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Mechanical Properties, Morphology and Biodegradability of Biopolymer Composites Prepared from Thermoplastic Starch and Polybutylene Succinate Reinforced with Rice Straw Fiber

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Abstract

Plastic utilization is increasing extensively with an increase serious impacts to human health and environment due to difficult degradation of petroleum-based plastics. This study was designed to develop biodegradable plastics from thermoplastic starch (TPS) and polybutylene succinate (PBS) reinforced with rice straw fiber (RSF) and investigate mechanical and physical properties, morphology and biodegradability of these plastic to verify whether they can be used as a petroleum-based plastic replacement. The biopolymer composites were prepared from TPS and BTS reinforced with various RSF content of 0, 10, 15, 20, 25, 30, and 35 %. The composites were prepared in an internal mixer at a temperature of 145 °C for 15 min and molded in Hot Compression Molding at 145 °C. The tensile test, impact test, hardness test, flexural test along with morphological examination and biodegradability determination were performed. The results revealed that tensile strength and tensile modulus increased while elongation at break decreased with increasing RSF content. Also, increasing RSF content increased hardness and flexural modulus but decreased impact strength. Scanning electron micrographs demonstrated the composites uniform and compact surface structure, homogenously and effectively distribution, interfacial adhesion of the RSF within the matrix and decreased spaces in the matrix replaced by the RSF. The morphological characteristics of the composites were correlated with physical and mechanical properties. The biodegradability of the composites was influenced by the RSF content and duration of soil burial treatment. The biopolymer composites developed from TPS and PBS reinforced with RSF can be used as a replacement of petroleum-based plastics and provide the sustainable, biodegradable, low cost, and environmental friendly bioplastics, especially reinforced with 30 % RSF.

Keywords: Thermoplastic starch, Polybutylene succinate, Rice straw fiber, Physico-mechanical test, Scanning electron micrographs, Biodegradability

Introduction

Global utilization of petroleum - based plastics is high and rapid increasing in various fields, including agriculture, industry, construction and packaging [1]. They have a number of valuable properties with low production cost [2-4]. Unfortunately, it takes a very long time for degradation of these plastics [5]. In addition, extensive utilization of petroleum-based plastics results in dramatic plastic waste worldwide [6] and adverse impacts on the humans and environment. Development of bioplastics is one of the efforts to replace petroleum -

based plastics [6,7] and are used in variety fields, such as in biomedical systems which produce large amount of single-use plastic waste [8].

TPS is a homogeneous thermoplastic made from native starch by applying mechanical and thermal energy onto the starch granules to improve starch behavior [9-11]. It is utilized in various fields in commercial applications such as food packaging and disposable utensils [12,13]. Meanwhile, PBS is aliphatic polyester with excellent biodegradability and exhibits physico-mechanical characteristics similar to polyethylene [8,14]. It is one of the most alternative materials for the production of high-performance and environmentally friendly biodegradable plastic composites [15-19].

A number of researches are attempted to develop the properties and potential of TPS and PBS by adding other materials, reinforcing agents or filler [20]. Natural fibers are the most attractive reinforcing agents [21,22]. RSF have been added to TPS and PBS to provide higher advantages in connection with less health hazard, less energy consumption, biodegradability, low cost, and ecofriendly [23,24]. Rice straw is the rice plant residue after the rice grains are separated [25]. It is an excellent material with low cost, eco-friendliness and renewability. However, residue burning in rice is highly residue burned in Thailand [26]. Burning of rice straw emits pollutants such as PM 2.5 that causes negative impacts on air quality and human health [27-29]. Nevertheless, rice straw can be used as an alternative to substitute fossil source for various aspects, such as to improve the effects of synthetic plastics, enhance the physical and mechanical properties along with biodegradability of the bioplastics, and minimize the impact on environment and human health from stubble burning and eradicating of the synthetic plastic utilization, provide low-cost of plastic production with high-performance eco-friendly, and more sustainable, and value-added in the rice crop cultivation [30-34]. It is recommended as a potential eco-material for applications [35].

This study was aimed to study on the mechanical and physical properties, morphology and biodegradability of the biopolymer blends developed from TPS and PBS reinforced with various percentages RSF content.

Materials and methods

Materials

The TPS was produced by mixing glutinous flour and glycerol with a ratio of 70:30 %wt at 50 °C for 24 h and evaporated to eliminate the humidity. PBS, FZ91PM grade was obtained from PTT MCC-Biochem Co., Ltd. (Bangkok, Thailand). Rice straws were collected from a paddy field, after freshly harvesting during December 2023, in Maha Sarakham province, Northeast Thailand. TPS and PBS were provided as composite matrices, meanwhile RSF as reinforced material.

Preparation of RSF

The RSF were prepared according to a procedure previous described [36] with some modifications. In brief, the rice straws were shade dried for 2 days to eliminate humidity, cut into 0.5 - 1 cm in length, ground using an electrical grinder machine and sieved using mesh 50 - 120. The fiber size was based on optimum tensile, flexural and impact strength [21]. The obtained fibers were soaked in 10 % NaOH (sodium hydroxide) solution, with a ratio of 1 g of RSF in 10 mL of 10 % NaOH, and boiled at 100 °C for 2 h. The boiled fibers were washed thoroughly with abundance distilled water until the pH of fibers was pH7. The resulted fibers were oven dried at 50 - 70 °C for 24 h. Subsequently, they were ground into powder, as shown in **Figure 1**.

