Assessing the Technological Maturity of Vegetable Protein-Based Biodegradable Packaging Material Production

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Abstract: The insurgence of plastic waste has posed a detrimental challenge to the environment. Despite actions taken, the plastic problem persists, giving rise to several other issues affecting life on Earth. One of the identified solutions to avert this is to create a biodegradable alternative that would limit plastic dependency and limit the pressure on the environment. In this paper, the current vegetable protein-based packaging industry was explored. This includes the emergence of biodegradable films, innovations applied in their development, and market adoption barriers. This also considers synthesizing the developed films' pertinent properties as a vital component to knowing whether it satisfies its purpose as intended. From a set of established criteria, a narrative review was conducted on 40 selected published journal articles from the Elsevier-Science Direct database on vegetable protein-based biodegradable packaging (PBBP) material. The findings of the study present a wide range of credible alternatives exhibiting competitive properties. While PBBP is still not at par with conventional plastics, the defined gaps in this sector could be a stepping stone for future studies to focus on developing low-cost methods and materials while giving equal importance to durability and biodegradability, hence, a broader scale for PBBP adoption.

Key Words: plastic alternatives; bioplastic; mechanical properties; plastic pollution

1. INTRODUCTION

Throughout the years, plastics were widely used by society. According to Thompson et al. (2009), plastics are lightweight, durable, corrosion-resistant materials with high thermal and electrical insulation properties, and were given importance due to its versatility and convenience. However, plastics have negatively impacted the environment. Plastic pollution became one of the pressing environmental issues, as its rapid increase in production overwhelms the world's capability to deal with it. The world's plastic production totaled around 359 million metric tons in 2018, where non-biodegradable single-use plastics account for 40 percent (Tiseo, 2021).

In the Philippines, plastic pollution is also rampant. An article by the World Wide Fund for Nature (2018) pointed out the factors causing the enormous amount of plastics: people continuously purchasing in small amounts that resulted in more waste; and improper waste disposal, making the country one of the world's leading plastic polluters. While environmental preservation is a significant task for the government and other environmentally-allied professionals, it is incumbent among all people to be vigilant and concerned about this issue.

To address this problem, biodegradable plastics derived from natural sources that do not contain harmful chemical fillers and quickly break down were created (Connecticut Plastics, 2020). However, biodegradable plastic production is deemed costly, given the pertinent processes and needed components.

That made the researchers interested in assessing the technological readiness of a plastic alternative, namely vegetable protein-based biodegradable packaging materials, if ready for mass production and utilization, that will take a step further in lessening conventional plastic use. With that, they would highlight and synthesize the recent innovations in PBBP material development and define the impediments that prevent its wider adoption in various industries.

2. METHODOLOGY

The study's design is a narrative review, a type of qualitative research synthesis that analyzes a body of literature with diverse methodologies and theoretical conceptualizations (Baumeister, 2013). It focused on a specific type of plastic alternative, biodegradable protein films.

To narrow down the research scope, a set of criteria was established for the article selection: (1) the film must have a vegetable protein matrix; (2) it must highlight any innovation in components, process, or properties; (3) it must present quantitative data on the mechanical properties; and (4) it must be a journal article published within the last five years. Although quantitative data is pertinent, the review did not employ the statistical significance of the individual findings.

Data collection was primarily done using the internet. The Elsevier-Science Direct database was mainly utilized as it provides a wide range of bibliographic data regarding biodegradable films. A comprehensive bibliographic search was carried out using the following search string keywords: Biodegradable Packaging Material; Biodegradable Films; Vegetable Proteins; Innovation; and Mechanical Properties, and with publication year ranging from 2015 to 2020. The search results were refined to published journal articles. No books and review articles were included because these do not provide a thorough discussion regarding the studies. A total of forty (40) studies on innovations in PBBP materials were pooled.

An analysis of the collated studies was also conducted. First, the studies were assessed based on the type of innovation and publication year to display the recent trends and characteristics of PBBP research by presenting illustrative representations. Second, the journal articles were sorted per innovation, and salient, emerging themes were identified. A qualitative discussion was imparted to synthesize the studies' findings. Lastly, an analysis of the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of PBBP production was undertaken to display extensive understanding of the industry's internal and external attributes.

3. RESULTS AND DISCUSSION

Fig. 1. Recent innovations on PBBP materials.

The most ventured innovation among the gathered studies, as shown in Figure 1, is the incorporation of bio composite materials as reinforcement and experimentation on film development process. Following those were studies that focused on strengthening mechanical properties and the causation of inhibitory properties as researchers also took note of bacterial infections and food spoilages.

