Valorization and Development of Acorn Starch as Sustainable and High-Performance Papermaking Additive for Improving Bagasse Pulp and Paper Properties

Ali Baradaran Khaksaar1 · Hossein Jalali Torshizi1 · Yahya Hamzeh2,3

Received: 21 February 2022 / Accepted: 18 August 2022 / Published online: 26 August 2022 © The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract
Improving bagasse pulp and paper properties using forest-byproduct biomass, native Acorn starch (NAS), was compared with conventional wet-end additive cationic corn starch (CCS). The extracted acorn starch was characterized by SEM, XRD, and GPC. The results clearly showed irregular granular shape (6–12 μm) with rough surfaces, C_A-type XRD pattern, and 436.2 kDa molecular weights for NAS. The bagasse pulp retention and drainage as keys of operation performance and runnability were superior by NAS in comparison with CCS, while the lowest dosage of NAS (0.5%) showed superior results than the highest dosages of CCS (1% & 1.5%). The higher NAS adsorption onto the fiber surfaces compared to CCS could be concluded by higher water retention value (WRV) of the pulp together with higher density (up to 20%) and mechanical properties of the produced paper, e.g., tensile (up to 63%), burst (up to 37%) and tear (up to 11%) indices. NAS exploiting naturally as a papermaking additive would provide performance higher than commercial chemically-modified starch.

Hossein Jalali Torshizi
H_Jalali@sbu.ac.ir

1 Department of Biorefinery, Faculty of New Technologies and Aerospace Engineering, Shahid Beheshti University, Velenjak, Tehran, Iran

2 Department of Wood and Paper Sciences and Technology, University of Tehran, Tehran, Iran

3 University Grenoble Alpes, CNRS, Grenoble INP Institute of Engineering University, Grenoble Alpes, LGP2, F-38000 Grenoble, France
Graphical abstract

Keywords | Valorization | Acorn starch | Bio-residuals | Industrial application

Statement of Novelty

Valorization of a useless, sustainable, abundant and non-foody biomass as an industrially bio chemical was performed. Starch extracted from Oak fruit, Acorn, as a forest bio residual was studied for key properties improvement of pulp and paper produced from bagasse bio-residual. Increasing competions and demands on starch feedstock as food and feed resources necessitate developing non-foody products based on non-foody bio-resources, as much as possible. The presented raw starch enhanced the intrinsically week properties of bagasse pulp and paper. In comparison with Corn starch, Acorn starch showed better performance. Therefore, this research outline potential application of Acorn starch, as a less studied biomaterial, for enhancing paper properties, especially from bagasse agro residual, which was not reported previously.

Introduction

Responding to environmental concerns and commitments towards green, sustainable, and cleaner manufacturing of products, scientists are trying to find novel bio-based alternatives instead of the conventionally available fossil-based products. Numerous researches are motivated and focused on the preparation of novel bioproducts based on low-cost natural raw materials, such as starch, cellulose, lignin, hemicellulose, vegetable oil, and chitin. However, among the bio-based materials, competitions are also rising in the dependent industries and consumers, originating from the insufficient availability of the bio raw materials and feedstock. For example, many countries have legislated against the grain resources application for non-food industrial feedstock due to the upcoming competition on grain resources. Therefore, it is imperative to develop biomaterials based on non-foody resources as much as possible. Starches and their origins like tubers, roots, and
cereals are the leading food and feed resources [8]. During the past decade, the prices of grain [9] and potato [10] have dramatically increased throughout the world, mainly due to the increased population demands, growing demand for starch-based bio-energy, bioplastic, and other bio-based products [11, 12, 13]. Most recently, escalating concerns about Coronavirus (COVID19) have increased longer-term uncertainty of production and consumption of grains that increased their prices, at least as a short-term phenomenon [14, 15].

Oak trees with about 300 species [16] belong to the genus Quercus and Fagaceae family, distributed in different world regions like China, India, the Middle East, the Mediterranean region, Europe, and North America in forests, parks, and gardens. Acorn is the non-grain starchy fruit of Oak trees with a bitter taste and only a tiny portion usage in traditional and forest-based food and herbal medicine [16, 17, 18]. Then, acorn fruit is usually considered as a useless abundant biomaterial and is commonly abandoned in large quantity around the world [8, 19, 20] estimated to be about 0.5 tonnes/hectare/year of Oak forests with considerably variations among individual trees, years, and locations [20].

