Impact of Natural Polymer Proportions on the Fire-Retardant Properties of Bioplastics

I Gusti Ngurah Nitya Santhiarsa[1*], Ni Made Dwidiani[1], I Gusti Ngurah Putu Tenaya[1], I Gede Artha Negara[2]

[1]*Department of Mechanical Engineering, University of Udayana, Jimbaran, Badung, 80361, Indonesia*
[2]*Department of Mechanical Engineering, Bali State Polytechnic, Jimbaran, Badung, 80364, Indonesia*
**Corresponding author:nitya_santhiarsa@unud.ac.id*

Article history:
Received: 27 October 2024 / Received in revised form: 3 November 2024 / Accepted: 6 November 2024
Available online 14 November 2024

ABSTRACT

This research investigates the influence of varying proportions of natural polymers on the fire-retardant properties of bioplastic. Tapioca starch (*Manihot esculenta*) and corn starch (*Zea mays*) were selected as the bioplastic materials, with different weight fractions employed in the analysis. These materials, as naturally occurring polymers, are biodegradable and serve as promising components in the development of bioplastics. Fire resistance testing was conducted in accordance with ASTM D635-03, utilizing weight ratios of tapioca to corn starch at 70:30, 60:40, and 50:50. The results included photographic documentation of each specimen alongside the corresponding outcomes from the fire resistance tests. These images provide insight into the physical condition of the specimens prior to testing, emphasizing any notable morphological features that may affect their fire resistance properties. The optimal burning rate was observed in the bioplastic with a 50:50 weight fraction ratio of tapioca starch to corn starch, which exhibited a combustion rate of 8.420 mm/s. Additionally, the bioplastic with the highest weight loss rate, recorded at 0.0346 g/s, was also composed of a 50:50 weight fraction of the two starches. The observed increase was 2.36% relative to the 60:40 weight fraction and 13% relative to the 70:30 weight fraction. This increased weight loss rate can be attributed to the higher corn starch content, which is characterized by inherent flammability due to its structural composition.

Keywords: *Biodegradable, bioplastic, fire resistance, manihot esculenta, zea mays*

I. Introduction

The issue of waste management remains a prominent concern in contemporary society, particularly with regard to plastic waste. As global populations continue to rise, the volume of waste generated from anthropogenic activities is expected to increase correspondingly. Current estimates indicate that organic waste constitutes approximately 60-70% of total waste, while non-organic waste accounts for 30-40% [1]–[3]. Within the category of non-organic waste, plastic waste represents a significant portion, estimated at around 14%, predominantly comprising plastic bags. The environmental ramifications of plastic waste are profound, as unchecked accumulation can lead to severe pollution, adversely affecting ecosystems, wildlife, and human health [4]. Effective countermeasures are imperative to mitigate these challenges. One of the most widely endorsed strategies for addressing plastic waste is the 3R principle—Reduce, Reuse, Recycle [5]. This framework encourages the minimization of plastic consumption, the repeated use of plastic products, and the recycling of plastic materials to extend their lifecycle. Implementing the 3R principle requires a multifaceted approach involving policy changes, public education, and technological

DOI: 10.17977/um016v8i22024p434

innovation. Governments, businesses, and communities must collaborate to establish infrastructure that supports recycling initiatives and promotes sustainable consumption patterns. Furthermore, research into alternative materials and biodegradable options is essential to reduce dependence on conventional plastics. By adopting these comprehensive strategies, we can significantly diminish the impact of plastic waste on the environment and promote a more sustainable future [6], [7].

The predominant plastics utilized in contemporary applications are synthetic polymers derived from petroleum, which are produced in limited quantities and lack renewability. This situation underscores the urgent need for alternative plastic materials that are abundant in nature, easily accessible, cost-effective, and capable of exhibiting comparable mechanical properties—commonly referred to as bioplastics [8], [9]. Bioplastics are defined as polymers that can undergo natural degradation facilitated by microorganisms or environmental factors such as humidity and solar radiation. These materials can be synthesized by combining cellulose with starch, gelatin, and various other biopolymers, thereby addressing the inherent limitations associated with starch-based plastics [10]. Starch [11], a naturally occurring polymer, is biodegradable, and serves as a promising component in the development of bioplastics. By incorporating starch into synthetic polymer matrices, it is anticipated that the resulting composite materials will exhibit enhanced biodegradability. The degradation process of starch-based biodegradable plastics occurs through microbial action, where bacteria metabolize the polymer chains, breaking them down into simpler monomers [12]. Starch can be extracted from a variety of plant sources, including roots, tubers, stems, and seeds, making it a readily available resource for bioplastic production [13]. The integration of bioplastics into the market not only offers a sustainable alternative to conventional plastics but also contributes to reducing the environmental impact associated with plastic waste. Continued research and development in this field are essential to optimize the properties of bioplastics and expand their applications, thereby fostering a transition towards more sustainable materials in various industries.