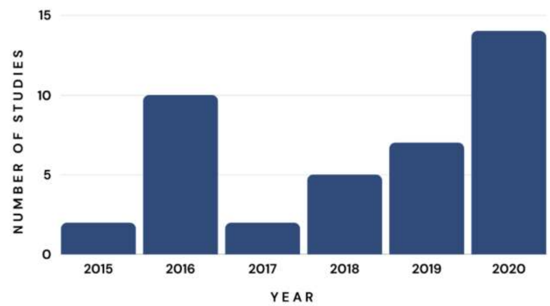

Fig. 2. Pooled studies based on publication year.

Figure 2 shows the collated studies based on publication year from 2015 to 2020, to ensure a synthesis that is relevant in today's context. Out of all 40 gathered studies, 14 were published in 2020, whereas 10 of the studies were published in 2016, as slightly old but still pertinent innovations were considered. Lastly, 5 and 7 studies were from 2018 and 2019, respectively, while 2 studies were published in 2015 and 2017 each.

3.1 Innovations Incorporating Composite Materials

Table 1. Remarkable innovations incorporating composite materials on PBBP.

Vegetable Protein	Incorporated Composite Material	Notable Findings	Reference
Soy	Cellulose nanocrystals (CNCs); pine needle extract (PNE)	The addition of CNCs: • lowered moisture content; • enhanced TS and EAB. The addition of PNE decreased WVP.	Yu et al. (2018)
	Cellulose nanofibers (CNFs)	The addition of 1.0 mL CNFs led to: • highest TS; • higher heat capacity.	Borela & Apolinar (2020)
Whey	Oat husk nanocellulose (ONC)	The addition of 5 wt% ONC: • decreased moisture content; • decreased WVP by 34%; • increased TS by 93%; • increased Young's modulus by 47%;.	Qazanfarzadeh & Kadivar (2016)
	Cellulose nanofibers with polymethyl methacrylate (CNF-g-PMMA)	The addition of CNF: • decreased water permeation by 51-64%; • enhanced TS.	Samadani et al. (2019)
Zein	Pomegranate peel extract (PE) in chitosan nanoparticles (CSNPs)	The addition of CSNPs/PE increased: • TS; • EAB; • heat flow.	Cui et al. (2020)

Note: TS - tensile strength; WVP - water vapor permeability; EAB - elongation at break

Various studies in creating protein-based biodegradable films sought into adding composite materials into the film matrix for reinforcement. The incorporated biocomposites commonly include cellulose fibers, chitosan particles, and plant extracts. The findings of these studies, as shown in Table 1, highlighted improved barrier and mechanical properties, especially moisture content, water vapor permeability, and tensile strength that are usually assessed in biodegradable packaging materials. Hence, the incorporation of composite materials led to enhanced properties of vegetable PBBP films that could springboard future studies that will venture into creating improved biodegradable packaging materials for wider adoption.

3.2 Innovations on Film Development Process

Components	Process	Notable Findings	References
PPI, glycerol	Injection molding	A 70:30, PPI:glycerol ratio, exhibits: • enhanced elastic bending, TS; • ability to absorb mechanical energy before rupturing; • fast water uptake capacity.	Perez et al. (2016)
SPI, cassava starch, stearic & citric acid	Extrusion, thermocompression	A 40:60, cassava starch: SPI ratio, exhibits: • high maximum TS, water solubility; • good WVP and oil permeability.	Ferreira et al. (2020)
WPI, glycerol	Ultraviolet radiation treatment, heat treatment	The highest dose of UV treatment, 12 J cm^{-2}, increased: • TS; • puncture strength; • deformation; • elastic modulus. Heat treatment improved the film's functionality.	Diaz et al. (2016)
Zein, chitosan	Cold plasma treatment	Films treated with cold plasma: • increased barrier properties; • enhanced zein and chitosan molecules compatibility.	Chen et al. (2019)
WPI, carboxymethylated chitosan (CMC)	Transglutaminase (TGase) treatment	WPI-CMC (75:25) film treated with TGase improved: • WVP; • mechanical properties.	Jiang et al. (2016)

Note: SPI - Soy Protein Isolate; WPI - Whey Protein Isolate; PPI - Pea Protein Isolate; TS - Tensile Strength; WVP - Water Vapor Permeability

Based on the studies, an inhibiting factor for PBBP utilization is the costly and complex processing methods of transforming proteins into biodegradable films. Different processes have been explored, including integrating conventional techniques like injection molding, and extrusion. However, this still requires reinforcement techniques that emanate additional costs. Some of these techniques are shown in Table 2. As indicated, the incorporation of such processes improved the films' properties, enabling them to achieve their packaging function.

3.3 Innovations Strengthening Mechanical Properties

Table 3. Recent innovations strengthening mechanical properties of the films.