Acorn fruit mainly consists of a considerable amount of amyllopectin rich starch (up to 60%), flavonoids, protein (3–6%), vitamins, microelements, and bitter polyphenol substances, such as hydrolyzable and condensed tannins (5–12%), and tannic acid [16, 19, 21]. Regarding the above-mentioned acorn components, acorn fruit could offer sustainable and promising alternative raw materials for various applications. Food industries [22, 23, 24], bioenergy [16, 19, 20, 25], edible film [16], biocomposites [8], and adsorbent [26, 27] were reported as the potential applications of raw acorn material.

The papermaking industries, mainly the fine paper industry, are under pressure to fulfill the increasing demand for writing and printing papers through the environmentally friendly process [28]. At present, wood is the main used raw material for pulp and paper manufacturing [29]. The utilization of non-wood raw materials like sugarcane bagasse, bamboo, wheat straw, and rice straw for pulp and paper manufacturing has attracted significant attention, especially for regions with limited wood supply [30, 31, 32]. However, this development is currently facing a lot of environmental concerns due to the difficulty of black liquor treatment from non-woods, thus development of economical and efficient chemical and energy recovery strategy is the key and urgent priority to the successful and clean production of pulp and paper from non-wood raw materials [30, 31, 32]. Sugarcane bagasse, as the fibrous residue of the sugarcane industry, is one of the vital wood substitutes in the pulp and paper industries that could be easily collected and stored on-site [33, 34]. Bagasse is renewable, low-cost, and abundant fibrous raw material for pulping and paper making, which its worldwide production is estimated to be as much as 540 million t/y [35, 36]. However, mechanical strengths, drainage, runnability, and freeness levels of these pulps are usually lower than woody pulps [37]. Papermakers often apply different practices to resolve these challenges toward facilitating the non-wood pulps utilization [37]. For instance, the non-wood pulp has historically been used in different types of paper and paperboards as an admixture of recycled paper to improve the pulp and paper properties [30, 31]. Furthermore, blending long fiber softwood pulps with the short fiber non-wood pulps [38, 39, 40], mechanical treatment, i.e., separate or co-refining of pulps [41, 42], and application of dry strength and retention additives [43, 44, 45] are considered as the major solutions for improving the quality of papers made from non-woods.

For decades, several dry-strength additives have been studied for various purposes in papermaking as promising alternatives to the mechanical treatments [46, 47, 48]. Besides the extensive energy consumption of beating and refining, the treatments also make undesirable and irreversible changes in fiber structure [49, 50]. The undesirable changes including wall thickness reduction and weakness, more extensive fiber hornification during drying and recycling, length shortening, higher fines production and consequently losing, all are in paradox with cleaner and the more economical production of pulp and paper [51, 52]. While, application of dry strength additives instead of the mechanical treatments prevents the undesirable changes, e.g., hornification [52, 53, 54]. In this regard, cationic starch is the most widely used additive to enhance the strength properties of the paper due to its compatibility and intrinsic electrostatic interactions with the cellulosic fiber surface [48, 55, 56].

Due to the large amount of starch, acorn fruit could be valorized as an economical and renewable raw material in various industries. In this regards, application of starches from non-conventional sources such as acorn fruit in pulp and paper industries, especially as a wet-end additive could promote the development of new cost effective and value-added paper products with desired functional properties. This requires comprehensive and practical information to enhance competitive advantage of acorn starch over conventional starches that are used in paper-making process. Nevertheless, to the best of our knowledge there is little information available in literature relating to the properties and practical applicability of non-conventional acorn starch as papermaking wet-end additive. Therefore, this research focused on the extraction, characterization and application of extracted acorn starch as a dry strength additive to improve the performance of paper made from bagasse, in comparison with commercially corn starch.
Materials and Methods

Main Raw Materials

The refined bagasse pulp (Table 1) supplied kindly by Pars Pulp and Paper Company, Iran and kept in 4 °C before utilization. Commercially available cationic corn starch (Table 2) that is conventionally used in papermaking industries; kindly provided by Glucosan Co., Iran, with an average degree of substitution (DS) of 0.025% (0.015–0.035%). Q. persica acorns fruits were randomly collected as their maturity state in October from Fars province oak forests in the southwest of Iran (Fig. 1a). The harvested fresh fruits were air dried and stored in dark conditions at 4 °C. Before milling by a conventional blender, the acorn fruits were subjected to hand peeling to remove the tegument and pericarp. Other used chemicals such as NaOH, ethanol, dichloromethane, and acetone were selected from analytical grade.