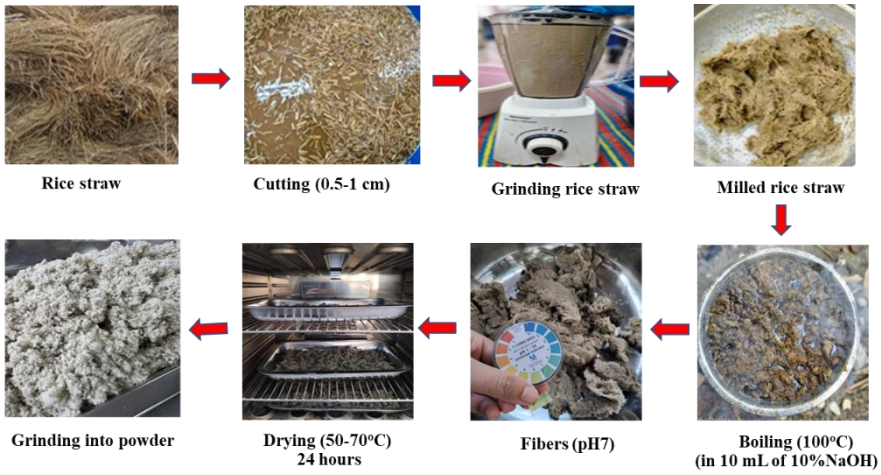

Figure 1 Schematic representation of the preparation steps to produce bioplastic composites from TPS and PBS reinforced with RSF.

Preparation of polymer composites

The polymer composites were prepared by mixing various ratios of TPS, PBS and RSF. The RSF was reinforced at 0, 10, 15, 20, 25, 30, and 35 %wt. Hence, the ratios among TPS: PBS: RSF were 80:20:00, 72:18:10, 68:17:15, 64:16:20, 60:15:25, 56:14:30 and 52:13:35, as shown in **Table 1**.

The TPS, PBS and RSF were thoroughly mixed in an internal mixer (MX 500-D75L90, **Figure 2(A)**) at 145 ± 10 °C for 15 min with a rotation speed of 50 rpm. Thereafter, the resulting polymer composites were ground using blender machine, oven dried at 50 °C for 24 h followed by molding in a Hot Compression molding (PR2D-W300L350 PM-WCL-HMI, **Figure 2(B)**). The molding process was performed at a condition of 145 °C, 5 min heating, 5 min molding, and 5 min cooling according to ASTM D2240, ASTM D790, ASTM D256, and ASTM D638 standard.

Table 1 Material ratios (TPS: PBS: RSF) for preparing biopolymer composites from TPS and PBS reinforced with RSF.

Bioplastic ratio	TPS (g)		PBS (g)	RSF	
	Glutinous rice (g)	Glycerol (g)		(g)	(%)
80:20:0	56	24	20	0	0
72:18:10	50.4	21.6	18	10	10
68:17:15	47.6	20.4	17	15	15
64:16:20	44.8	19.2	16	20	20
60:15:25	42	18.0	15	25	25
56:14:30	39.2	16.8	14	30	30
52:13:35	36.4	15.6	13	35	35

Figure 2 An internal mixer (MX 500-D75L90) (A) and a hot compression molding (PR2D-W300L350 PM-WCL-HMI) (B).

Investigation of physico-mechanical properties

The investigation of physico-mechanical properties including the tensile test, impact test, hardness test, and flexural test were carried out according to the conditional standard test method. The investigation of each sample was conducted for 5 replications under the same conditions to give an average value of the data and standard deviation.

Tensile test

The test was carried out according to ASTM D638, using a Universal Testing Machine, UTM (LR10 KN plus, ILOYD instrument) equipped with a 10 KN load cell, with testing speed of 5 mm/min, and gauge length of 50 mm. The testing was conducted at a condition of 30 ± 2 % relative humidity (RH) at room temperature. Tensile modulus, tensile strength and elongation at break were evaluated.

Impact test

The test was performed according to ASTM D256 standard using Izod impact tester (Instron 9050 - Motorized Mode) equipped with a weight of 2.7 J. The impact strength was investigated.

Hardness test

The hardness property was conducted following ASTM D2240 standard using a Shore Durometer GS-612/G-S-720, equipped with a weight of 5 Kg compression. The Shore D was investigated.

Flexural test

The flexural property was carried out according to ASTM D 790 standard using Universal Testing Machine (UTM) equipped with a 10 KN load cell with a span length of 48 mm. The flexural modulus was investigated.

Morphological examination

The microscopic morphology of the polymer composite specimens with a size of 3×13×2 mm^3 was examined using Scanning Electron Microscope (TM4000PlusSEM instrument). Prior to conducting scanning electron microscopy, the specimens were coated with gold dust at 5 mA for 300 s to prevent unnecessary charging before the SEM examination at an accelerating voltage of 10 kV. Examination was performed directly after processing. Micrographs were captured using a scanning electron microscope (SEM) on a SUT FE SEM (EHT = 3.00 kV, Mag = 100× WD = 9.9 mm, Signal A = SE2). This allowed us to examine the microstructure providing insights into the state of fiber adhesion and dispersion within the matrix.

Biodegradability determination

The biodegradability of composites refers to their ability to break down into CO_2, methane, microbial

cellular components, miscellaneous by-product, and water through naturally occurring degrading enzymes and microorganisms after disposal [37].