Components	Mechanical Properties	Notable Findings	References
SPI, GPTMS, POSS	TS: SPI: 33.3 SPI/GPTMS/POSS: 62.1 EAB: SPI: 213.5 SPI/GPTMS/POSS: 101.2	Adding GPTMS and POSS increased TS and offset yield strength.	Xia et al. (2016)
SPI, CNC, glycerol	TS: 3.13 to 4.79 EAB: 98.2 to 86.5	Modified film using CNC increased TS by 23%.	Zhang et al. (2016)
Nanocellulose, whey protein isolate, bergamot oil	WPI: EM:135.8 ± 32.0b TS: 19.8 ± 2.5ab E:14.7 ± 2.7bc WPI-10NC: EM:180.7 ± 20.7b TS:29.4 ± 1.4a E:26.3 ± 8.9ab	Mixing nanocellulose and bergamot oil with WPI enhanced the mechanical resistance and WVP.	Sogut (2020)
SPI, rapeseed oil concentration (ROC)	TS: ROC1: 1.21(0.42) ROC3: 0.91(0.19) YM: ROC1: 0.91(0.29) ROC3: 0.68(0.12) EAB: ROC1: 4.12(0.14) ROC3: 4.19(0.16)	ROC improved WVP. Increasing dosage from 1% to 3% induced favorable mechanical properties.	Galus (2018)
SPI, ZPI	1/1TS: 1.320±0.288 2/1TS: 1.628±0.861 1/2TS: 3.387±0.564	Higher amounts of zein in composite films strengthened its structure.	Tsai & Weng (2020)

Note: SPI - Soy Protein Isolate; TS - Tensile Strength in MPa; EAB - Elongation at Break in %; YM - Young Modulus in MPa;

3.4 Innovations Triggering Inhibitory Properties

Table 4. Notable studies venturing into PBBPs' causation of inhibitory properties.

Components	Method Used	Microbes Tested		Inhibition Zone	References
WPI, water soluble chitosan	Agar Disk Diffusion Method	Fungi	*Aspergillus niger*	WPI[c]: ND WSCh1.5%(w/w): 54.17[a] WSCh3%(w/w): 87.50[a]	Vanden Braber et al. (2020)
			Fusarium sp.	WPI[c]: ND WSCh1.5%(w/w): 52.50[a] WSCh3%(w/w): 52.50[a]	
			Penicillium roqueforti	WPI[c]: ND WSCh1.5%(w/w): 82.50[a] WSCh3%(w/w): 97.50[a]	
			Rhizopus sp.	WPI[c]: ND WSCh1.5%(w/w): 52.50[a] WSCh3%(w/w): 97.50[a]	
WPI, TiO_2 nanoparticles, cellulose nanofibers (CNFs), rosemary essential oil (REO)		Gram-positive	*S. aureus*	WPI/CNFs[c]: ND WPI/TiO_2/REO had the most effect Besides the control, WPI/REO had the least effect	Alizadeh-Sani et al. (2018)
			L. monocytogenes		
		Gram-negative	*E. coli O157:H7*		
			P. fluorescens		
			S. enteritidis		
ZPI, cinnamon essential oil (CEO), chitosan nanoparticles (CNP)		Gram-positive *S. aureus*		zein[c]: ND zein & CNPs: ND zein & CEO: 21.66±0.57[b] zein, CNPs & CEO: 27.33±1.93[b]	Vahedikia et al. (2019)
		Gram-negative *E. coli*		zein[c]: ND zein & CNPs: ND zein & CEO: 11.00±1.00[b] zein, CNPs, & CEO: 11.33±1.61[b]	
Chinese chive extract root, chitosan		Gram-positive	*S. aureus*	CS[c]: 7.13±0.14[a] CS-CRE1: 10.64±0.21[a] CS-CRE3: 14.73±0.29[a] CS-CRE5: 18.12±0.36[a]	Riaz et al. (2020)
			B. cereus	CS[c]: 6.21±0.12[a] CS-CRE1: 11.83±0.23[a] CS-CRE3: 15.39±0.30[a] CS-CRE5: 18.79±0.37[a]	
		Gram-negative	*E. coli*	CS[c]: 4.43±0.08[a] CS-CRE1: 7.18±0.14[a] CS-CRE3: 12.87±0.25[a] CS-CRE5: 16.21±0.32[a]	
			S. typhimurium	CS[c]: 4.11±0.08[a] CS-CRE1: 6.87±0.13[a] CS-CRE3: 11.54±0.23[a] CS-CRE5: 14.91±0.29[a]	
SPI, cortex phellodendron extract		Gram-positive *S. aureus*		The inhibition zones for *S. aureus* were larger than for *E. coli*.	Liang & Wang (2018)
		Gram-negative *E. coli*			

Note: WPI - whey protein isolate; SPI - soy protein isolate; ZPI - zein protein isolate;
ND - not detected; [a] diameter in mm; [b] diameter in mm^2; [c] control group;

Some conducted studies gave attention to the provocation of inhibitory properties, aside from strengthening the mechanical properties in a produced PBBP material. These researchers sought to obtain active packaging films that can help prevent food spoilages or bacterial infection. In doing that, the credibility of the film improved, and as seen in Table 4, said researchers were successful in doing so.