The recent research on fire-resistant bioplastics by Beata et al. [14] details the preparation of bioplastics derived from polylactide (PLA), utilizing kraft lignin (L), sulfonated kraft lignin ($L\text{-}SO_3$), and combinations with silica ($L\text{-}SO_3H+SiO_2H$) as natural additives. The functional groups present in the resulting bioplastics were analyzed using Attenuated Total Reflectance Fourier Transform Infrared Spectroscopy (ATR-FTIR), while their thermal properties were examined through Differential Scanning Calorimetry (DSC) and Thermogravimetric Analysis (TG). The study thoroughly investigates the effects of various additive combinations and the aging process on the properties of the bioplastics, including their flammability characteristics. Furthermore, mechanisms have been proposed to elucidate the observed network fragmentation during combustion. Research by Hamidah et al. [15] indicates that the objective of this study was to investigate the effect of incorporating starfruit filtrate (*A. bilimbi L*) on water absorption and biodegradation. The research employed the phase inversion method, utilizing varying volumes of starfruit filtrate at 10 ml, 15 ml, 20 ml, and 25 ml. The results indicated that the formation of biodegradable plates with the addition of starfruit filtrate yielded a brown coloration, a hard texture, and a rough surface. The findings demonstrated that each increment in the volume of starfruit filtrate significantly enhanced the water absorption and biodegradation characteristics, achieving percentages of 48.29%, 51.78%, 53.62%, and 55.27% for water absorption, and 11.77%, 24.52%, 28.42%, and 36.88% for biodegradation, respectively. Surface characterization through scanning electron microscopy revealed that the resulting bioplastic exhibited a less dense particle arrangement and the presence of pores on its surface. The starfruit filtrate (*A. bilimbi L*) is deemed suitable for modifications due to its content of weakly acidic compounds, with a pH of 5. Research by Nandiyanto et al. [16] indicates that the objective of this study was to investigate the mechanical and biodegradation properties of bioplastic produced from pure cornstarch, without the inclusion of any reinforcing components. The fabrication procedure involved the following steps: (1) diluting cornstarch in water, (2) creating a homogeneous mixture of the diluted cornstarch, glycerol, and acetic acid by heating at temperatures below 100ºC, (3) molding the mixture, and (4) drying the resulting product to obtain a solid bioplastic. The bioplastic demonstrated favorable biodegradability, as it degraded easily within two weeks of immersion in water, as evidenced by weight loss and the appearance of fungi on its surface. While the mechanical performance was satisfactory, it remained lower than that of standard bioplastics of moderate grade. Consequently, the incorporation of additional reinforcing components, such as co-polymers or additives, is necessary to enhance the mechanical properties.

In this study, a comprehensive fire resistance assessment of bioplastics was conducted, employing variations in the weight fractions of tapioca starch and corn starch as key variables. The objective of this investigation was to evaluate how different proportions of these natural polymers influence the fire-retardant properties of the resultant bioplastic composites. Bioplastics, derived from renewable resources, are gaining traction as sustainable alternatives to conventional plastics. However, their susceptibility to combustion poses significant challenges for practical applications, particularly in sectors requiring enhanced fire safety standards. Despite the insights gained from varying the weight fractions of tapioca and corn starch, there remains a notable research gap regarding the synergistic effects of other natural additives, such as lignin or cellulose, on the fire resistance of bioplastics. Additionally, the long-term stability and performance of these bioplastics under real-world conditions have not been thoroughly investigated. By addressing these gaps, the study aims to provide a more comprehensive understanding of how to optimize bioplastic formulations. The findings from this research are expected to significantly contribute to the field of bioplastic development, offering valuable data that could inform the creation of safer, more effective bioplastic materials.