In the present study, a soil burial method, which the microorganisms break down the biopolymer chains and consume the materials was employed. The determination was performed according to ISO 846 standard. The composite specimens with a size of 13×30×3 mm^3 were oven dried at 70 °C for 24 h and then weighed (W_0). The known weight specimens were buried in aerated and moisture soil (50 - 55 % RH) for 7, 15, 30, 45, and 60 day-duration. After the setting duration, the specimens were unburied, cleaned, oven dried at 70 °C for 24 h and then weighed (Wt). The weighing was carried out until the constant weight was obtained. The biodegradability as a function of the weight loss (W_L) was calculated using the following equation:

$$W_L\ (\%) = [(W_0 - Wt)/W_0]\times 100 \quad (1)$$

Statistical analysis

Data were analyzed through the program SPSS. The results are represented as mean ± standard deviation (SD) for 5 replications of each sample. A one-way analysis of variance (one-way ANOVA) was conducted to assess if there was a statistically significant difference ($\alpha = 0.05$) in the properties of the samples. Duncan's New Multiple Range Test (DMRT) was employed in order to distinguish between each treatment. *P*-values of less than 0.05 ($p < 0.05$) were regarded as significant.

Results and discussion

Tensile strength

Tensile strength is the maximum force that can be held by the specimens when stretched or pulled before the material is broken. The tensile test revealed that the tensile strength of the biopolymer composites increased with increasing RSF content and ranged from 5.28 ± 0.25 to 16.76 ± 0.37 MPa, as presented in **Figure 3**. The 0 % RSF (80:20:00; TPS: PBS: RSF %wt) bioplastic composite exhibited the lowest tensile strength of 5.28 ± 0.25 MPa significantly ($p < 0.05$). Meanwhile, the 30 % RSF (56:14:30) composite exhibited the highest tensile strength (16.76 ± 0.37 MPa). The 35 % RSF bioplastic composite exhibited lower tensile strength when compared to the 30 % RSF composite, but this did not reach significance. Indicating 30 % RSF is the optimal content for tensile strength. The 30 % RSF bioplastic composite provided the highest adhesion and dispersion between the fibers and the polymer matrix. This occurring is confirmed by SEM images (**Figure 9**). Increasing RSF content to 35 % disrupted adhesion and dispersion between the fibers and the polymer matrix resulting in a decrease in tensile strength. Indicating, the tensile strength depends more on effective and uniform distribution [21]. The result is concomitance with the tensile strength of biodegradable composite containing waste cellulose fiber increases with increasing cellulose fiber content [38], the presence of graphene in the PP matrix led to increase in tensile strength of PP/graphene/glass fiber/EPDM nanocomposites [39], the addition of maple wood fibers substantially increases both flexural strength and modulus of the high-density polyethylene composites [40], and an addition of agricultural by-products of RSF slightly increases the compressive strength, while it significantly improves the tensile properties in concrete production [41]. Conversely, tensile strength of wood-plastic composites decreased with higher wood flour content [42], large amount of microcrystalline cellulose contents exhibit a divergent effect on the tensile properties of cellulose-PE blend [38] and copolymerization leads to a decrease in the tensile strength [43].

The controversial results among tensile strength of fibers can be influenced by the types of fibers as the tensile strength of basalt fiber is higher than that of the fibers from palm, bamboo and banana [44,45], the shape of the fibers, the direction of the fibers, the manufacturing process, the amount of fiber loading [46], the strength of the fibers [21], and the fiber length [47].

Basically, the RSF alone do not exhibit their full strength. However, an addition of rice straw nanofiber produces the tensile strength larger than the tensile strength of pure bioplastic [48] which confirm effectively used of RSF as reinforcement in a matrix of materials [21].