Table 1 Bleached bagasse pulp properties

| Cellulose (%) | Hemicelluloses (%) | Lignin(%) | pH | Extractives (%) | Ash (%) | Humidity(%) | Brightness (%) | Fiber length(mm) |
|---------------|-------------------|----------|----|-----------------|--------|-------------|---------------|-----------------|
| 90.5          | 8                 | <1       | 8.1| 0.22            | 1.14   | 10          | 83.7          | 0.75            |

Table 2 Cationic corn starch (CCS) properties

| Form        | Humidity | Whiteness | Ash | Water solubility | Nitrogen | Protein |
|-------------|----------|-----------|-----|------------------|----------|---------|
| Powder      | < 14%    | > 80%     | < 2%| Completely at 90 °C | < 0.3%  | 0.8–1.5% |

Methods

Acorn Starch Extraction

Starch isolation from the dried deshelled acorn fruit flour was conducted using the alkaline solvent method [57]. Briefly, 120 g oven dried acorn flour was soaked in 240 ml of aqueous NaOH solution (0.25% wt.) at 5 °C for 24 h. The mixture was homogenized and screened through 80 (< 180 μm) and 200 (< 75 μm) mesh sieves using three sieving times. The passed starch suspension was centrifuged at 800 G for 15 min using centrifuge model Z366 (Hermle Labortechnik GmbH, Germany) and decanted. Centrifugation is an essential factor for starch purification and separation from other components, mainly fats and proteins [58]. After scraping the mucilaginous layer off, the precipitated starch was suspended in water. The centrifugation, decantation, and separation of the two prepared phases were repeated thrice. Next, the residue was mixed and refluxed for 3 h by diethyl ether to maximize the proteins and fatty acids removal. The isolated and purifed starch was dried.
for two days at 30 °C in a ventilated drying chamber and then ground, passed through a 100-mesh sieve, and stored in tightly closed bags until its application.

**Acorn Starch SEM**

The morphology features of the dried and purified acorn starch including size, shape, and surface structure were evaluated using the Scanning Electron Microscopy (SEM, ZEISS Sigma 300, Germany) operated at 10 kV. For this, the acorn starch was firstly coated with Gold using a Sputter coater to avoid electrical charging during the observation. Then, the imaging was performed with the range of 3000–60,000 magnification.

**Acorn Starch XRD**

X-ray powder diffraction pattern was obtained using a STOE diffractometer with monochromatized Cu Kα radiation. The radiation wavelength was 1.5406 Å. The analysis was conducted at a voltage of 40 kV, current of 40 mA, and moisture content between 4 and 6%. The sample was scanned through the 2θ (diffraction angle) of 3–30°, stepped by 0.060° performed at 1 s (at a speed of 3.6°/min).

**Acorn Starch Molecular Weight Analysis**

Molecular weight was determined by size-exclusion chromatography (SEC) using pollutants for the calibration (10–500 kDa). Aqueous solution (1% wt.) of acorn and cationic corn starch starches in the presence of 0.1 M NaNO3 was prepared and analysed using PL-GPC 110 system instrument (Polymer Laboratories Ltd., U.K.) equipped with PL aqua gel-OH Guard 8 µm pre-column, two PL aqua gel-OH MIXED 8 µm 300 × 7.5 mm columns and a refraction index (RI) detector. The injection system, columns, and detector were kept at 36 °C. Eluent (0.1 mol L⁻¹ solution of NaNO3 in MilliQ water) pumped with a flux of 0.9 mL/min. The injection volume was 100 µL. Starch samples were completely soluble after 24 h dissolution in aqueous solution under stirring at room temperature, followed by 3 h at 100 °C. The sample was filtered off by a 40 µm nylon filter before the analysis. The starch samples illustrated bimodal distribution and had minor contaminations with Mw ca 20 kDa.