II. Material and Methods

1. Material

A variety of equipment is employed in the manufacturing of bioplastics as well as in the assessment of their fire resistance properties. The equipment utilized includes mixers, ovens, digital scales, measuring cups, teflon molds, thermometers, and specialized fire resistance testing apparatus. The specialized fire resistance testing apparatus is specifically designed to evaluate the flammability and combustion characteristics of bioplastics, providing essential data on their safety and performance in various applications. The configuration of the equipment used for fire resistance testing is illustrated in Figure 1. Moreover, the materials employed in the production of bioplastics comprise tapioca starch, corn starch, chitosan, glycerol, and acetic acid. Each of these components plays a crucial role in determining the physical, chemical, and mechanical properties of the resulting bioplastic materials. All of these materials are sourced from a manufacturing facility located in Indonesia.

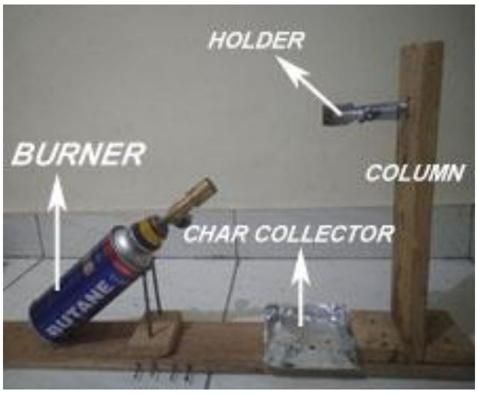

Fig. 1. Combustion resistance assessment apparatus

Tapioca starch is a natural polymer extracted from the cassava root (*Manihot esculenta*)[17], a tuberous plant native to South America. This starch is composed primarily of amylose and amylopectin, which are polysaccharides that contribute to its functional properties. For normal tapioca starch, the amylose content generally ranges from 15.2% to 26.5% (20.7% on average). As a primary biopolymer in bioplastic formulations, tapioca starch offers several advantages, including biodegradability, renewability, and non-toxicity. Its gelatinization process, which occurs when heated in the presence of water, allows it to form a viscous paste that can be molded into various shapes [18]. The unique characteristics of tapioca starch, such as its high-water absorption capacity and film-forming ability, make it an ideal candidate for bioplastic production, enhancing the flexibility and mechanical strength of the final product.

Similarly, corn starch, derived from the endosperm of maize (*Zea mays*) [19], is another biodegradable polymer that significantly contributes to the mechanical properties of bioplastics. Corn starch consists of a mixture of amylose and amylopectin, similar to tapioca starch, but with different ratios that affect its gelatinization and retrogradation behavior. Normal corn starch consists of approximately 25% amylose and 75% amylopectin. The incorporation of corn starch into bioplastic formulations not only enhances the material's tensile strength and elasticity but also improves its thermal stability [20]. The biodegradability of corn starch is a key factor in its application, as it breaks down into natural components when exposed to environmental conditions, thereby reducing plastic pollution. Furthermore, corn starch can be modified chemically or physically to tailor its properties, allowing for the development of bioplastics with specific performance criteria. The tapioca and corn starch are shown in Figure 2.

Fig. 2. a. Tapioca starch (*Manihot esculenta*), b. Corn starch (*Zea mays*)

2. Method

The production of bioplastics involves several systematic steps, beginning with the preparation of the necessary tools and materials for the research. Upon completion of this preparatory phase, the process continues witfigh the mixing of tapioca starch, corn starch, chitosan, acetic acid, and glycerol. All of these materials are sourced from a manufacturing facility located in Indonesia. This mixture is achieved using a mechanical mixer to ensure a uniform distribution of all components. Following thorough mixing, the resulting composite is transferred into a Teflon mold with a diameter of 20 cm, ensuring even distribution within the mold. The next phase involves the drying process, which is conducted in an oven set to a temperature of 60°C for a duration of 16 hours. This drying step is crucial for the removal of moisture and for achieving the desired physical properties of the bioplastic.

After the drying period, the Teflon mold is carefully removed, and the bioplastic specimen is allowed to cool at room temperature for 24 hours. During this cooling phase, the integrity of the specimen is assessed. If the surface exhibits any corrugation or irregularities, this indicates a failure in the manufacturing process, necessitating a return to the initial mixing step for reprocessing. Conversely, if the surface of the specimen is smooth and free of defects, the production of the bioplastic specimen is deemed successful. The variations in the weight fractions of the specimen mixture are detailed in Table 1.