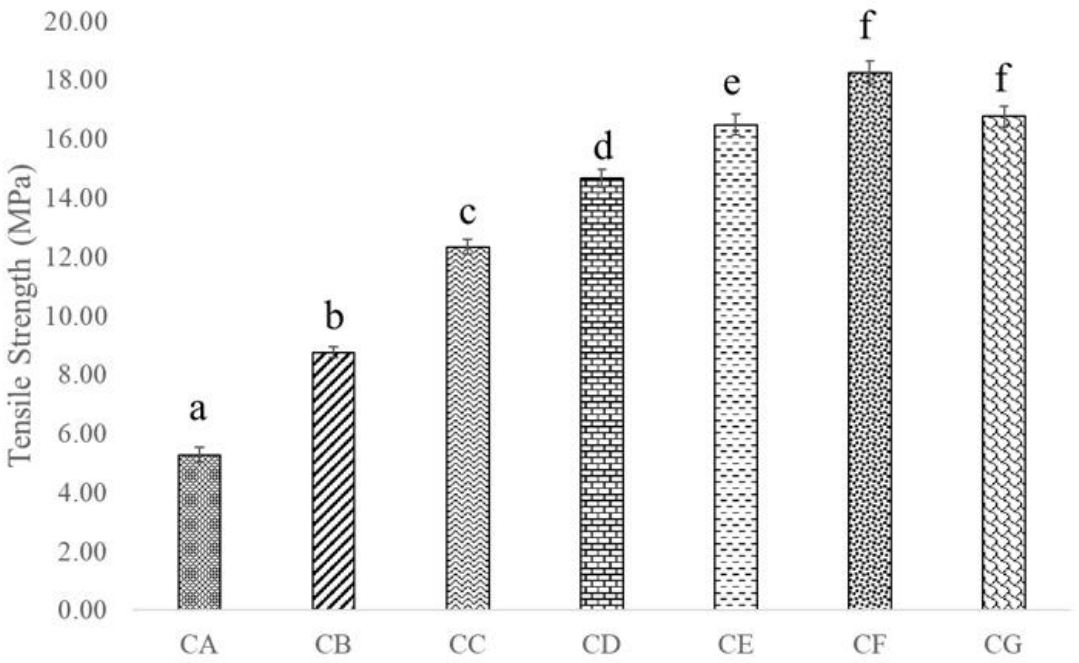

Figure 3 Tensile strength of the biopolymer composites developed from TPS and PBS reinforced with various % RSF; CA = 0 % RSF, CB = 10 % RSF, CC = 15 % RSF, CD = 20 % RSF, CE = 25 % RSF, CF = 30 % RSF, and CG = 35 % RSF, Data are shown as mean ± SD for 5 replications. Bars having different letters are significantly different at $p < 0.05$.

Elongation at break

Elongation at break is the percentage increase in length a material can stretch before breaking. Elongation at break is the ratio between changed length and initial length after breakage of the tested specimen. It expresses the capability of natural plant fiber to resist changes of shape before breaking. Elongation at break is important for several reasons, including material selection and predicting material behavior. Factors that can affect elongation at break include micro-fillers, plasticizers, additives, and processing techniques. A higher elongation at break combined with good tensile strength usually indicates a better-quality material.

The elongation at break of the composites prepared from TPS and PBS reinforced with RSF is shown in **Figure 4**. The elongation at break of the composites varied and ranged from 2.85 ± 0.29 to 31.91 ± 0.98 %. The lowest RSF content, 0 % RSF composite significantly ($p < 0.05$) exhibited the highest elongation at break by 31.91 ± 0.98 %. Conversely, the highest RSF content, 35 % RSF composite exhibited the lowest elongation at break of 2.85 ± 0.29 %. Indicating, increasing RSF contributed to decrease the polymer matrix and led to decrease in both elasticity and toughness of the polymer matrix. The similar result is in line with the addition of wood flour decreased elongation of wood-plastic composites [42]. In contrast, the addition of graphene in the PP matrix leads to increase in elongation at break [39] and increase in composition of the copolymerization leads to an increase in the elongation at break [43].

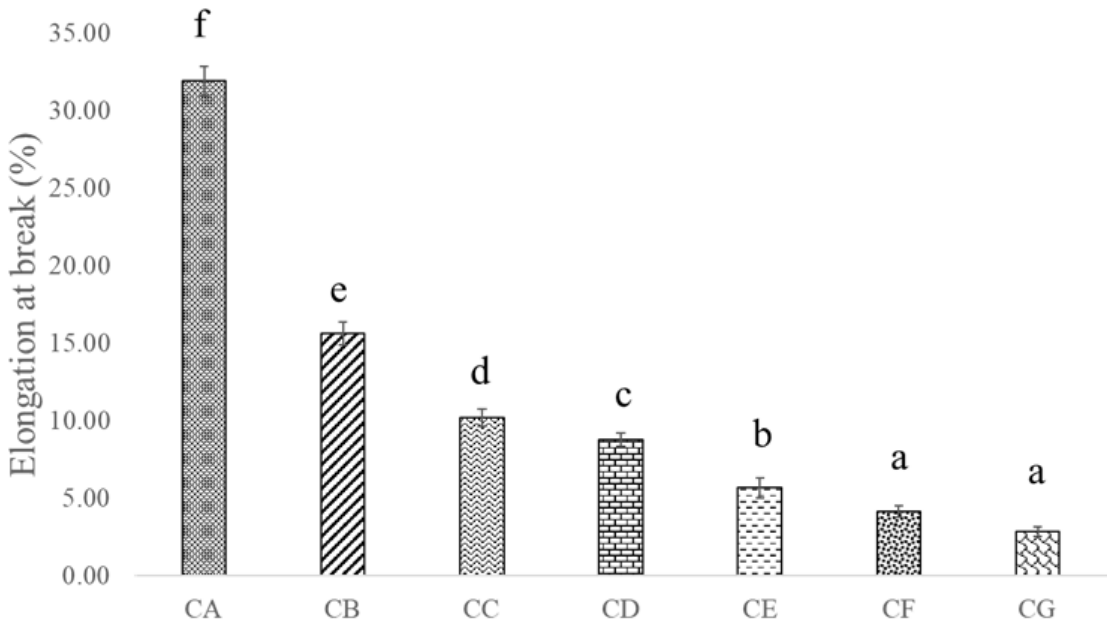

Figure 4 Elongation at break of the biopolymer composites developed from TPS and PBS reinforced with various % RSF; CA = 0 % RSF, CB = 10 % RSF, CC = 15 % RSF, CD = 20 % RSF, CE = 25 % RSF, CF = 30 % RSF, and CG = 35 % RSF, Data are shown as mean ± SD for 5 replications. Bars having different letters are significantly different at $p < 0.05$.