**Starch Solution Preparation as Papermaking Additive**

Before adding starch into any aqueous slurries like the fiber pulp, it must be a water-soluble product through gelatinization in hot water because native starches are insoluble in cold water. For this, 1000 ml beakers containing water and the two different starches (1% wt.) were placed in a water bath with continuous stirring (450 rpm) and gently increased temperature until 90 °C inside the beakers and kept for 30 min. For avoiding the water evaporation, the beakers were sealed during the process. After cooling down to room temperature, the cooked starches were used during the preparation day without retrogradation.

**Laboratory Papermaking and Testing**

After the daily starches preparation, the native acorn starch (NAS) and cationic corn starch (CCS) were added at three dosages, 0.5%, 1%, and 1.5%, based on oven-dried (O.D.) mass of refined bagasse pulp. Freeness (CSF, ml) of blank and the starches containing pulps were measured according to TAPPI T 227 om-99 method. Then, the laboratory handsheets (159 mm × 159 mm in size) were fabricated with a target basis weight of 60 ± 1 g/m² using laboratory hand-sheet maker FORMAX, according to TAPPI T 205 sp-02. During the laboratory papermaking process, the pulp drainage time was measured according to TAPPI T 221 cm-99. Before determination of physical and mechanical properties, the prepared handsheets were conditioned for 24 h at 23 ± 1 °C and 50 ± 2% RH according to TAPPI T 402 sp-08. Pulp retention was calculated based on the handsheet O.D. mass divided by the O.D. mass of initial pulp. The other properties were measured in accordance with TAPPI standards as follow: pulp water retention value (WRV): Um-256; paper thickness: T 411 Om-10; burst strength: T 403 Om-02; tensile strength: T 494 Om-01; tear strength: T 414 Om-04; paper apparent density: T 220 sp-01. Repetitions of the used tests were carried out according to the related test method.

**Data Analysis**

One-way ANOVA (p < 0.01) was used for data analysis by using SPSS software. Duncan’s multiple range test (DMRT) was used to determine the statistically significant difference between the obtained means.

**Results and Discussion**

**SEM Images Analysis**

Powder ground from the dried deshelled acorn fruit had light goldish appearance (Fig. 1b). However, after the solvent extraction, the native isolated starch transformed to white-milky powder (Fig. 1c). As seen from SEM image, acorn starch granules were irregular, spherical, semispherical, and mostly elliptical (Fig. 1d), illustrating rough surfaces with depressions and numerous holes and fractures (Fig. 1e&f). Their size distribution was found in the range of (6–12 µm).
According to Wilson et al. (2006) who classified starch granules into three size ranges (A-type granules (> 15 μm), B-type granules (5–15 μm), and C-type granules (< 5 μm)) [59], the native acorn starch granules classify predominantly as B-type granules. Therefore, the same equipment used for starch extraction from wheat could be used for acorn starch extraction.

**X-ray Diffraction (XRD) Pattern**

The X-ray diffraction patterns of native starches exhibit polymorphs with varying proportions, including the strongest diffraction peaks at 2θ about 17° and 23° together with a few small peaks at around 15°, 20°, and 26°. Wheat and maize starches exhibit a shoulder/doublet peak at around 17° and 18°, classified as A-type starches. Potato and some legumes starches which are defined as B-type starch show a strong diffraction peak at around 17°, and few small peaks at around 15°, 22°, and 24° [, 60, 61]. The starches classified as C-type show diffraction intermediate pattern between the A-type (cereal) and the B-type (tuber) [62]. Moreover, the XRD pattern could contain various superpositions of the characteristic diffraction peaks depending on the ratio between the contents of these polymorphs, classified into C_A-type, C_B-type, and C_C-type [, 63, 64]. According to He and Wei (2017), the C_C-type polymorph of starch X-ray pattern shows two main peaks at 2θ of 17° and 23°, with a few small peaks at 20° around 5.6° and 15° [64]. Both polymorphs of C_A- and C_B-type present a shoulder peak at 20° around 18°, with a strong singlet at 23° for C_A-type starch, and two shoulder peaks at 20° about 22° and 24° for the C_B-type starches. Therefore, and according to the X-ray diffraction pattern peaks revealed in Fig. 2, native acorn starch extracted from *Q. persica* illustrated two sharp diffraction peaks at 2θ of 14.94°, 22.92°, and doublet diffraction peaks at 17.02° and 18.06°, thus could be classified as CA-type.

