NUST Journal of Engineering Sciences, Vol. 17, No. 1, 2024

Corn Waste A Sustainable Solution For Plastic Pollution: A Mini Review

Abdul Mueez Ahmad[1], Asad Ali[1], Anas Afzal[1], Nimra Tanveer[1], Almas Mustafa[1]

[1]National Institute of Food Science and Technology, University of Agriculture, Faisalabad, 38000, Pakistan.

[*]*Corresponding author*: Abdul Mueez Ahmad mueez183@gmail.com

Received: 03-06-2024, Received in Revised form: 22-06-2024, Accepted: 27-06-2024, Published: 30-06-2024

Abstract

Plastic pollution is a critical environmental issue leading to extensive ecological damage and posing health risks due to the persistence of petrochemical-derived plastics. Biodegradable films, particularly those derived from renewable resources like corn waste, offer a promising solution to this issue. Corn waste including husks, stalks and cobs are rich in cellulose, hemicellulose and lignin making it suitable for biodegradable film production. Various methods such as chemical treatments, enzymatic hydrolysis and mechanical processes are used to extract useful components from corn waste followed by film formation techniques like casting and extrusion. Corn waste films exhibit mechanical and barrier properties comparable to conventional plastics with the added benefit of faster biodegradability. These films have potential applications in packaging and agriculture reducing plastic waste and supporting sustainable practices.

Keywords: Plastic Pollution, Biodegradable Films, Corn Waste, Sustainable Packaging, Renewable Resources

Introduction

Plastic pollution has emerged as a significant environmental concern, contributing to widespread ecological damage and posing a threat to both terrestrial and marine ecosystems [1]. These plastic based materials not only harm the environment but also have severe consequences for human health. The latest research has revealed that the plastics of microscale have been discovered in the human blood [2], liver [3], human testicles and semen [4]. The plastic materials have been utilized for their lightweight, low cost, chemical resistance and easy processing [5]. Traditional plastics derived from petrochemicals are persistent pollutants that can take centuries to degrade and are difficult to manage [6]. Today the lion's share of environmental pollution is caused by plastic materials [7]. Consequently, there is an urgent need for sustainable alternatives that can alleviate the burden of plastic waste.

Biodegradable films have emerged as a viable solution to this problem. These films are designed to break down more rapidly than conventional plastics when exposed to environmental conditions such as moisture, heat, and microbial activity [8]. These biodegradable films can be derived from various sources like Polysaccharides [9-11], Proteins [12-14] and Microbes [15, 16]. Made from renewable resources, biodegradable films can decompose into natural substances like water, carbon dioxide, and biomass, leaving no toxic residues [17]. This ability to integrate into natural cycles makes biodegradable films particularly attractive for applications where traditional plastic waste poses significant disposal challenges. The adoption of biodegradable films not only reduces the volume of persistent plastic waste but also supports a more sustainable and circular economy.

Recently lignocellulosic biomass has received attention as an abundant, sustainable and organic alternative resource to petroleum-based resources [18]. It is a naturally occurring composite generated by plant cells, comprising of three major biopolymers cellulose, hemicellulose and lignin as well as several minor components [19]. Lignocellulosic biomass is the most abundant substance on Earth, it is widely available and forms the cell walls of woody plants. Agricultural and forest leftovers are among the various sources of lignocellulosic biomass that can be utilized by industry [20]. The structure and composition of lignocellulose can differ amongst plant species according to factors such as growth conditions, plant parts and species [21].

Corn is a major cereal crop having wide applications in industry, animal feed and human food [22]. It is an abundant source of plant residues and have various benefits like accessibility, biodegradability and its rich starch content [23]. Corn waste is an abundant agricultural byproduct presenting a promising solution to the plastic problem. The conversion of corn husks, stalks, and cobs into biodegradable films offers a dual benefit of waste valorization and pollution mitigation. Figure 1 provides an overview of Corn waste conversion to bioplastics.

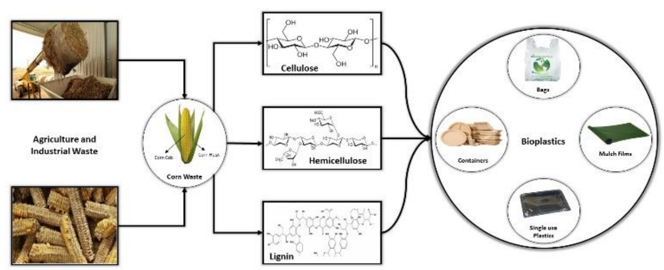

Figure 1 Corn Waste Conversion to Bioplastics

This review examines the composition, properties, conversion methods and potential applications of corn waste-derived films, highlighting their benefits and the challenges that must be addressed to realize their full potential.

Composition and Properties of Corn Waste

Corn waste comprises various parts of the corn plant, including husks [24], stalks [25] and cobs [26], each with distinct physical and chemical properties. These materials are rich in cellulose (35-50%), hemicellulose (20-30%), and lignin (15-20%), which are essential for film formation [27]. Table 1 shows the lignocellulosic composition of various corn byproducts. The high cellulose content, in particular imparts strength and flexibility to the films [28], while hemicellulose and lignin contribute to the film's barrier properties and structural integrity [29]. The fibrous nature of corn waste enhances the tensile strength and durability of the resultant

https://doi.org/10.24949/njes.v17i1.817

films, which are crucial for practical applications. Additionally, the presence of other organic compounds, such as proteins and waxes, can influence the film's mechanical properties and biodegradability [30].

Table 1 Lignocellulosic Composition of Corn Byproducts.

Source	Composition			
	Cellulose	Hemicellulose	Lignin	References
Corn Cob	35 – 45	35 – 40	6 – 15	[22, 31]
Corn Stover	35 – 40	20 – 25	11 – 19	[32]
Corn Husk	38 – 42	21 – 44	6 – 12	[31, 33]
Corn Stalk	34 – 42	29	20 – 21	[31, 34]

Methods of Converting Corn Waste into Biodegradable Films

The conversion of corn waste into biodegradable films involves several key steps. Initially, useful components are extracted from the raw material through processes such as chemical treatment, enzymatic hydrolysis or mechanical separation [35]. Chemical treatments often involve the use of alkali or acid solutions to break down the lignocellulosic structure and release cellulose and hemicellulose [36]. Enzymatic hydrolysis utilizes specific enzymes such as cellulases and hemicellulases to achieve a similar outcome, offering a more environmentally friendly approach [37]. Figure 2 (a&b) shows the Chemical and Enzymatic treatment to extract Cellulose and Hemicellulose.