Table 1. The variations in the weight fractions of the specimen composition

Comparison of weights (%) between tapioca starch and corn starch	Weight of starch blend (gr)	Chitosan weight (gr)	Acetic acid weight (gr)	Glycerol weight (gr)
70:30				
60:40	60	5	2.5	2.5
50:50				

The fire resistance test was conducted in accordance with ASTM D635-03. Nine specimens were prepared, consisting of three starch mixture ratios: 70:30, 60:40, and 50:50. Initially, the dimensions of each specimen were recorded, including initial length (L_0), thickness (t), width (l), initial cross-sectional area (A_0), and initial weight (w_0), under controlled laboratory conditions. Each specimen was marked with two straight lines positioned at distances of 25 ± 1 mm and 100 ± 1 mm from the ignition tip. The flame was applied at an angle of 45 ± 2 degrees, utilizing either gauze or aluminum foil as the wire type placed beneath the specimen. Sufficient space was maintained at the end of the specimen clamp to prevent any interference with the fire during the burning test.

The burner was calibrated to produce a blue flame measuring 20 mm in length. If the flame height was found to be less than 20 ± 2 mm, adjustments to the gas flow were made to achieve the desired flame height. Once the flame was stabilized at 20 ± 2 mm, it was directed at the tip of the test specimen to a depth of approximately 6 mm, at which point a stopwatch was initiated. The duration of the burn was measured as the time taken for the flame to traverse from the 25 mm mark to the 100 mm mark, corresponding to a total burning length of 75 mm. If the flame continued to propagate to the 100 mm mark, the flame and stopwatch were extinguished. Subsequently, the time (t) was recorded, along with the burning length (L) to the 100 mm mark, the weight of the composite post-testing (w_1), and the weight loss during the test (w). Observations were made to determine if the flame front crossed the 25 mm mark without reaching the 100 mm mark. The statistical method employed in this study for data analysis is solely the calculation of standard deviation, which serves to quantify the variability or dispersion of the data set around the mean value.

III. Results and Discussions

1. Photographic Documentation of Each Bioplastic Specimen

The analysis included a comprehensive evaluation of the specimens, specifically those with starch mixture ratios of 70:30, 60:40, and 50:50. The photographic documentation of each specimen, along with the corresponding results from the bioplastic fire resistance tests, provides valuable insights into the performance characteristics of the materials under investigation. These images illustrate the physical condition of the specimens prior to testing, highlighting any notable features or variations in morphology that may influence their fire resistance properties. Figure 3 present a visual representation of the specimens before the initiation of the fire resistance tests, allowing for a comparative analysis of the different starch mixture ratios. This visual data is crucial for understanding the effects of varying compositions on the overall fire resistance performance of the bioplastic materials. The specimens were meticulously prepared and assessed to ensure that the results accurately reflect their inherent properties and behaviors in response to fire exposure.

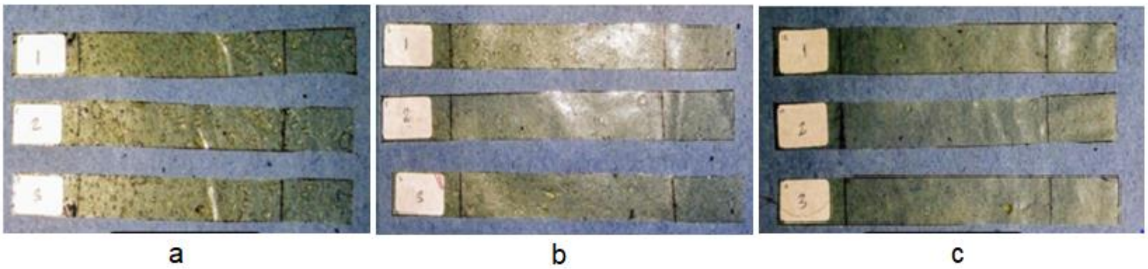

Fig. 3. Visual representation of the specimens before fire resistance tests. a. Specimen with a 70:30 ratio, b. Specimen with a 60:40 ratio, c. Specimen with a 50:50 ratio.

This systematic approach to testing not only enhances the robustness of the findings but also contributes to a deeper understanding of the relationship between material composition and fire resistance. The subsequent analysis of the test results will further elucidate the implications of these findings for the development of fire-resistant bioplastics. Specimens that have undergone fire resistance testing are illustrated in Figure 4.