**Starch Molecular Weight**

NAS starch displayed a bimodal molecular weight distribution with weight-average molecular weight ($M_w$), number-average molecular weight ($M_n$) and polydispersity of 436.2 KDa, 226.7 kDa and 1.92, respectively. However, CCS displayed a trimodal distribution with $M_w$, $M_n$ and polydispersity of 43.6 KDa, 30.2 kDa, and 1.44, respectively (Fig. 3). Usually, chemically modified starches indicate lower molecular weight than unmodified ones due to the backbone degradation during the modification process [, , 57, 65, 66].

**Pulp Drainage and Retention**

Shorter drainage time leads to higher paper machine speed, and consequently greater production efficiency [, 28, 67]. As depicted in Fig. 4, CCS at the highest dosage (1.5%) significantly increased the drainage time of the bagasse pulp (28% higher). However, at the same level of acorn starch addition, the drainage time prolongation was negligible (only 5%) compared to the control sample without any additive. Moreover, the lowest dosage of NAS (0.5%) decreased slightly the drainage time, indicating good agreement between flocculation and drainage effects of NAS at this dosage. At the higher dosage of both polymers, the drainage rate of pulp decreased, presumably due to the increasing furnish
viscosity and formation of water-loving large and porous flocs in which the water removal is more difficult [68].

As shown in Fig. 4, by increasing the dosage of both starches, the retention of pulp elements increased, yet this effect was more pronounced for NAS, presumably due to the higher molecular weight of NAS [53, 62, 67]. As noted in recent reviews the achievement to the optimum equilibrium between retention and drainage using suitable polymeric additives is an important and complex task in papermaking, reducing the utilization of cellulosic raw materials for papermaking and energy requirement for paper drying and wastewater treatment [68].

**Water Retention Value (WRV) and Freeness of Pulp (CSF)**

Due to the highly hydrophilic character of carbohydrates like starches, the WRV value is a valuable tool for evaluating polymeric additives adsorption on the fiber surfaces. Strand et al. (2017) reported that adsorbed starch and carboxymethyl cellulose (CMC) onto the cellulose surfaces act as soft gels, promoting the water uptake by the fibers [47]. As shown in Fig. 5, both NAS and CCS increased the bagasse pulp WRV. However, the WRV enhanced more significantly when NAS was added, probably due to its relatively higher molecular weight and higher adsorption onto the fiber surfaces. On the other hand, polymeric additives could react as retention agents by attaching the fine particles on the fiber surfaces that inhibit the undesirable blockage of the channels through which the water is quickly removed from pulp. As showed in Fig. 5, NAS treated pulps revealed a more and sharp reduction in CSF value than CCS ones. This could be attributed to the higher molecular weight of NAS, forming a 3D network that efficiently contributes fines retention during the pulp mat formation. Interestingly, the sharp reduction of CSF occurred by the small application of NAS, which is in accordance with the pulp retention, drainage and WRV of 0.5% NAS application.

**Paper Thickness and Apparent Density**

The lower thickness at the constant grammage reveals a more compact and denser structure of the paper network, resulting higher fiber bonding capability and paper strength properties [28, 54, 67]. The NAS and CCS both decreased the paper thickness significantly (Fig. 6). Regarding the higher retention and lower thickness revealed by NAS compared to CCS, the apparent density of the NAS-contained papers was higher than that CCS-contained papers (Fig. 6), that could improve the mechanical properties of paper.

**Strength Properties of Paper**

Tensile strength, which is the maximum force developed in a paper strip before producing a rupture, is usually used as a potential indicator of paper resistance to breaking during
printing on a web-fed press or other web-fed converting processes [43, 53, 69]. Dry strength additives improve the surface area and strength of bonds between the fibers in the paper network during drying process, resulting in higher tensile strength [28, 52, 70]. NAS increased the tensile strength of the bagasse paper drastically, much more than conventionally CCS (Fig. 7), probably due to its higher retention onto the fiber surfaces according to the WRV results (Fig. 5) and more and closer contact surface area, which confirmed by the paper thickness results (Fig. 6).