Following extraction, the film formation process can be carried out using techniques like casting and extrusion. On the lab scale casting involves dissolving the extracted components in a suitable solvent to form a film-forming solution, which is then spread onto a surface and allowed to dry [38]. This method allows for precise control over film thickness and uniformity but may be less scalable. Casting is a relatively inexpensive process that works well for laboratory-scale manufacturing [39]. To reach the required throughput, scaling up the casting process for industrial applications would necessitate a sizable investment in automation and equipment. Cellulose and cellulose nanocrystals derived from corn cobs were utilized in combination with chitosan to form biodegradable films by Escamilla-García [40]. Edible films from corn cobs were formed by Sari [41] and Sari [42]. Corn hull arbinoxylan was utilized by Zhang and Whistler [43] to form films. Similarly, corn hull nanofibrillated cellulose was used to form films by Xiao, et al. [44]. Zhang [45] extracted cellulose from corn straw and utilized it to form ecofriendly packaging films. Corn stalk pulp was utilized by Han [46] to form regenerated cellulose films.

Extrusion, on the other hand, involves melting the components and forcing them through a die to form continuous films [47]. This technique is more suitable for large-scale production but may require more sophisticated equipment and precise control of processing conditions [48]. Extrusion approach is already widely utilized in the plastics sector for large-scale production and it provides a more scalable alternative [47]. Its excellent efficiency and continuous operation, which lower labor and energy costs can offset its capital expenditures. Furthermore, its versatility in handling different biopolymer blends contributes to its economic attractiveness. Extrusion of xylans extracted from corncobs were utilized by Bahcegul [49] to form biodegradable polymeric materials. Hemicellulose based films from corn cobs were formed via extrusion by Akınalan [50].

Each method has its own advantages and limitations in terms of efficiency, scalability, and the properties of the resulting films. Comparative studies have shown that while casting provides better control over film properties, extrusion offers higher production rates and is more suitable for industrial applications.

Performance and Biodegradability of Corn Waste Films

Films made from corn waste have mechanical attributes such tensile strength, flexibility and elongation at break that are similar to those of traditional plastics [44]. These characteristics are necessary to guarantee that the films can resist handling and be utilized in a variety of applications. Tensile strength for example is essential in packaging applications where the film needs to be able to withstand tearing and stretching.

Films made from corn waste have a variety of mechanical qualities that allow them to be utilized in packaging.

They often exhibit sufficient tensile strength, which can be raised by employing plasticizers [62] and cross-linking agents [63]. Tensile strengths of corn waste films [49,52,43] are lower as compared to the tensile strengths of conventional polyethylene films [70]. The flexibility of corn waste-derived films indicated by elongation at break values between 10-90% [52,49] can be adjusted by modifying the plasticizer content [62]. In comparison, conventional plastic films like low-density polyethylene have elongation values of up to 600% [71] showing the need for further optimization in biofilm formulations. Figure 3 (a) provides a comparison of mechanical properties to corn waste films with mechanical properties of conventional plastic

In addition to mechanical properties the barrier properties of the films such as water vapor permeability and oxygen permeability are also critical for applications in packaging. Corn waste films generally exhibit good barrier attributes making them suitable for preserving the quality and shelf-life of packaged goods [46]. But the barrier attributes of these films such as water vapor permeability and oxygen transmission rates are often inferior to those of conventional plastics but they can be enhanced by blending with other biopolymers or incorporating nanomaterials. The permeability of these films can be adjusted by altering the composition and processing conditions, allowing for customization based on specific application requirements.