Note: The complete list of innovations is available upon request.

3.5 SWOT Analysis

Table 5. SWOT analysis on the collated studies regarding PBBP films.

Factor	Highlights			
Strengths	Lessened environmental burden	Reduced petroleum consumption	Expanding interest in the field of PBBP	Competitive properties
Weaknesses	Availability of pertinent equipment for production	Innovations further aligned into strengthening mechanical properties	Fastidious environmental conditions	
Opportunities	Environmental consciousness	Unintended benefits	Variety of applications	Business opportunity
Threats	Consumer acceptance	Unpreparedness for mass-market production	Expensiveness of the production process and raw materials	Risk of an environmental crisis due to waste build-up

3.5.1 Strengths

The PBBPs showed biodegradability varying from weeks to months, depending on raw materials added into the formulation, and they were composed of vegetable proteins and other bio-based materials, instead of non-renewable petroleum, which is harmful to the environment. An increase in the number of PBBP-related studies was also observed, mirroring that, people become more engaged and aware of climate change while addressing the sustainability problem. Lastly, promising properties of PBBPs that are not present with conventional plastics are being initiated, like inhibitory properties.

3.5.2 Weaknesses

Some steps in creating PBBP materials require proper treatment of raw materials using certain pieces of equipment that are not usually available for most countries that could be interested in producing PBBPs for market use. Meanwhile, studies usually lean into achieving sufficient mechanical properties and not on the improvement of film biodegradation. That is crucial, for the driving force behind the PBBP creation is producing packaging materials that help address plastic pollution. Regarding biodegradability, some films degrade only in a certain environment, where others require composting facilities that cater to biodegradable packaging waste, while some employ chemical and other degrading techniques.

3.5.3 Opportunities

People start to realize the possible consequences of harmful activities to the environment. Amongst studies exploring PBBP, plastic pollution is the common dilemma motivating researchers to contribute to the existing body of knowledge and create a step towards limiting single-use plastic consumption. Concerning the development of biodegradable films, utilizing by-products like pomegranate and banana peels to reinforce their properties was seen to have an unintended benefit of solving poor waste disposal. Although some films and coatings show appreciable potential in biodegradable packaging production, conducting physical and chemical modifications may pave the way for market adoption, since people are more inclined to invest in environmentally-sound products nowadays. Producing viable plastic alternatives could become a sustainable market opportunity that both individuals and the environment can benefit from.

3.5.4 Threats

At present, few consumers have knowledge on the existence of PBBP films and its production, which can stem uncertainty, making it difficult to kickstart market consumption of such films. Additionally, due to the assurance that PBBP films can degrade, importance of preferable biodegradation conditions was downplayed, focusing instead on enhancing mechanical properties. As composite manufacturing is a highly specialized field and raw materials are costly, spending high amounts of money is inevitable in the production of composite PBBP films, leading to the question if the product is worth the trouble or not. Lastly, despite the created sustainable solution, the accumulation of PBBP film wastes is still inevitable as biodegradation requires certain conditions. Therefore, if said conditions are not met, that could potentially worsen the condition of the environment.

4. CONCLUSIONS

Over the past five years, innovative research on PBBPs has risen, predominantly on infusing composite materials and performing strengthening processes for the improvement of its properties. With that, its possibility of market production is high. However, the availability of pertinent equipment and uneconomical production cost makes its adoption still implausible. To accelerate development, future studies should consider developing ways in creating durable yet cost-friendly PBBPs. In addition to that, biodegradability should also be considered. Shortening the biodegradation time and establishing a wide range of environmental conditions for degradation are some aspects to improve on. While PBBPs can reduce plastic consumption, it is not the silver bullet to ending plastic pollution.

5. ACKNOWLEDGMENTS

The authors would like to express their sincerest gratitude to Dr. Jose Isagani Janairo, Professor of the DLSU–Biology Department, for his valuable guidance and the knowledge that he has imparted to complete this project. They would also like to thank Ms. Liezl Rillera-Astudillo, STEM's SHS Research Coordinator, for the encouragement and enlightenment that she has provided in this research endeavor. Above all, glory and thanks goes to God

Almighty for giving the authors the strength, knowledge, and ability to undertake this study. Without his providence, this accomplishment would not have been achieved.

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