Bursting strength as a fast, easy, and inexpensive property is widely used to measure the paper resistance to rupture by constantly increasing hydrostatic pressure applied through a rubber diaphragm. The test combines tensile strength and stretch (elongation) of a paper because the pressure is applied to one side of paper until the rupture occurs. In general, bursting strength is mainly dependent on the sheet formation quality and inter-fiber bonding, which is usually achieved by refining process [46, 47, 71]. As shown in Fig. 7, both starches significantly improved the burst strength of the produced paper, however NAS showed superior results (+75%) compared to CCS (+45%). Enhanced fiber–fiber bonding by adding NAS starch enables paper-makers to open up its application as dry strength additive.

Tearing resistance measures the paper behavior in various applications, which highly correlated to productivity, such as paper web runnability, printing and writing quality control, and paper toughness characterizing where the shock absorption is essential, especially for packaging [46, 47, 71]. Fibers length and inter-fiber bonding are both critical factors influencing tearing strength, while the longer fibers and more inter-fiber bonding improve tear strength due to distributing the stress over the expansive area and more bonds. An initial decline in tear resistance by dry strength additives [67] and pulp refining [50] has been reported previously. The usual explanation noted that a higher level of inter-fiber bonding could render the paper more brittle, lowering the energy consumption during paper tearing [50, 56, 72]. According to the Fig. 8, upon CCS addition the tear strength remained unchanged or slightly reduced. However, NAS increased the tear strength significantly (max: 10%). Similarly, tear strength improvement was reported for addition of unmodified hemicellulose to a papermaking furnish [45, 73, 74].

Conclusions

Conversion of agricultural and industrial residuals to value-added products has great importance, particularly through green and clean production routes. Bagasse, as an agro-industrial bio-residual, is used for papermaking. However, the intrinsically lower strength of the produced paper from bagasse, make it necessary the utilization of other reinforcing fibers or additives, both accompanied with severe shortage and ever-growing competition.

In order to provide practical information enhancing competitive advantage of acorn starch over conventional starches used in paper making, in this study the application of non-conventional and natural acorn starch was evaluated as papermaking additives for bagasse pulp and compared instead of chemically cationized corn starch. The results demonstrated that extracted natural acorn starch revealed higher molecular weight than commercial cationic corn starch and improved pulp drainage, retention and WRV in comparison to commercially corn starch, providing cleaner and more profitable production. The enhancement of mechanical strengths of the bagasse paper by natural acorn starch was higher than commercially available cationic corn starch. Overall, native acorn starch could be a promising source of native starch for the paper industry, even without chemical modification. The encouraging results may open up new application for highly available and renewable acorn...
starch as a new sustainable and high-performance papermaking additive.

**Author Contributions** ABK Conceptualization, Investigation, Methodology, Writing—Original Draft. HJT Conceptualization, Project administration and supervision, validation, Methodology, Writing—Review & Editing. YH Writing—Review & Editing, validation, Methodology.

**Funding** The authors declare that no funds, grants, or other supports were received during the preparation of this manuscript.

**Data Availability** The datasets generated and analyzed during the current study are not publicly available due to the authors policy but are available from the corresponding author on reasonable request.