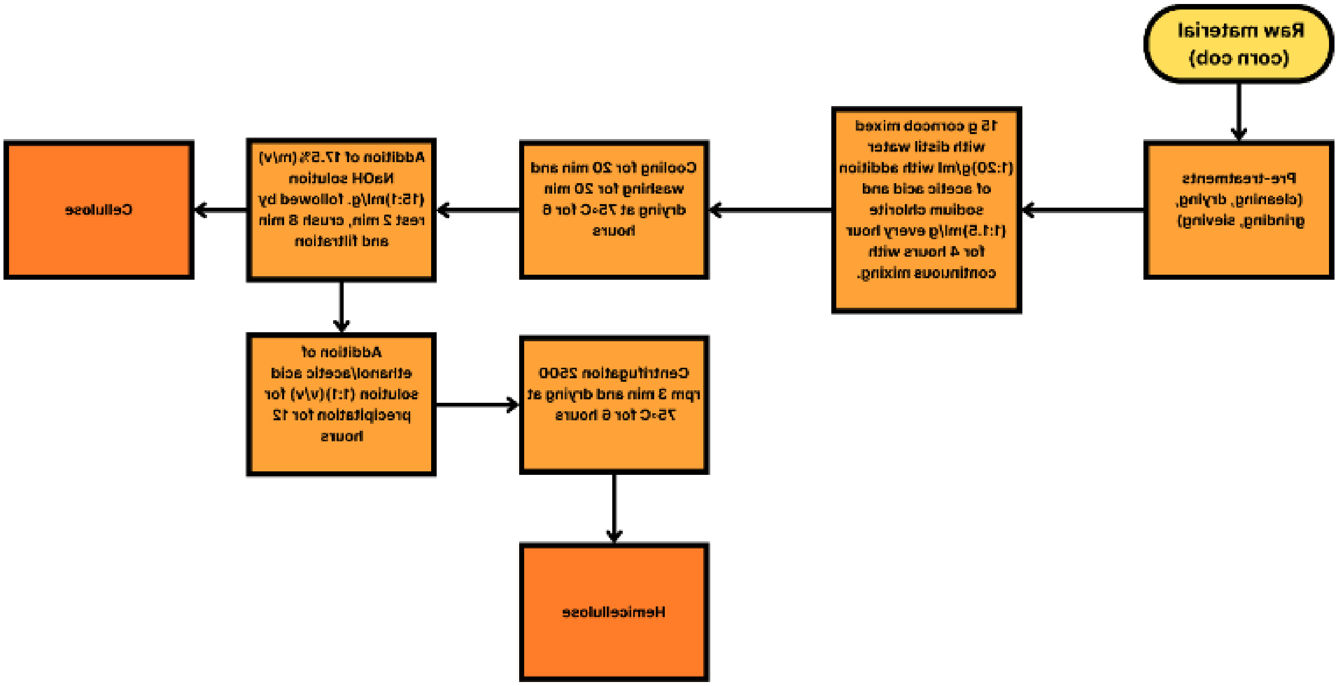

Figure 2 (a) Chemical Treatment to Extract Cellulose and Hemicellulose.

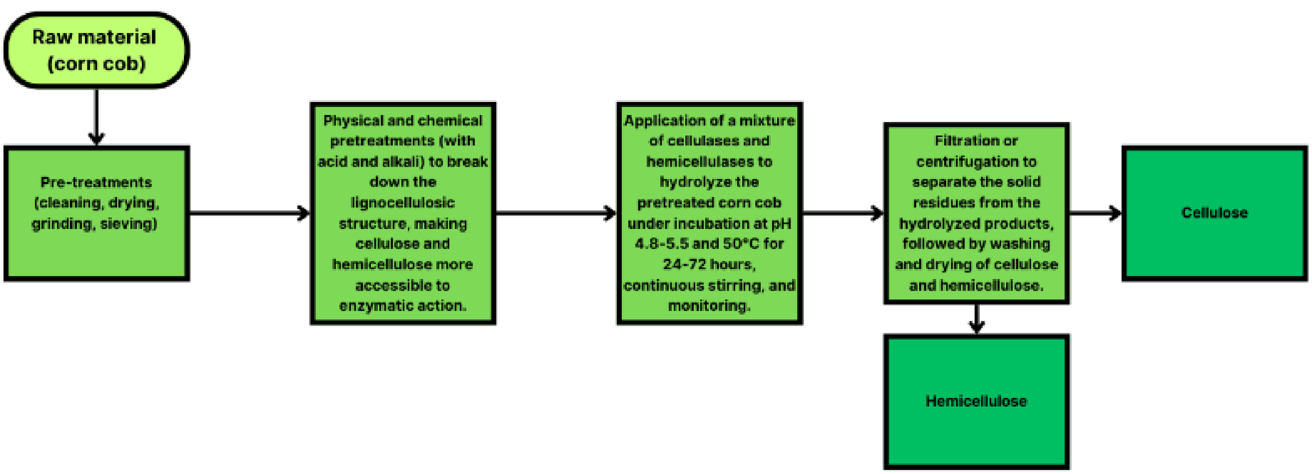

Figure 2 (b) Enzymatic Treatment to Extract Cellulose and Hemicellulose.

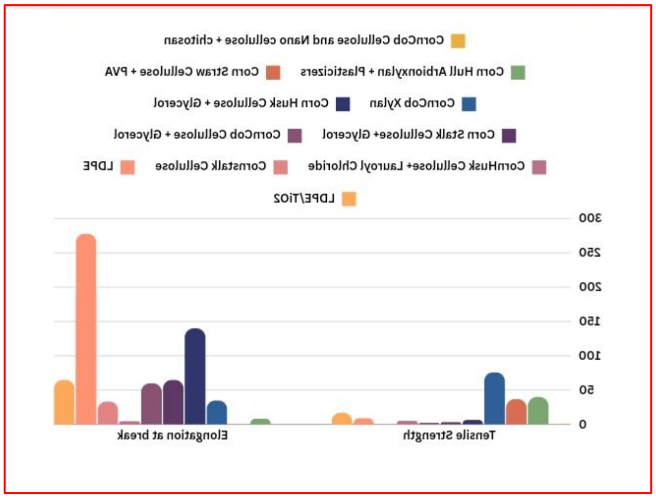

Figure 3 (a) Comparison of Mechanical properties of Corn waste films and Conventional Plastic

The biodegradability of corn waste films is one of its main benefits. According to studies these films have a smaller environmental impact because they break down much more quickly than traditional plastics. The composition of the film and environmental variables (temperature, humidity, and microbial activity) affect how quickly the film degrades. Laboratory testing and field investigations have shown that in comparison to the conventional plastics which can take hundreds of years to degrade [6] corn waste films can entirely decompose in a few months to a year depending on the conditions [40]. The biodegradation process involves microbial activity that breaks down the polymer chains into water, carbon dioxide and biomass [72]. Figure 3 (b) provides a comparison of biodegradability to corn waste films with biodegradability of conventional plastic.

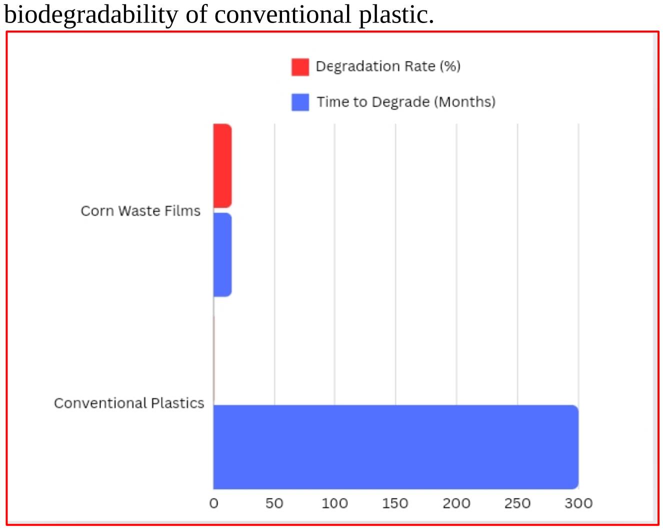

Figure 3 (b) Comparison of Biodegradability of Corn waste films and Conventional Plastic

Although corn waste films do not match the mechanical strength of conventional plastics they offer a sufficient advantage in environmental sustainability through enhanced biodegradability. Table 2 lists the characteristics of films made from corn waste.