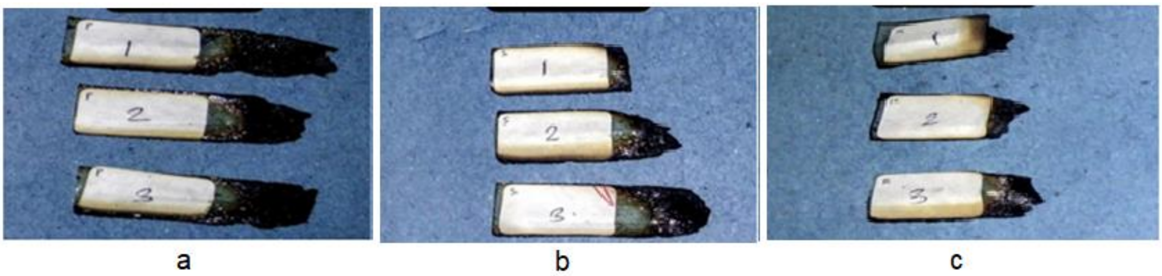

Fig. 4. Specimens that have been tested for fire resistance. a. Specimen with a 70:30 ratio, b. Specimen with a 60:40 ratio, c. Specimen with a 50:50 ratio.

Figures 4 provide a detailed visual representation of the specimens post-testing, capturing the effects of fire exposure on their structural integrity and material characteristics. The images illustrate various aspects such as char formation, deformation, and any observable damage that may have occurred during the testing process. By analyzing these visual data points, researchers can assess the performance of each starch mixture ratio (70:30, 60:40, and 50:50) in relation to their fire resistance capabilities.

The examination of these specimens is critical for understanding the thermal degradation mechanisms at play. Observations from the figures will facilitate a comparative analysis of the fire resistance properties across different compositions, allowing for insights into how variations in starch content influence the overall behavior of the bioplastics when subjected to high temperatures. Furthermore, the documentation of these post-test conditions serves as a foundational aspect for subsequent discussions regarding material improvements and potential applications in fire-sensitive environments.

2. Fire Resistance

Figure 5 shows the combustion rates of various bioplastic specimens. The data indicate that the optimal burning rate is observed in bioplastics with a 50:50 weight fraction ratio, specifically a blend of tapioca starch and corn starch, which exhibits a combustion rate of 8.420 mm/s. This phenomenon can be attributed to the higher proportion of corn starch in the mixture, which possesses inherently flammable properties due to its molecular structure and composition [21]. Corn starch, being primarily composed of amylose and amylopectin, facilitates more efficient combustion when compared to tapioca starch. Additionally, the moisture content plays a crucial role in the combustion characteristics of these materials. The water content in tapioca starch is approximately 13.18% higher than that of corn starch, which significantly impacts its ignitability and combustion efficiency. Higher moisture levels in tapioca starch can lead to increased thermal inertia, thereby hindering the combustion process and resulting in a lower burning rate.