Tensile modulus

Tensile modulus, Young's modulus or elastic modulus is a measure of stiffness to elastic deformation under loading. It is one of the crucial performances for selecting materials in applications. A high tensile modulus property indicates that a material is very stiff or resists deformation. Adding fibers can cause material stiffer and requires more force for deformation under tension.

Tensile test as shown in **Figure 5** revealed that the composites prepared from various ratios of TPS and PBS reinforced with RSF exhibited the different tensile moduli and ranged from 184.36 ± 13.49 to 1463.92 ± 26.55 MPa. The 35 % RSF composite significantly ($p < 0.05$) exhibited the highest the tensile modulus of 1511.94 ± 41.94 MPa and was comparable to that of the 30 % RSF composite. Meanwhile the lowest tensile modulus (184.36 ± 13.49 MPa) was found in the 0 % RSF composite.

The RSF increased tensile modulus might due to the strong hardness RSF produced homogeneous dispersion along with the solid connection between the RSF and biopolymer matrix led to decrease elasticity and increase rigidity of the polymer matrix. Typically, the fibers themselves have a much higher modulus than the matrix material that they are embedded in. The higher addition of fibers increases higher tensile modulus, depending on various factors like fiber orientation and interfacial bonding. The fibers within a composite increase, the tensile modulus also increases proportionally.

The obtained result is in accordance with the tensile moduli of rice straw/polypropylene composites which increase by the increase in the amount of rice straw nanoparticles in the matrix [49]. In general, the composite consists of low stiffness matrix with high stiffness filler (i.e. fibers), hence increasing the volume of fibers, the stiffness increases. In addition, strain decreases when increasing fiber loading. This is a normal consequence of the increase of fibers volume which is having a low strain [50].

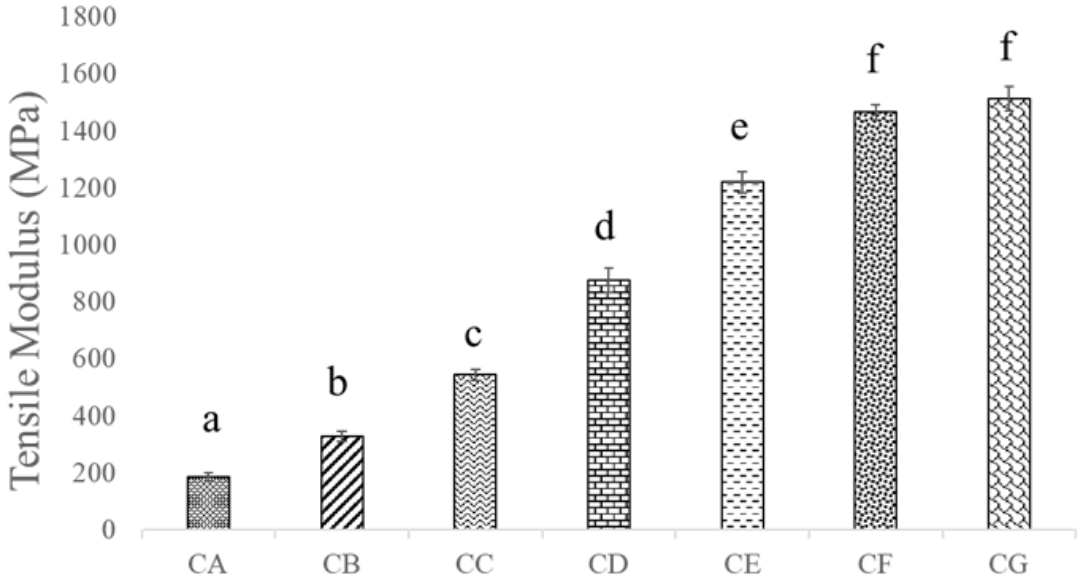

Figure 5 Tensile modulus of the biopolymer composites developed from TPS and PBS reinforced with various % RSF; CA = 0 % RSF, CB = 10 % RSF, CC = 15 % RSF, CD = 20 % RSF, CE = 25 % RSF, CF = 30 % RSF, and CG = 35 % RSF, Data are shown as mean ± SD for 5 replications. Bars having different letters are significantly different at $p < 0.05$.

Impact strength

Impact strength is ability of a material to resist fracture under stress applied. It is an important for the equipment selection [51]. It is a critical property for most plastic materials due to the impact strength is related to the product performance and influences product safety and liability. Moreover, addition of different fibers can contribute to composite impact strength.

The impact test revealed that the impact strength of the composites prepared from TPS and PBS reinforced with RSF decreased with increasing the RSF content. The highest impact strength (12.65 ± 0.55 kJ/m^2) was found in the 0 % RSF biopolymer composite. Meanwhile the lowest impact strength (3.58 ± 0.15 kJ/m^2) was found in the 35 % RSF biopolymer composite (**Figure 6**). This indicating the impact strength depends on RSF content (% RSF) inversely. This same result is occurred in the biodegradable polymers from polylactic acid, PBS, and RSFa studied by Thaipakdee and Chiaranpanpong [52] also is in line with the studies by Mahdy *et al.* [41], Boztoprak [42] and Ashori [49]. In contrast, the impact strength increases with increasing polymer ratio in the mix composition in the banana pseudo-stem filled unplastisized PVC composites [53], impact resistance of concrete increases by increasing RSF [41] and increasing copolymer composition leads to an increase in the impact strength of isodimorphic poly (butylene succinate-ran-butylene adipate) random copolymers component [43].