Economic Feasibility and Scalability of Corn Waste Films

Various vital factors like the availability of raw material, cost of processing and market demand influence the economic feasibility of corn waste biofilms. In corn producing regions of the world corn waste is obtained as a by-product of agricultural activities which makes it an affordable and desirable raw material [23]. The availability of corn waste in abundant amount not only diminishes the initial cost of material but also reduces environmental pollution by contributing to value to waste. However, transforming this waste into commercially viable biofilms requires investment in technology and infrastructure.

The casting technique is well-known for its accuracy in regulating uniformity and film thickness. It is economical when utilized in laboratories but presents difficulties when applied on an industrial scale [39]. The casting process can be labor-intensive and have slower production rates which can lead to higher costs when applied to larger-scale industries. Automation and advanced casting technologies can contribute to diminish these costs but would require significant upfront investment. In contrast, extrusion is a highly scalable technique which is already being applied widely in the plastics industry [47]. Extrusion equipment can be modified to handle various biopolymer blends raising its versatility and potential to produce various types of biofilms. The continuous nature of extrusion processes makes efficient use of energy and labor leading to a greater output and rendering extrusion economically advantageous for large-scale production.

The economic viability of corn waste biofilms is also sufficiently influenced by market dynamics. The growing consumer demand for sustainable packaging and raising regulatory pressures to diminish plastic waste creates a favorable environment for producing biofilms [61]. In terms of price and functionality these biofilms must be comparable to the well-known synthetic polymers. More research and development are needed to enhance the attributes of corn waste biofilms and to lower their manufacturing costs.

Environmental Impact of Corn Waste Biofilms

There are several environmental advantages and difficulties associated with the production of corn waste films. When corn waste is employed for producing films it adds value to agricultural waste and lowers the amount of methane emission from landfills as a result of biomass decomposition [68,69]. The films are biodegradable reducing the long-term environmental impact in comparison to conventional plastics. Moreover, employing renewable biomass as feedstock results leads to a lesser carbon footprint than fossil fuel-derived plastics [69]. Chemical treatments are frequently employed to convert raw corn waste to biodegradable films and to enhance the properties of these films. Treatments such as alkaline hydrolysis, acid hydrolysis [36] and the incorporation of plasticizers [62] or cross-linking agents [63] can effectively enhance the mechanical and barrier attributes of biofilms but they can also generate by products that are hazardous to the environment.

.

Table 2 Properties of Corn waste Films

Corn Waste	Lignocellulosic Biomass	Additives	Film Forming Method	Properties of Films			
				Mechanical	Barrier	Other Properties	References
Corn Cob	Cellulose and Cellulose Nanocrystals	Chitosan	Casting	Tensile strength ranged from 0.79-0.83MPa	Water Vapor permeability ranged from 1.05-1.5 $gm^{-1}s^{-1}Pa^{-1}$	High Biodegradability	[40]
Corn Hull	Arabinoxylan	Propylene glycol, glycerol, or sorbitol	Casting	Tensile Strength varied from 19-60MPa Elongation at break varied from 5.5% - 12.1% Youngs modulus ranged from 365-1320MPa	Water Vapor permeability ranged from 0.05-0.43 $gm^{-1}s^{-1}Pa^{-1}$	Good Barrier properties were reported	[43]
Corn Straw	Cellulose	Polyvinyl Alcohol	Casting	Tensile strength 37MPa	Low Water Vapor Transmission rate	Low Biodegradability	[45]
Corn Stalk	Cellulose	-	Casting	Youngs Modulus of 0.12-0.82MPa Elongation at break 17-42%	-	-	[46]
Corn Cob	Xylan	-	Extrusion	Ultimate tensile strength of 76MPa and Elongation at break of 35%	-	-	[49]
Corn Cob	Xylan	-	Extrusion	Ultimate tensile strength of 0.93MPa and Elongation at break of 0.16%	-	-	[50]

Corn Husk	Starch	Chitosan	Casting	-	-	High Biodegradability	[51]
Corn Husk	Cellulose	Glycerol	Casting	Tensile strength 1.8-10.2MPa Elongation at break 31-239% Youngs Modulus 13-50MPa	Water Vapor Permeability 7.21-19.44 g.mm/kPa.d.m^2	Water Solubility 6.44-7.62	[52]
Corn Stalk	Cellulose	Glycerol	Casting	Tensile strength 2.12-4.24MPa Elongation at break 29-99% Youngs Modulus 15-50MPa	Water Vapor Permeability 6.15-12.27 g.mm/kPa.d.m^2	Water Solubility 6.78-19.30	[52]
Corn Cob	Cellulose	Glycerol	Casting	Tensile strength 1.41-3.80MPa Elongation at break 13.24-96% Youngs Modulus 15.87-50MPa	Water Vapor Permeability 6.33-11.46 g.mm/kPa.d.m^2	Water Solubility 6.78-18.56	[52]
Corn Husk	Cellulose	lauroyl chloride	Casting	Tensile Strength 5.15MPa and Elongation at break 6.55%	-	High Biodegradation	[53]
Corn Husk	Nanocellulose	-	Surface Coating	-	-	High transparency, High surface roughness and excellent hydrophobic anti-fouling properties.	[54]
Corn Husk	Cellulose Nanocrystals	-	Casting	Tensile Strength 14-18	-	Low water Solubility	[55]

Alkaline hydrolysis breaks down lignocellulosic materials by employing sodium or potassium hydroxide. The residual alkaline solutions and salts that are produced if left unmanaged can lead to alkalization of the soil and water [64]. Utilizing sulfuric or hydrochloric acid acid hydrolysis generates acidic byproducts that if not properly disposed of can lead to soil and water acidification which can have a negative impact on the health of the soil and aquatic ecosystems [65]. While the employment of plasticizers and cross-linking agents such as sorbitol and glycerol improves flexibility and durability of the biofilms [62] they can also contribute to an adverse effect on microbial communities and plant life by releasing or not fully reacting during degradation which can be hazardous to the environment.