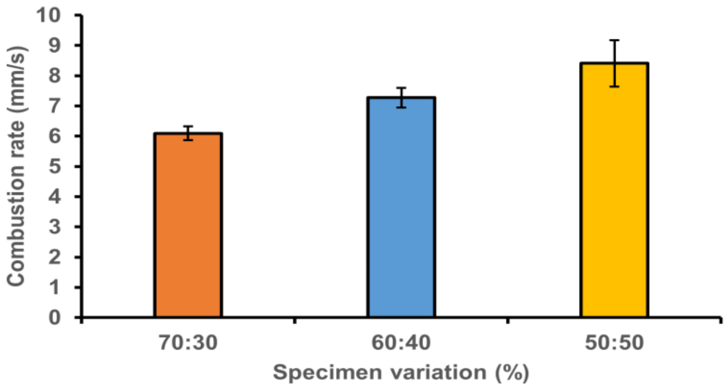

Fig. 5. Combustion rates of different bioplastic specimens

Conversely, the lowest combustion rate was recorded in bioplastics with a 70:30 weight fraction ratio, where the proportion of tapioca starch exceeds that of corn starch, yielding a combustion rate of 6.085 mm/s. This reduction in combustion efficiency can be explained by the dominance of tapioca starch in the mixture, which, due to its higher moisture content and lower flammability, impedes the overall combustion process. The interplay between the starch composition and moisture content is critical in determining the combustion characteristics of bioplastics, underscoring the importance of optimizing these parameters for enhanced performance in practical applications. The standard deviations from the three repetitions were ±0.226 (for specimen variation 70:30), ±0.321 (for specimen variation 60:40), and ±0.766 (for specimen variation 50:50). The specimen variation 70:30 exhibited the lowest standard deviation value, indicating a higher consistency and reliability in its combustion rate measurements compared to the other formulations. A lower standard deviation implies that the combustion rates are more closely clustered around the mean, suggesting that the experimental conditions and material properties were more uniform for the 70:30 specimen. This consistency is critical in material science, as it reflects the reproducibility of results, which is essential for validating experimental outcomes and ensuring the reliability of bioplastic performance under combustion conditions.

Figure 6 shows the weight loss rates of various bioplastic specimens, highlighting significant differences based on their composition. The bioplastic exhibiting the highest weight loss rate, recorded at 0.0346 g/s, is composed of a 50:50 weight fraction of tapioca starch and corn starch. This elevated rate can be attributed to the predominant corn starch content, which possesses inherent flammability properties due to its structural composition[22]. Corn starch, being more thermally degradable than tapioca starch, facilitates a more rapid decomposition process when subjected to heat or combustion. Conversely, the bioplastic with a weight fraction ratio of 70:30, where tapioca starch is present in greater proportion than corn starch, exhibited the lowest weight loss rate of 0.0306 g/s. The increased presence of tapioca starch, which has a higher thermal stability and lower flammability compared to corn starch, contributes to this reduced rate of weight loss. These findings underscore the influence of starch composition on the thermal degradation characteristics of bioplastics.

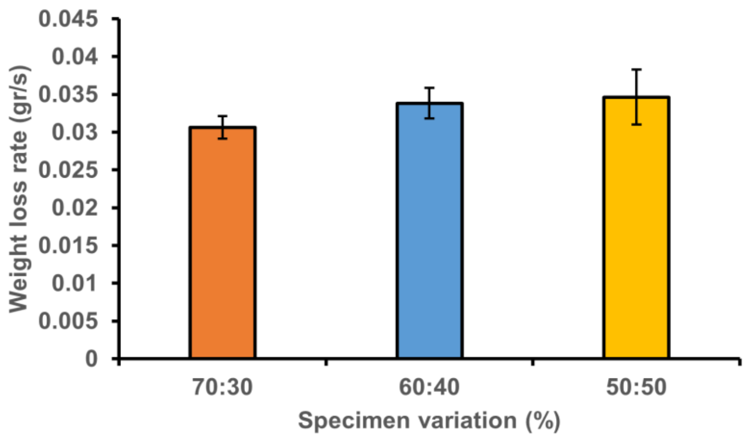

Fig. 6. Weight loss rates of different bioplastic specimens

The standard deviations from the three repetitions were ±0.0015 for the specimen with a weight fraction ratio of 70:30, ±0.0020 for the specimen with a ratio of 60:40, and ±0.0036 for the specimen with a ratio of 50:50. These values indicate the degree of variability in the weight loss rates across the different bioplastic formulations. The lower standard deviation observed in the 70:30 specimen suggests a more consistent weight loss rate, while the higher standard deviations in the 60:40 and 50:50 specimens indicate greater variability in their weight loss measurements. This variability may reflect differences in material properties, processing conditions, or other experimental factors that influence the degradation behavior of the bioplastics. Understanding these statistical measures is essential for evaluating the reliability of the experimental data and for optimizing bioplastic formulations to achieve improved performance characteristics [23].

IV. Conclusions

The study examining the influence of natural polymer proportions on the fire-retardant properties of bioplastics concludes that formulations with a weight fraction composition of 50:50 exhibit the highest combustion rate and the most significant weight loss. This increased combustion rate can be attributed to the balanced presence of both starch types, with corn starch contributing to enhanced flammability due to its intrinsic thermal properties. In contrast, bioplastics formulated with a weight fraction ratio of 70:30, where tapioca starch predominates, demonstrated the lowest combustion rate and minimal weight loss. This reduced flammability is likely due to the superior thermal stability of tapioca starch compared to corn starch, resulting in a more resilient material under combustion conditions. These findings highlight the critical role of starch composition in determining the combustion characteristics of bioplastics. By optimizing the weight fraction ratios of starch components, it is feasible to tailor the fire resistance properties of bioplastics for specific applications, such as in construction materials, automotive components, or packaging solutions requiring enhanced fire safety. However, challenges may arise when scaling up these bioplastic formulations for industrial production. Factors such as consistency in raw material quality, processing conditions, and the potential for batch variability could impact the performance of the final products. Furthermore, the integration of these bioplastics into existing manufacturing processes may require modifications to ensure compatibility and efficiency.