**Declarations**

**Conflict of interests** The authors have no relevant financial or non-financial interests to disclose.

**References**

1. Saijjadi, M., Ahmaddoor, F., Nasrollahzadeh, M., Ghafuri, H.: Lignin-derived (nano) materials for environmental pollution remediation: Current challenges and future perspectives. Int. J. Biol. Macromol. 178, 394–423 (2021). https://doi.org/10.1016/j.ijbiomac.2021.02.165
2. Aririm, N., Madhan, B.: Development of bio-acceptable leather using bagasse. J. Clean. Prod. 250, 119441 (2020)
3. Mahmood, N., Yuan, Z., Schmidt, J., Xu, C.C.: De-polymerization of lignins and their applications for the preparation of polyols and rigid polyurethane foams: A review. Renew. Sust. Energ. Rev. 60, 317–329 (2016)
4. Sinha, A.S.K., Dhanraj, R.R.: Response surface optimization of rice straw treatment with oxalic acid for production of xylose, cellulose and lignin. Green Chem. 9, 163–174 (2017)
5. Xu, C., Nasrollahzadeh, M., Selva, M., Issaabadi, Z., Luque, R.: Waste-to-wealth: biowaste valorization into valuable bio (nano) materials. Chem. Soc. Rev. 48(18), 4791–4822 (2019)
6. Collins, M.N., Nechifor, M., Tanașă, F., Ţănoaă, M., McLoughlin, A., Strozyk, M.A., Culebras, M., Teacă, C.A.: Valorization of lignin in polymer and composite systems for advanced engineering applications – A review. Int. J. Biol. Macromol. 131, 828–849 (2019). https://doi.org/10.1016/j.ijbiomac.2019.03.069
7. Ayodele, B.V., Alsaﬀar, M.A., Mustapa, S.I.: An overview of integration opportunities for sustainable bioethanol production from ﬁrst-and second-generation sugar-based feedstocks. J. Clean. Prod. 245, 118857 (2019)
8. Li, S., Xia, J., Xu, Y., Yang, X., Mao, W., Huang, K.: Preparation and characterization of acorn starch/poly (lactic acid) composites modiﬁed with functionalized vegetable oil derivatives. Carbohydr. Polym. 142, 250–258 (2016)
9. Yoo, S.H., Lee, C.S., Kim, B.-S., Shin, M.: The properties and molecular structures of guisilijam starch compared to those of acorn and chestnut starches. Starch/Stärke 64, 339–347 (2012). https://doi.org/10.1002/star.2011010104
10. Zhang, L., Zhao, L., Bian, X., Guo, K., Zhou, L., Wei, C.: Characterization and comparative study of starches from seven purple sweet potatoes. Food Hydrocoll. 80, 168–176 (2018)
11. Mueller, S.A., Anderson, J.E., Wallowing, T.J.: Impact of biofuel production and other supply and demand factors on food price increases in 2008. Biomass Bioenergy 35(5), 1623–1632 (2011)
12. Popp, J., Lakner, Z., Harangti-Rakos, M., Fari, M.: The effect of bioenergy expansion: food, energy, and environment. Renew. Sust. Energ. Rev. 32, 559–578 (2014)
13. Subramaniam, Y., Masron, T.A., Azman, N.H.N.: The impact of biofuels on food security. J. Int. Econ. 160, 72–83 (2019)
14. Albulescu, C.: Coronavirus and financial volatility: 40 days of fasting and fear. arXiv preprint arXiv:2003.04005 (2020)
15. Torero, M.: Coronavirus Food Supply Chain under Strain, what to do? FAO (2020)
16. Zheng, K., Xiao, S., Li, W., Wang, W., Chen, H., Yang, F., Qin, C.: Chitosan-acorn starch–eugenol edible ﬁlm: Physico-chemical, barrier, antimicrobial, antioxidant and structural properties. Int. J. Biol. Macromol. 135, 344–352 (2019)
17. Tadayoni, M., Sheikh-Zeinoddin, M., Soleimanian-Zad, S.: Isolation of bioactive polysaccharide from acorn and evaluation of its functional properties. Int. J. of Biol. Macromol. 72, 179–184 (2015). https://doi.org/10.1016/j.ijbiomac.2014.08.015
18. Stevenson, D.G., Jane, J.L., Inglett, G.E.: Physicochemical properties of pin oak (Quercus palustris Muench.) acorn starch. Starch/Stärke 58(11), 553–560 (2006)
19. Heidari, F., Asadollahi, M.A., Jeihanipour, A., Kheyrandish, M., Rismani-Yazdi, H., Karimi, K.: Biobutanol production using unhydrolyzed waste acorn as a novel substrate. RSC adv. 6(11), 9254–9260 (2016)
20. Chao, B., Liu, R., Zhang, X., Zhang, X., Tan, T.: Tannin extraction pretreatment and very high gravity fermentation of acorn starch for bioethanol production. Bioresour. Technol. 241, 900–907 (2017)
21. Karimi, A., Moradi, M.T., Saeedi, M., Asgari, S., Rafeian-Kopaei, M.: Antiviral activity of Quercus persica L.: high efﬁcacy and low toxicity. Adv. Biomed. Res. 2, 36–42 (2013)
22. Rakić, S., Povrenović, D., Tešević, V., Simić, M., Maletić, R.: Oak acorn, polyphenols and antioxidant activity in functional food. J. Food Eng. 74(3), 416–423 (2006)
23. Claudia, P.: Acorn bread: A traditional food of the past in Sar­dinia (Italy). J. Cult. Herit. 14(3), S71–S74 (2013)
24. Torabi, S., Mohtarami, F., Dabbagh Mazhary, M.R.: The in­fluence of acorn flour on physico-chemical and sensory properties of gluten free biscuits. Food Sci. Technol. 16(97), 171–181 (2020)
25. Bhatia, S.K., Joo, H.S., Yang, Y.H.: Bio waste-to-bioenergy using biological methods–A mini-review. Energy Convers. Manag. 177, 640–660 (2018)
26. Ghaedi, M., Hossainian, H., Montazerzohori, M., Shokrollahi, A., Shojapour, F., Solyak, M., Purska, M.K.: A novel acorn based adsorbent for the removal of brilliant green. Desalination 281, 226–233 (2011)
27. Saﬁnia, Ō., Saka, C.: Preparation and characterization of activated carbon from acorn shell by physical activation with H2O–CO2 in two-step pretreatment. Bioresour. Technol. 136, 163–168 (2013)
28. Tajik, M., Jalali Torshizi, H., Resalati, H., Hamzeh, Y.: Ef­fects of cellulose nanofibrils and starch compared with polyacrylamide on fundamental properties of pulp and paper. Int. J. Biol. Macromol. 192, 618–626 (2021). https://doi.org/10.1016/j.ijbiomac.2021.09.199
29. González-García, S., Moreira, M.T., Artal, G., Maldonado, L., Feijoo, G.: Environmental impact assessment of non-wood based pulp production by soda-anthraquinone pulp production. J. Clean. Prod. 18(2), 137–145 (2010)
30. Judt, M.: Non-wood plant fibres, will there be a come-back in paper-making? Ind. Crops. Prod. 2(1), 51–57 (1993)
67. Kim, G.-Y., Hubbe, M.A., Kim, C.-H.: Engineering of a wet-end additives program relative to process parameters and to the physical and optical properties of filled paper. Ind. Eng. Chem. Res. 49(12), 5644–5653 (2010)