Risks associated with these chemical treatments include soil contamination which can alters soil chemistry and biology lowering agricultural production and biodiversity and water pollution where untreated effluents can alter the pH and conductivity of the water damaging the aquatic life and entering the human food chain [66]. Furthermore, some of these procedures generate volatile organic compounds which raises the greenhouse gas emissions and contribute to air pollution [67]. Effective waste management and treatment techniques such as chemical recovery and neutralization for reuse toxicity mitigation with biodegradable or bio-based chemicals and closed-loop production systems for by-product collection and recycling are essential for reducing these environmental effects. Adhering to environmental regulations ensures that chemical usage and waste disposal meet safety and sustainability criteria.

Applications and Benefits

Biodegradable films made from corn waste have potential uses in many different industries. They can be utilized in packaging to create environmentally friendly and functional bags, wrappers, and containers [56, 57]. These films can reduce plastic waste by taking the place of traditional plastics in single-use applications [58]. Corn waste films can be employed in agriculture where they can be utilized as mulch films or seed coatings, increasing crop yields and decreasing plastic waste [51]. Corn waste can be utilized to make mulch films that improve soil temperature, inhibit weed growth, and assist conserve soil moisture for optimal plant growth. The applications of corn waste are depicted in Figure 4.

The principal benefits of maize waste films in comparison to conventional polymers are their capacity to biodegrade and their lower carbon footprint. As a result, the products generated from these films will have a more sustainable lifecycle and a smaller environmental effect. Reliance on fossil fuels declines and greenhouse gas emissions are mitigated by the employing renewable resources such as crop residues in the film industry [59].

Economically, adding value to agricultural wastes and generating new revenue streams for farmers can be achieved through the use of corn waste for film production. This can boost rural economies and improve the sustainability of agricultural methods [60]. By using biodegradable films, environmental dangers connected with plastic pollution can be greatly reduced, improving ecological health and leaving ecosystems healthier.

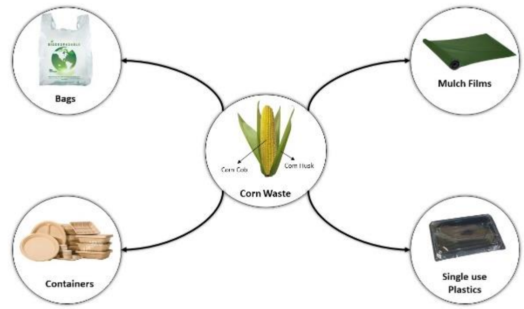

Figure 4 Applications of Corn Waste

Challenges and Future Prospects

Despite their potential the production and utilization of corn waste films face several challenges. The scalability of production processes is a major constraint. Ensuring consistency in film properties and quality on a large scale remains a technical hurdle. The reliability and effectiveness of the finished product might be impacted by variations in the equipment, processing parameters and raw material composition.

Technical constraints include creating effective and economical film forming procedures, refining the mechanical and barrier properties of the films, and optimizing extraction methods to maximize purity and yield. To improve the qualities of maize waste films, more research is required to investigate the usage of additives, crosslinking agents and mixing with other biopolymers.

The studies that are presently available on films produced from corn waste indicates that agricultural wastes can be utilized as sustainable raw materials for developing biodegradable plastics that have effective mechanical, thermal and barrier qualities. Benefits to the environment such as reduced carbon emissions and landfill waste have been emphasized by these research. However, because the majority of research is restricted to laboratory-scale pilot tests, there is a lack of extensive information on long-term performance and degradation behavior under different situations. Furthermore, not enough attention is paid to the life cycle analyses and economic viability, which are crucial for evaluating the sustainability and commercial potential of the films. Although additives and integrating with other biopolymers have been a focus of some research, little is known about their interactions and the impact on biodegradability and film performance. An interdisciplinary approach incorporating material science, environmental science and economics is typically lacking in current studies.

Future research should focus on improving the efficiency of extraction and film formation processes, enhancing the properties of the films and developing cost-effective production methods. Furthermore, investigations into the incorporation of corn waste films into current recycling and waste management systems ought to be conducted. Collaborations amongst government, businesses and academic institutions can speed up the creation and marketing of maize waste films and encourage their use across a range of industries.

Conclusion

The transformation of corn waste into biodegradable films represents a sustainable and innovative approach to addressing plastic pollution. The abundance of corn waste and its rich composition of cellulose, hemicellulose and lignin provide a valuable resource for producing biodegradable films with properties comparable to conventional plastics. The methods for converting corn waste into films including chemical treatments, enzymatic hydrolysis and mechanical processes are well-established and the resulting films exhibit desirable mechanical and barrier properties. The biodegradability of these films ensures a reduced environmental impact making them a viable alternative to traditional plastics.

Corn waste films hold significant potential for applications in packaging and agriculture, contributing to the reduction of plastic waste and supporting a circular economy. The economic and environmental benefits of utilizing agricultural byproducts for film production are substantial, adding value to waste materials and creating new revenue streams for farmers. However, challenges such as scalability, consistency in film properties and cost-effective production methods need to be addressed. Future research should focus on optimizing extraction methods, improving film properties and developing efficient production techniques to enhance the commercial viability of corn waste films.

Overall, the use of corn waste for biodegradable film production offers a promising path towards mitigating plastic pollution and promoting sustainable practices. With continued research and collaboration between academia, industry, and government agencies, corn waste-derived films can play a crucial role in creating a more sustainable and environmentally friendly future.