Acknowledgment

The authors express their sincere gratitude for the financial support provided by the LPPM of Udayana University, Bali, Indonesia. This assistance has been instrumental in facilitating the research and development efforts undertaken in this study. The authors appreciate the commitment of LPPM to advancing academic research and fostering innovation within the institution.

References

[1] P. Purwaningrum, D. Indrawati, T. Oemar, and G.C. Simatupang, “The study of waste management and its usefulness in the old city area, Jakarta,” *Serambi Eng.*, vol. VII, no. 3, pp. 3583–3588, 2022.

[2] I.G.A. Negara, A.A.N.B. Mulawarman, I.G. Santosa, and L.P.I. Midiani, “Studi Eksperimental generator elektrik berbahan bakar biogas guna mendukung net zero emission,” vol. 14, no. 2, pp. 689–700, 2023, doi: 10.21776/jrm.v14i2.1431.

[3] A. Setiawan, F. D. Wahyuningsih, and R. Z. Mirahati, “Mechanical Properties of biocomposite with various composition of $CaCO_3$ and starch,” *J. Mech. Eng. Sci. Technol.*, vol. 7, no. 1, p. 1, 2023, doi: 10.17977/um016v7i12023001.

[4] I.G.N.N. Santhiarsa, I.G.A.A. Praharsini, and I.G.A.A. Suryawati, “Weight fraction effect of sugar palm fiber as polypropylene-elastomer matrix reinforcement on fire resistance of hybrid composite,” *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 12, no. 2, pp. 649–654, 2022, doi: 10.18517/ijaseit.12.2.15848.

[5] A. Ioannidis, K.J. Chalvatzis, L.C. Leonidou, and Z. Feng, “Applying the reduce, reuse, and recycle principle in the hospitality sector: Its antecedents and performance implications,” *Bus. Strateg. Environ.*, vol. 30, no. 7, pp. 3394–3410, 2021, doi: 10.1002/bse.2809.

[6] J. Junaidi and A.A. Utama, "Analisis pengelolaan sampah dengan prinsip 3R (reduce, reuse, recycle) (Studi kasus di desa Mamak Kabupaten Sumbawa)," *JISIP (Jurnal Ilmu Sos. dan Pendidikan)*, vol. 7, no. 1, pp. 706–713, 2023, doi: 10.58258/jisip.v7i1.4509.

[7] I.N. Santhiarsa, I.G.B.W. Kusuma, and I.G.A. Negara, "Mechanical characterization of NaOH-treated agel fiber-cotton composites," *J. Mech. Eng. Sci. Technol.*, vol. 7, no. 2, p. 214, 2023, doi: 10.17977/um016v7i22023p214.

[8] T. Narancic, F. Cerrone, N. Beagan, and K.E. O'Connor, "Recent advances in bioplastics: Application and biodegradation," *Polymers (Basel)*, vol. 12, no. 4, 2020, doi: 10.3390/POLYM12040920.

[9] I.G.N.N. Santhiarsa, I.G.A.A. Praharsini, I.G.A.A. Suryawati, and Pratikto, "Analysis of mechanical strength of weight fraction variation sugar palm fiber as polypropyleneelastomer matrix reinforcement of hybrid composite," *Eastern-European J. Enterp. Technol.*, vol. 5, no. 12–113, pp. 20–29, 2021, doi: 10.15587/1729-4061.2021.238507.

[10] C. Charnock, "Norwegian soils and waters contain mesophilic, plastic-degrading bacteria," *Microorganisms*, vol. 9, no. 1, pp. 1–18, 2021, doi: 10.3390/microorganisms9010094.

[11] D. Sandra Fitriany, S. Annaziha, H. Sains Assajuly Syamsuddin, and A. Khumaira, "Bio-Pack : Biodegradable packaging pati singkong sebagai solusi pencemaran limbah plastik konvensional," *J. Compr. Sci.*, vol. 2, no. 1, pp. 430–437, 2023, doi: 10.59188/jcs.v2i1.229.