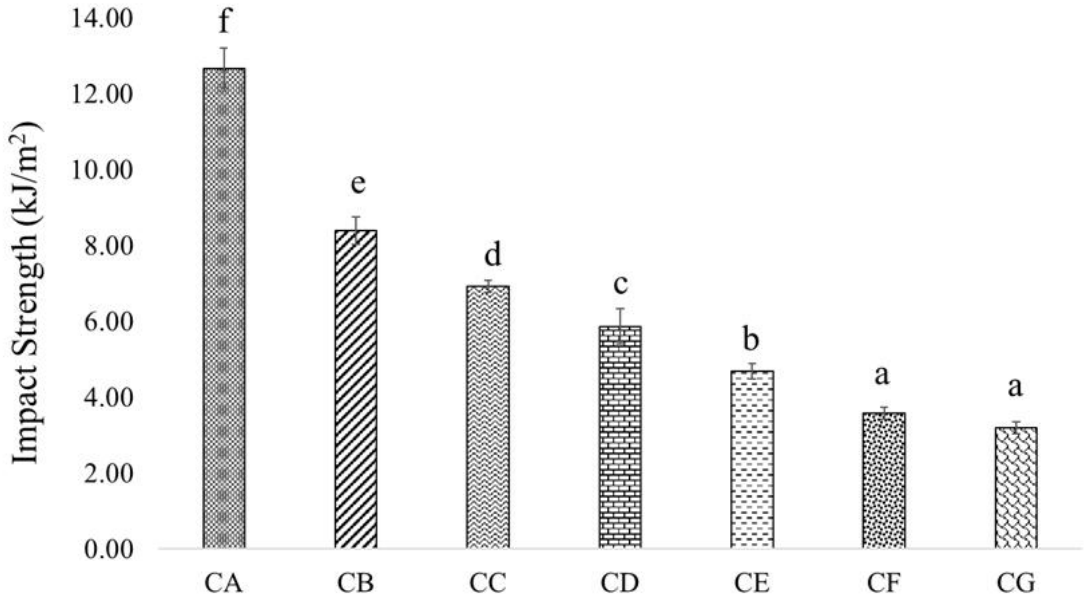

Figure 6 Impact strength of the biopolymer composites developed from TPS and PBS reinforced with various % RSF; CA = 0 % RSF, CB = 10 % RSF, CC = 15 % RSF, CD = 20 % RSF, CE = 25 % RSF, CF = 30 % RSF, and CG = 35 % RSF, Data are shown as mean ± SD for 5 replications. Bars having different letters are significantly different at $p < 0.05$.

Base on the 30 % RSF content exhibited well dispersion within the biopolymer matrix, which is attributed to challenges in achieving a uniform distribution as shown in SEM micrographs. Also, the matrix spaces were decreased resulting from the matrix was replaced by the RSF. The lower space leads to decrease elasticity of the polymer matrix resulting in a decrease in strength, which leads to increase brittleness of the composites that would be broken easily.

Hardness

Hardness is a mechanical property that the materials resist to permanent indentation or deformation, scratching, abrasion or cutting. It is one of the crucial factors in selecting materials for applications. Materials with higher hardness typically exhibit greater resistance. Hardness property produces material to have high resistance to variety kinds of shape change when any force is applied [54].

The hardness test demonstrated that the hardness of the composites significantly ($p < 0.05$) increased with increasing RSF content and ranged from 21.80 ± 0.65 to 73.28 ± 0.38. The highest hardness (73.28 ± 0.38) was found in the 35 % RSF composite, meanwhile the lowest hardness (21.80 ± 0.65) was found in the 0 % RSF composite (**Figure 7**). The RSF could increase the hardness of the composite might due to the homogenous penetration and dispersion along with a strong connection between the RSF and polymer matrix resulting in decreasing biopolymer matrix. Also, the RSF could lower softness and elasticity of the biopolymer matrix which leads to increase compressive strength. The similar result is observed in a study by Wertsungnoen and Puangklang [55]. The result is also in accordance with increasing wood flour content which leads to increase hardness of the wood-polymer composites [42] and a Shore D hardness increased in the wood-xHDPE composites [40].