References

1. M. O. Rodrigues, N. Abrantes, F. J. M. Goncalves, H. Nogueira, J. C. Marques, and A. M. M. Goncalves, "Impacts of plastic products used in daily life on the environment and human health: What is known?," *Environ Toxicol Pharmacol*, vol. 72, p. 103239, Nov 2019.
2. H. A. Leslie, M. J. M. van Velzen, S. H. Brandsma, A. D. Vethaak, J. J. Garcia-Vallejo, and M. H. Lamoree, "Discovery and quantification of plastic particle pollution in human blood," *Environ Int*, vol. 163, p. 107199, May 2022.
3. T. Horvatits *et al.*, "Microplastics detected in cirrhotic liver tissue," *eBioMedicine*, vol. 82, p. 104147, 2022/08/01/ 2022.
4. Q. Zhao *et al.*, "Detection and characterization of microplastics in the human testis and semen," *Science of The Total Environment*, vol. 877, p. 162713, 2023/06/15/ 2023.
5. K. Molina-Besch, F. Wikström, and H. Williams, "The environmental impact of packaging in food supply chains—does life cycle assessment of food provide the full picture?," *The International Journal of Life Cycle Assessment*, vol. 24, no. 1, pp. 37-50, 2018.
6. A. Okunola A, O. Kehinde I, A. Oluwaseun, and A. Olufiropo E, "Public and Environmental Health Effects of Plastic Wastes Disposal: A Review," *Journal of Toxicology and Risk Assessment*, vol. 5, no. 2, 2019.
7. F. Bilo *et al.*, "A sustainable bioplastic obtained from rice straw," *Journal of Cleaner Production*, vol. 200, pp. 357-368, 2018/11/01/ 2018.
8. S. Jafarzadeh, S. M. Jafari, A. Salehabadi, A. M. Nafchi, U. S. Uthaya Kumar, and H. P. S. A. Khalil, "Biodegradable green packaging with antimicrobial functions based on the bioactive compounds from tropical plants and their by-products," *Trends in Food Science & Technology*, vol. 100, pp. 262-277, 2020.
9. L. Dai, C. Qiu, L. Xiong, and Q. Sun, "Characterisation of corn starch-based films reinforced with taro starch nanoparticles," *Food Chem*, vol. 174, pp. 82-8, May 1 2015.
10. Y. Liu, Z. Cai, L. Sheng, M. Ma, Q. Xu, and Y. Jin, "Structure-property of crosslinked chitosan/silica composite films modified by genipin and glutaraldehyde under alkaline conditions," *Carbohydrate Polymers*, vol. 215, pp. 348-357, 2019.
11. S. Roy and J.-W. Rhim, "Carboxymethyl cellulose-based antioxidant and antimicrobial active packaging film incorporated with curcumin and zinc oxide," *International Journal of Biological Macromolecules*, vol. 148, pp. 666-676, 04/01 2020.
12. M. R. Khan, S. Volpe, M. Valentino, N. A. Miele, S. Cavella, and E. Torrieri, "Active Casein Coatings and

Films for Perishable Foods: Structural Properties and Shelf-Life Extension," *Coatings,* vol. 11, no. 8, 2021.
13. M. Rezaei, S. Pirsa, and S. Chavoshizadeh, "Photocatalytic/Antimicrobial Active Film Based on Wheat Gluten/ZnO Nanoparticles," *Journal of Inorganic and Organometallic Polymers and Materials,* vol. 30, no. 7, pp. 2654-2665, 2019.
14. M. Schmid and K. Müller, "Whey Protein-Based Packaging Films and Coatings," in *Whey Proteins*, 2019, pp. 407-437.
15. C. Igwe Idumah, J. T. Nwabanne, and F. A. Tanjung, "Novel trends in poly (lactic) acid hybrid bionanocomposites," *Cleaner Materials,* vol. 2, 2021.
16. N. Israni and S. J. B. A. o. P. Shivakumar, "Polyhydroxyalkanoates in Packaging," 2019.
17. L. Yao, L. Fan, and Z. Duan, "Effects of different packaging systems and storage temperatures on the physical and chemical quality of dried mango slices," *LWT,* vol. 121, p. 108981, 2020/03/01/ 2020.
18. M. Fitzpatrick, P. Champagne, M. F. Cunningham, and C. J. C. J. o. C. E. Falkenburger, "Application of optical microscopy as a screening technique for cellulose and lignin solvent systems," vol. 90, pp. 1142-1152, 2012.
19. M. Chen, X. Zhang, C. Liu, R. Sun, and F. Lu, "Approach to Renewable Lignocellulosic Biomass Film Directly from Bagasse," *ACS Sustainable Chemistry & Engineering,* vol. 2, pp. 1164–1168, 03/28 2014.
20. A. Brandt, J. Gräsvik, J. P. Hallett, and T. Welton, "Deconstruction of lignocellulosic biomass with ionic liquids," *Green Chemistry,* 10.1039/C2GC36364J vol. 15, no. 3, pp. 550-583, 2013.
21. Y. H. Zhang *et al.*, "Fractionating recalcitrant lignocellulose at modest reaction conditions," (in eng), *Biotechnol Bioeng,* vol. 97, no. 2, pp. 214-23, Jun 1 2007.
22. Z. Ruan, X. Wang, Y. Liu, and W. Liao, "Corn," in *Integrated Processing Technologies for Food and Agricultural By-Products*, 2019, pp. 59-72.
23. M. D. Hazrol, S. M. Sapuan, E. S. Zainudin, M. Y. M. Zuhri, and N. I. Abdul Wahab, "Corn Starch (Zea mays) Biopolymer Plastic Reaction in Combination with Sorbitol and Glycerol," *Polymers (Basel),* vol. 13, no. 2, Jan 12 2021.
24. Z. Chen, P. Li, Q. Ji, Y. Xing, X. Ma, and Y. Xia, "All-polysaccharide composite films based on calcium alginate reinforced synergistically by multidimensional cellulose and hemicellulose fractionated from corn husks," *Materials Today Communications,* vol. 34, p. 105090, 2023/03/01/ 2023.
25. A. C. Puițel, G. Bălușescu, C. D. Balan, and M. T. Nechita, "The Potential Valorization of Corn Stalks by Alkaline Sequential Fractionation to Obtain Papermaking Fibers, Hemicelluloses, and Lignin—A Comprehensive Mass Balance Approach," vol. 16, no. 11, p. 1542, 2024.
26. E. Bahcegul, B. Akinalan, H. E. Toraman, D. Erdemir, N. Ozkan, and U. Bakir, "Extrusion of xylans extracted from corn cobs into biodegradable polymeric materials," *Bioresour Technol,* vol. 149, pp. 582-5, Dec 2013.
27. K. Thangavelu, R. Desikan, O. P. Taran, and S. Uthandi, "Delignification of corncob via combined hydrodynamic cavitation and enzymatic pretreatment: process optimization by response surface methodology," *Biotechnol Biofuels,* vol. 11, p. 203, 2018.
28. S. L. El Halal *et al.*, "Films based on oxidized starch and cellulose from barley," *Carbohydr Polym,* vol. 133, pp. 644-53, Nov 20 2015.
29. J. Rao, Z. Lv, G. Chen, and F. Peng, "Hemicellulose: Structure, chemical modification, and application," *Progress in Polymer Science,* vol. 140, p. 101675, 2023/05/01/ 2023.
30. A. Bhardwaj, T. Alam, V. Sharma, M. S. Alam, H. Hamid, and G. K. Deshwal, "Lignocellulosic Agricultural Biomass as a Biodegradable and Eco-friendly Alternative for Polymer-Based Food Packaging," *Journal of Packaging Technology and Research,* vol. 4, no. 2, pp. 205-216, 2020/07/01 2020.
31. P. Li *et al.*, "Effect of acid pretreatment on different parts of corn stalk for second generation ethanol production," *Bioresource Technology,* vol. 206, pp. 86-92, 2016/04/01/ 2016.
32. V. Menon and M. Rao, "Trends in bioconversion of lignocellulose: Biofuels, platform chemicals & biorefinery concept," *Progress in Energy and Combustion Science,* vol. 38, no. 4, pp. 522-550, 2012/08/01/ 2012.
33. M. I. J. Ibrahim, S. M. Sapuan, E. S. Zainudin, and M. Y. M. Zuhri, "Preparation and characterization of cornhusk/sugar palm fiber reinforced Cornstarch-based hybrid composites," *Journal of Materials Research Technology*, 2020.
34. Z. Luo *et al.*, "Comparison of performances of corn fiber plastic composites made from different parts of corn stalk," *Industrial Crops and Products,* vol. 95, pp. 521-527, 2017/01/01/ 2017.
35. I. Egüés, A. M. Stepan, A. Eceiza, G. Toriz, P. Gatenholm, and J. Labidi, "Corncob arabinoxylan for new materials," *Carbohydrate Polymers,* vol. 102, pp. 12-20, 2014/02/15/ 2014.
36. D. Sutay, S. Yağcı, E. Yurtdaş, and M. Toptaş, "Multiproduct biorefinery from defatted olive mill waste: preparation of hemicellulose-based biodegradable films and instant controlled pressure drop (DIC)-assisted isolation of value-added products," *Biomass Conversion and Biorefinery,* 2023.