68. Hubbe, M.A., Heitmann, J.A.: Review of factors affecting the release of water from cellulosic fibers during paper manufacture. BioResources 2(3), 500–533 (2007)

69. Freeness of pulp (Canadian standard method), Test Method T 227 om-99, TAPPI Standards, (1999).

70. Rana, V., Malik, S., Joshi, G., Rajput, N.K., Gupta, P.K.: Preparation of alpha cellulose from sugarcane bagasse and its cationization: Synthesis, characterization, validation and application as wet-end additive. Int. J. Biol. Macromol. 170, 793–809 (2021). https://doi.org/10.1016/j.ijbiomac.2020.12.165

71. Strand, A., Kouko, J., Oksanen, A., Salminen, K., Ketola, A., Retulainen, E., Sundberg, A.: Enhanced strength, stiffness and elongation potential of paper by spray addition of polysaccharides. Cellulose 26(5), 3473–3487 (2019)

72. Zeng, X., Vishtal, A., Retulainen, E., Sivonen, E., Fu, S.: The elongation potential of paper – how should fibres be deformed to make paper extensible? BioResources 8(1), 472–486 (2018)

73. Han, W., Zhao, C., Elder, T., Chen, K., Yang, R., Kim, D., Pu, Y., Hsieh, J., Ragauskas, A.J.: Study on the modification of bleached eucalyptus Kraft pulp using birch xylan. Carbohydr. Polym. 88(2), 719–725 (2012)

74. Song, X., Hubbe, M.A.: Enhancement of paper dry strength by carboxymethylated β-D-glucan from oat as additive. Holzforschung 68(3), 257–263 (2014)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.