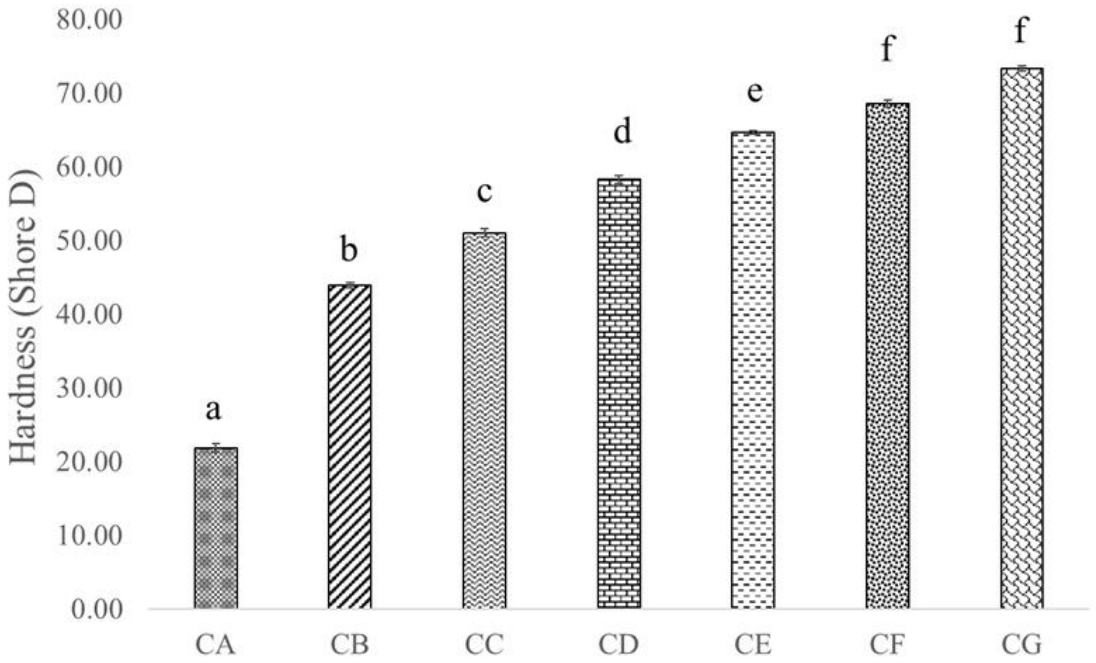

Figure 7 Hardness of the biopolymer composites developed from TPS and PBS reinforced with various % RSF; CA = 0 % RSF, CB = 10 % RSF, CC = 15 % RSF, CD = 20 % RSF, CE = 25 % RSF, CF = 30 % RSF, and CG = 35 % RSF, Data are shown as mean ± SD for 5 replications. Bars having different letters are significantly different at $p < 0.05$.

Flexural modulus

The flexural testing can measure the force required to bend a beam of plastic material and determines the resistance to flexing or stiffness of a material. It is also known as the bending modulus or modulus of elasticity in bending. Usually, the materials with higher flexural modulus display the more rigid and resistant to bending.

The flexural test (**Figure 8**) revealed that flexure modulus of the composites significantly ($p < 0.05$) increased with increasing % RSF content. The 30 % RSF composite exhibited the highest flexural modulus (624973.78 ± 73830.81 MPa). Meanwhile, the 0 % RSF composite exhibited the lowest flexural modulus. Indicating, the 30 % RSF content is the optimal content for the flexural modulus. Except 35 % RSF composite, the flexural modulus of the 35 % RSF composite was lower than that of the 30 % RSF composite. This might be due to the higher RSF content, the higher adhesion of the fibers leading to decrease flexural modulus (6 - 7) and increase replacement of the RSF within the matrix, consequently decrease toughness and elasticity of the composites. Possibility, RSF possess higher modulus compared to the polymer matrix, acting as effective stiffening agents. These fibers distribute more efficiently the applied forces within the composites, sharing a greater proportion of the applied stress, promoting a more uniform distribution of fibers, contributing to improved load transfer, and consequently increase flexural strength and modulus.

This result is in agreement with several studies which shown that increasing the fiber contents increase flexural moduli [41,43,49,53] but it is in contrast to the addition of wood flour which decreases flexural strength of wood-plastic composites [45].

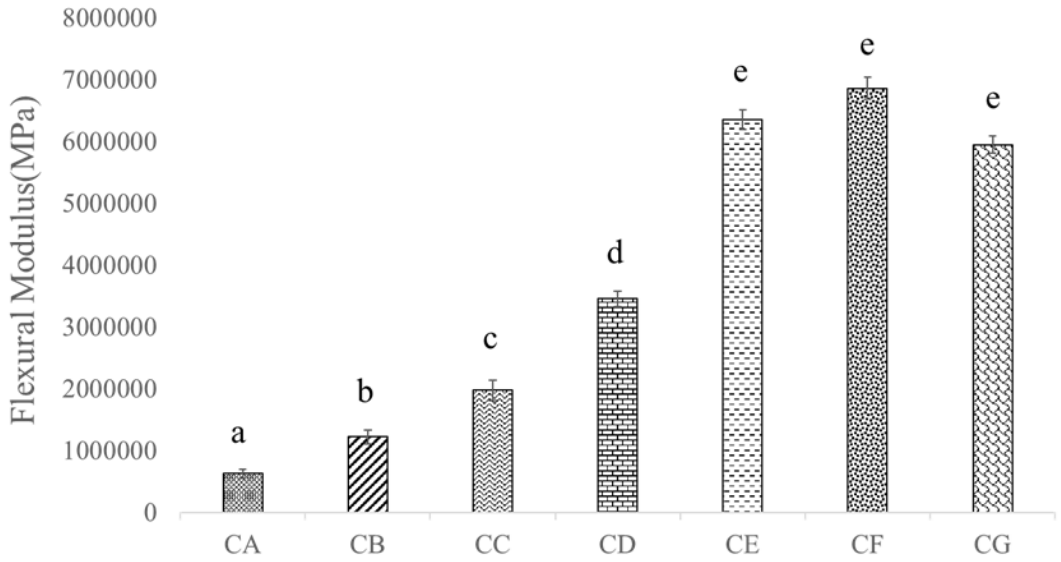

Figure 8 Flexural moduli of the biopolymer composites developed from TPS and PBS reinforced with various RSF; CA = 0 % RSF, CB = 10 % RSF, CC = 15 % RSF, CD = 20 % RSF, CE = 25 % RSF, CF = 30 % RSF, and CG = 35 % RSF, Data are shown as mean ± SD for 5 replications. Bars having different letters are significantly different at $p < 0.05$.