37. T. S. P. de Souza and H. Y. Kawaguti, "Cellulases, Hemicellulases, and Pectinases: Applications in the Food and Beverage Industry," *Food and Bioprocess Technology*, vol. 14, no. 8, pp. 1446-1477, 2021/08/01 2021.
38. M. Asad, N. Saba, A. M. Asiri, M. Jawaid, E. Indarti, and W. D. Wanrosli, "Preparation and characterization of nanocomposite films from oil palm pulp nanocellulose/poly (Vinyl alcohol) by casting method," *Carbohydrate Polymers*, vol. 191, pp. 103-111, 2018/07/01/ 2018.
39. S. Mangaraj, A. Yadav, L. M. Bal, S. K. Dash, N. K. J. J. o. P. T. Mahanti, and Research, "Application of Biodegradable Polymers in Food Packaging Industry: A Comprehensive Review," vol. 3, pp. 77-96, 2018.
40. M. Escamilla-García *et al.*, "Properties and Biodegradability of Films Based on Cellulose and Cellulose Nanocrystals from Corn Cob in Mixture with Chitosan," *International Journal of Molecular Sciences*, vol. 23, no. 18. doi: 10.3390/ijms231810560
41. N. K. Sari, A. Hayu Regita, D. Wahyu Dwi Putra, D. Ernawati, and W. J. E. S. W. C. Wurjani, "Optimizing Edible Film from Corn Cobs with Surface Response Method," vol. 328, p. 08009, 2021.
42. N. K. Sari, D. Ernawati, and W. J. M. W. C. Wurjani, "Edible Film from Corn Cob and Plasticizer with Mixing Process," vol. 372, p. 01001, 2022.
43. P. Zhang and R. L. Whistler, "Mechanical properties and water vapor permeability of thin film from corn hull arabinoxylan," *Journal of Applied Polymer Science*, vol. 93, no. 6, pp. 2896-2902, 2004/09/15 2004.
44. S. Xiao, R. Gao, L. Gao, and J. Li, "Poly(vinyl alcohol) films reinforced with nanofibrillated cellulose (NFC) isolated from corn husk by high intensity ultrasonication," *Carbohydrate Polymers*, vol. 136, pp. 1027-1034, 2016/01/20/ 2016.
45. X. Zhang, C. Fang, Y. Cheng, M. Li, and J. Liu, "Fine extraction of cellulose from corn straw and the application for eco-friendly packaging films enhanced with polyvinyl alcohol," *International Journal of Biological Macromolecules*, vol. 268, p. 131984, 2024/05/01/ 2024.
46. Q. Han, X. Gao, H. Zhang, K. Chen, L. Peng, and Q. Jia, "Preparation and comparative assessment of regenerated cellulose films from corn (Zea mays) stalk pulp fines in DMAc/LiCl solution," *Carbohydrate Polymers*, vol. 218, pp. 315-323, 2019/08/15/ 2019.
47. M. Hyvärinen, R. Jabeen, and T. Kärki, "The Modelling of Extrusion Processes for Polymers-A Review," (in eng), *Polymers (Basel)*, vol. 12, no. 6, Jun 8 2020.
48. M. Krepker *et al.*, "Antimicrobial LDPE/EVOH Layered Films Containing Carvacrol Fabricated by Multiplication Extrusion," *Polymers*, vol. 10, no. 8, p. E864Accessed on: 2018/08//. doi: 10.3390/polym10080864
49. E. Bahcegul, B. Akinalan, H. E. Toraman, D. Erdemir, N. Ozkan, and U. Bakir, "Extrusion of xylans extracted from corn cobs into biodegradable polymeric materials," *Bioresource Technology*, vol. 149, pp. 582-585, 2013/12/01/ 2013.
50. B. Akınalan, "Investigation of Processing Parameters on Production of Hemicellulose Based Films from Different Agricultural Residues via Extrusion," M.S. - Master of Science, Middle East Technical University, 2014.
51. M. Norashikin and M. I. J. Ibrahim, "The potential of natural waste (corn husk) for production of environmental friendly biodegradable film for seedling," *World Academy of Science, Engineering and Technology*, vol. 58, no. 1, pp. 176-180, 2009.
52. G. C. Lenhani *et al.*, "Application of Corn Fibers from Harvest Residues in Biocomposite Films," *Journal of Polymers and the Environment*, vol. 29, no. 9, pp. 2813-2824, 2021/09/01 2021.
53. U. Ratanakamnuan, W. Manorom, and P. Inthasai, "Preparation of Biodegradable Film from Esterified Corn Husk Cellulose," *Advanced Materials Research*, vol. 701, pp. 229-233, 2013.
54. Q. Chen, J. Xiong, G. Chen, and T. Tan, "Preparation and characterization of highly transparent hydrophobic nanocellulose film using corn husks as main material," *International Journal of Biological Macromolecules*, vol. 158, pp. 781-789, 2020/09/01/ 2020.
55. D. Choque-Quispe *et al.*, "Effect of the Addition of Corn Husk Cellulose Nanocrystals in the Development of a Novel Edible Film," vol. 12, no. 19, p. 3421, 2022.
56. E. Díaz-Montes, "Polysaccharide-Based Biodegradable Films: An Alternative in Food Packaging," vol. 3, no. 4, pp. 761-775, 2022.
57. V. Gupta, D. Biswas, and S. Roy, "A Comprehensive Review of Biodegradable Polymer-Based Films and Coatings and Their Food Packaging Applications," *Materials*, vol. 15, no. 17. doi: 10.3390/ma15175899
58. M. Hasan, A. Kumar, C. Maheshwari, and S. Mangraj, "Biodegradable and edible film: A counter to plastic pollution," vol. 8, pp. 2242-2245, 01/01 2020.
59. de Sadeleer and A. Woodhouse, "Environmental impact of biodegradable and non-biodegradable agricultural mulch film: A case study for Nordic conditions," *The International Journal of Life Cycle Assessment*, vol. 29, no. 2, pp. 275-290, 2024/02/01 2024.
60. B. Sharma, B. Vaish, Monika, U. K. Singh, P. Singh, and R. P. Singh, "Recycling of Organic Wastes in Agriculture: An Environmental Perspective,"