[12] S. Paul, B. Sen, S. Das, S.J. Abbas, S.N. Pradhan, K. Sen et al., "Incarnation of bioplastics: recuperation of plastic pollution," *Int. J. Environ. Anal. Chem.*, vol. 103, no. 19, pp. 8217–8240, 2023, doi: 10.1080/03067319.2021.1983552.

[13] M.G. De Cesaris, N. Felli, L. Antonelli, I. Francolini, G. D'Orazio, C. Dal Bosco et al., "Recovery of cellulose acetate bioplastic from cigarette butts: realization of a sustainable sorbent for water remediation," *Sci. Total Environ.*, vol. 929, no. February, p. 172677, 2024, doi: 10.1016/j.scitotenv.2024.172677.

[14] B. Podkościelna, M. Gargol, M. Goliszek, T. Klepka, and O. Sevastyanova, "Degradation and flammability of bioplastics based on PLA and lignin," *Polym. Test.*, vol. 111, no. February, p.107622, 2022, doi: 10.1016/j.polymertesting.2022.107622.

[15] H. Hamidah, H. Muzaki, and N. Kholidah, "Rice flour potential as biodegradable plate (bioplastic) in terms of it's characteristics," *Stannum J. Sains dan Terap. Kim.*, vol. 3, no. 2, pp. 49–55, 2021, doi: 10.33019/jstk.v3i2.2382.

[16] A.B.D. Nandiyanto, M. Fiandini, R. Ragadhita, A. Sukmafitri, H. Salam, and F. Triawan, "Mechanical and biodegradation properties of cornstarch-based bioplastic material," *Mater. Phys. Mech.*, vol. 44, no. 3, pp. 380–391, 2020, doi: 10.18720/MPM.4432020_9.

[17] A. A. Fathima, M. Sanitha, L. Tripathi, and S. Muiruri, "Cassava (Manihot esculenta) dual use for food and bioenergy: A review," *Food Energy Secur.*, vol. 12, no. 1, pp. 1–26, 2023, doi: 10.1002/fes3.380.

[18] S.R.N.S.P. Mohidin, S. Moshawih, A. Hermansyah, M.I. Asmuni, N. Shafqat, and L.C. Ming, "Cassava (Manihot esculenta Crantz): A systematic review for the pharmacological activities, traditional uses, nutritional values, and phytochemistry," *J. Evidence-Based Integr. Med.*, vol. 28, 2023, doi: 10.1177/2515690X231206227.

[19] X. Ma, Y. Liu, J. Liu, J. Zhang, and R. Liu, "Changes in starch structures and in vitro digestion characteristics during maize (Zea mays L.) germination," *Food Sci. Nutr.*, vol. 8, no. 3, pp. 1700–1708, 2020, doi: 10.1002/fsn3.1457.

[20] M.D. Hazrol, S.M. Sapuan, E.S. Zainudin, and M.Y.M. Zuhri, “Corn starch (Zea mays) biopolymer plastic reaction in combination with sorbitol and glycerol,” *Polymer*, vol. 13, no. 2, pp. 1–22, 2021, doi: 10.3390/polym13020242.

[21] W. Abotbina, S.M. Sapuan, R.A. Ilyas, M.T.H. Sultan, M.F.M. Alkbir, S. Sulaiman et al., “Recent developments in cassava (Manihot esculenta) based biocomposites and their potential industrial applications: A comprehensive review,” *Materials (Basel).*, vol. 15, no. 19, 2022, doi: 10.3390/ma15196992.

[22] B. Bilate Daemo, D. Belew Yohannes, T. Mulualem Beyene, and W. Gebreselassie Abtew, “Biochemical analysis of cassava (manihot esculenta crantz) accessions in Southwest of Ethiopia,” *J. Food Qual.*, vol. 2022, 2022, doi: 10.1155/2022/9904103.

[23] T. Perroud, V. Shanmugam, R.A. Mensah, L. Jiang, Q. Xu, R.E. Neisiany et al., “Testing bioplastic containing functionalised biochar,” *Polym. Test.*, vol. 113, no. February, p. 107657, 2022, doi: 10.1016/j.polymertesting.2022.107657.