaluation as a tablet binder. *J. Pharm. Pharm. Sci.* **2012**, *4*, 347–352.
49. Kahraman, O.; Gülşen, N.; İnal, F.; Alataş, M.S.; İnanç, Z.S.; Ahmed, I.; Şişman, D.; Küçük, A.E. Comparative Analysis of In Vitro Fermentation Parameters in Total Mixed Rations of Dairy Cows with Varied Levels of Defatted Black Soldier Fly Larvae (*Hermetia illucens*) as a Substitute for Soybean Meal. *Fermentation* **2023**, *9*, 652. [CrossRef]
50. Taha, M.G.; Awad, M.; El-Raheem, M.A. Production of Bio-Ethanol from Potato Starch Wastes by *Saccharomyces cerevisiae*. *Egypt. J. Appl. Sci.* **2019**, *34*, 256–267.
51. Arapoglou, D.; Varzakas, T.; Vlyssides, A.; Israilides, C. Ethanol production from potato peel waste (PPW). *Waste Manag.* **2010**, *30*, 1898–1902. [CrossRef]
52. Neto, M.C.; Robaina, A.D.; Peiter, M.X.; Rodrigues, S.A.; Flores, Y.R.; Bruning, J.; da Silva, J.G.; Ferreira, L.D. Economic indicators for ethanol production from starch crops under different irrigation managements1. *Rev. Bras. Eng. Agric. E Ambient.* **2022**, *26*, 640–648. [CrossRef]
53. Viviana, M. Ethanol production from hydrolysis, fermentation and distillation by reduced pressure of the potato starch. *J. Biotechnol.* **2008**, *136*, S507. [CrossRef]
54. Fomina, M.O.; Ianieva, O.D.; Havrylenko, M.V.; Golovach, T.M.; Pidgorskyi, V.S. Ethanol Production by Co-Cultivation of Yeast and Lactic Acid Bacteria on Starch. *Mikrobiol. Zh* **2021**, *83*, 3–14. [CrossRef]
55. Onyeaka, H.; Obileke, K.; Makaka, G.; Nwokolo, N. Current Research and Applications of Starch-Based Biodegradable Films for Food Packaging. *Polymers* **2022**, *14*, 1126. [CrossRef]
56. AGamage, A.; Liyanapathiranage, A.; Manamperi, A.; Gunathilake, C.; Mani, S.; Merah, O.; Madhujith, T. Applications of Starch Biopolymers for a Sustainable Modern Agriculture. *Sustainability* **2022**, *14*, 6085. [CrossRef]
57. Thomas, A.P.; Kasa, V.P.; Dubey, B.K.; Sen, R.; Sarmah, A.K. Synthesis and commercialization of bioplastics: Organic waste as a sustainable feedstock. *Sci. Total Environ.* **2023**, *904*, 167243. [CrossRef]
58. Mtibe, A.; Nomadolo, N.; Hlekelele, L.; Mokhena, T.; Ofosu, O.; John, M.; Ojijo, V. Advanced of Starch-Based Bioplastics. In *Reference Module in Materials Science and Materials Engineering*; Elsevier: Amsterdam, The Netherlands, 2024. [CrossRef]
59. Ali, Z.; Abdullah, M.; Yasin, M.T.; Amanat, K.; Ahmad, K.; Ahmed, I.; Qaisrani, M.M.; Khan, J. Organic waste-to-bioplastics: Conversion with eco-friendly technologies and approaches for sustainable environment. *Environ. Res.* **2024**, *244*, 117949. [CrossRef]
60. European Commission. REACH Regulation. Available online: https://environment.ec.europa.eu/topics/chemicals/reach-regulation_en (accessed on 12 July 2025).

61. *EN 13432:2001*; Packaging—Requirements for Packaging Recoverable through Composting and Biodegradation—Test Scheme and Evaluation Criteria for the Final Acceptance of Packaging. European Committee for Standardization: Brussels, Belgium, 2001.
62. TÜV Austria. TÜV AUSTRIA Certification Scheme: OK Biobased. Available online: https://okcert.tuvaustria.com/ok-biobased-en/ (accessed on 12 July 2025).
63. Parlamento Europeo. Directiva (UE) 2019/904 del Parlamento Europeo y del Consejo, de 5 de Junio de 2019, Relativa a la Reducción del Impacto de Determinados Productos de Plástico en el Medio Ambiente. 2019. Available online: https://eur-lex.europa.eu/legal-content/ES/ALL/?uri=CELEX%3A32019L0904 (accessed on 12 July 2025).
64. Burelo, M.; Hernández-Varela, J.D.; Medina, D.I.; Treviño-Quintanilla, C.D. Recent developments in bio-based polyethylene: Degradation studies, waste management and recycling. *Heliyon* **2023**, *9*, e21374. [CrossRef]
65. European Bioplastics. Global Production Capacities of Bioplastics 2023–2028. Available online: http://www.european-bioplastics.org/news/publications (accessed on 21 July 2025).
66. Al Mahmud, M.Z.; Mobarak, M.H.; Hossain, N. Emerging Trends in Biomaterials for Sustainable food Packaging: A Comprehensive Review. *Heliyon* **2024**, *10*, e24122. [CrossRef]
67. Fatima, S.; Khan, M.R.; Ahmad, I.; Sadiq, M.B. Recent Advances in Modified Starch Based Biodegradable Food Packaging: A Review. *Heliyon* **2024**, *10*, e27453. [CrossRef]
68. Abioye, A.A.; Obuekwe, C.C. Investigation of the biodegradation of low-density polyethylene-starch Bi-polymer blends. *Results Eng.* **2020**, *5*, 100090. [CrossRef]
69. Liu, D.; Zhao, P.; Chen, J.; Yan, Y.; Wu, Z. Recent Advances and Applications in Starch for Intelligent Active Food Packaging: A Review. *Foods* **2022**, *11*, 2879. [CrossRef]
70. Lawal, O.S.; Ogundiran, O.O.; Awokoya, K.; Ogunkunle, A.O. The low-substituted propylene oxide etherified plantain (*Musa paradisiaca normalis*) starch: Characterization and functional parameters. *Carbohydr. Polym.* **2008**, *74*, 717–724. [CrossRef]
71. Khanal, S.; Karimi, K.; Majumdar, S.; Kumar, V.; Verma, R.; Bhatia, S.K.; Kuca, K.; Esteban, J.; Kumar, D. Sustainable Utilization and Valorization of Potato Waste: State of the Art, Challenges, and Perspectives. *Biomass Conv. Bioref.* **2023**, *14*, 23335–23360. [CrossRef]
72. Chauhan, A.; Islam, F.; Imran, A.; Ikram, A.; Zahoor, T.; Khurshid, S.; Shah, M.A. A review on waste valorization, biotechnological utilization, and management of potato. *Food Sci. Nutr.* **2023**, *11*, 5773–5785. [CrossRef]
73. Falua, K.J.; Pokharel, A.; Babaei-Ghazvini, A.; Ai, Y.; Acharya, B. Valorization of Starch to Biobased Materials: A Review. *Polymers* **2022**, *14*, 2215. [CrossRef]