International Journal of Environmental Research, vol. 13, no. 2, pp. 409-429, 2019/04/01 2019.
61. J. Nilsen-Nygaard et al., "Current status of biobased and biodegradable food packaging materials: Impact on food quality and effect of innovative processing technologies," Compr Rev Food Sci Food Saf, vol. 20, no. 2, pp. 1333-1380, Mar 2021.
62. M. G. A. Vieira, M. A. da Silva, L. O. dos Santos, and M. M. Beppu, "Natural-based plasticizers and biopolymer films: A review," European Polymer Journal, vol. 47, no. 3, pp. 254-263, 2011.
63. N. Reddy and Y. Yang, "Citric acid cross-linking of starch films," Food Chemistry, vol. 118, no. 3, pp. 702-711, 2010.
64. N. Kontogianni, E. M. Barampouti, S. Mai, D. Malamis, M. J. E. S. Loizidou, and P. Research, "Effect of alkaline pretreatments on the enzymatic hydrolysis of wheat straw," vol. 26, pp. 35648-35656, 2019.
65. G. Albiero, L. Santucci, E. J. W. Carol, Air,, and S. Pollution, "Assessment of acid sulfate drainage in an environmental liability associated with an ancient sulfuric acid industry in a sector of the Rio De la Plata Coastal Plain: impacts on soil and water quality," vol. 232, no. 4, p. 150, 2021.
66. M. Rashid et al., "Carbon sequestration in alkaline soils," Sustainable Agriculture Reviews 38: Carbon Sequestration Vol. 2 Materials and Chemical Methods, pp. 149-167, 2019.
67. W. Tao et al., "Components and persistent free radicals in the volatiles during pyrolysis of lignocellulose biomass," Environmental Science & Technology, vol. 54, no. 20, pp. 13274-13281, 2020.
68. B. C. Iheanacho et al., "A Comprehensive Study on the Production and Characterization of Eco-Friendly Biodegradable Plastic Films from Dent Corn Starch," Archives of Advanced Engineering Science, pp. 1-11, 2024.
69. N. Kukreti, P. Kumar, and R. Kataria, "A sustainable synthesis of polyhydroxyalkanoate from stubble waste as a carbon source using Pseudomonas putida MTCC 2475," Frontiers in Bioengineering and Biotechnology, vol. 12, p. 1343579, 2024.
70. T. J. Herald, E. Obuz, W. W. Twombly, and K. D. Rausch, "Tensile properties of extruded corn protein low-density polyethylene films," *Cereal chemistry*, vol. 79, no. 2, pp. 261-264, 2002.
71. O. Szlachetka, J. Witkowska-Dobrev, A. Baryła, and M. Dohojda, "Low-density polyethylene (LDPE) building films–Tensile properties and surface morphology," *Journal of Building Engineering*, vol. 44, p. 103386, 2021.
72. L. M. Koh and S. M. Khor, "Biodegradation Process: Basics, Factors Affecting, and Industrial Applications," in *Handbook of Biodegradable Materials*, G. A. M. Ali and A. S. H. Makhlouf, Eds. Cham: Springer International Publishing, 2022, pp. 1-39.