Taking together, the disputed results of the physical and mechanical properties of the reinforced composites are more likely resulted from the type, shape and length of the fibers, the volume fraction (percentage) of the fibers, and an effective adhesion and dispersion of the fibers within polymer matrix.

Morphological characteristics

Scanning Electron Microscopy (SEM) is a technique that can provide detailed images of the fiber distribution, interface bonding, and surface features within the composites. In this study, Scanning Electron Microscope (FESEM-FIB/EDS - Carl Zeiss/AURIGA) was employed to examine whether the different % RSF contents influenced the morphological characteristics of the composites. Distribution of the fibers in the matrix and RSF and matrix interfacial adhesion significantly impacts the overall performance of the composites.

The SEM images of the composites are shown in **Figure 9**. The 0 % RSF composite demonstrated the presence of the TPS and PBS granules (**Figure 9(A)**). The biopolymer composites reinforced with different % RSF content (**Figures 9(B) - 9(G)**) showed the spaces in polymer matrix were occupied by the RSF led to decreasing polymer matrix spaces. The higher % RSF contents, the lower spaces were observed. Due to the strong fiber structure increased the RSF and matrix interfacial adhesion. Therefore, increasing RSF increased the RSF and the polymer matrix interfacial adhesion. The higher stiffness of the fiber might make it is easier to better adhere to the fiber-matrix by their physical contact. The microscopic morphological characteristics of the biopolymer composites correspond to theirs physic-mechanical properties that trend to increase hardness and decrease elasticity of the composites due to rice straw consists of cellulose, hemicelluloses and lignin that are strongly intermeshed and chemically bonded in its structure [56]. The similar result is observed in the TPS and PLA composites studied by Jarakamjorn [57].

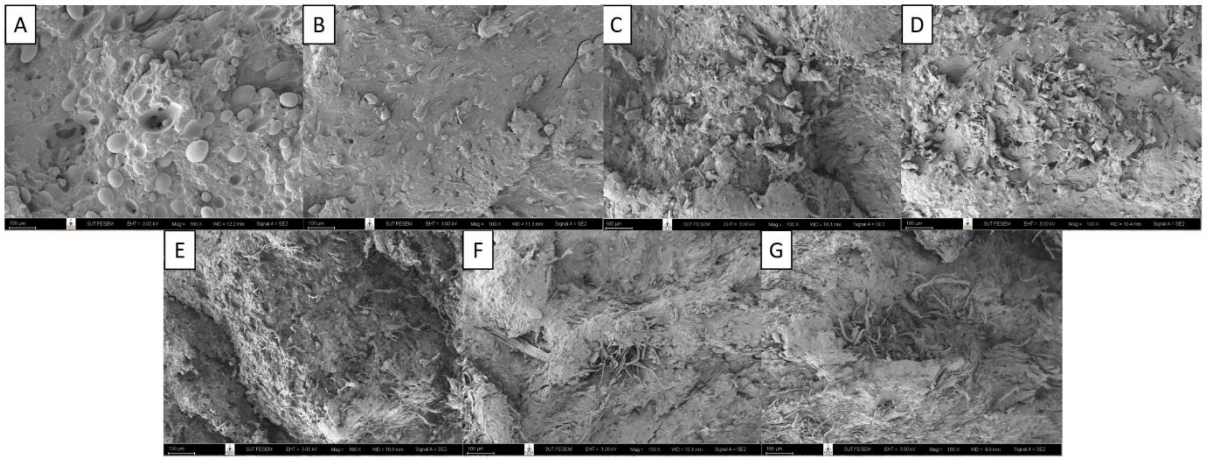

Figure 9 SEM image of the biopolymer composites developed from TPS and PBS reinforced with various % RSF; 0 % RSF (A), 10 % RSF (B), 15 % RSF (C), 20 % RSF (D), 25 % RSF (E), 30 % RSF (F), and 35 % RSF (G).

Biodegradability

Plastic waste has become a globally problem because most conventional plastic waste is difficult to degrade naturally. Environmentally degradable plastics can degrade through naturally occurring degrading enzymes and microorganisms [37]. The degradation of traditional plastics requires an unusually long time, which may lead to high cost, adverse effects to human and pollution. The serious problem of environmental pollution produced by the worldwide utilization of plastics impressed the research on biodegradable polymer composites and biodegradable plastics [58].

Biodegradable polymers and plastics are materials that are entirely decomposed when exposed and under attack to microorganism [38]. The biodegradability of biopolymers is influenced by various factors including their structure [58]. The degradable rate of biodegradation depends on both the biotic and abiotic factors including oxygen, humidity, temperature, and microorganisms [4]. The plastic degrading microorganisms are mainly fungi in the family Ascomycota, Basidiomycota, Microbotryomycetes, Tremellomycetes, Tritirachiomycetes [6]. Biodegradable plastics are decomposed through biological processes that produce natural compounds such as water, carbon dioxide, and organic matter. However, biodegradable plastics may provide microorganisms and microbial attachment sites than traditional plastics [60].

During degradation process, the bioplastics must biodegrade in specific environments such as in soil. Biodegradation products under aerobic conditions are carbon dioxide, water and biomass, while under anaerobic conditions methane, water and biomass are produced [35]. Decreasing rice straw particle size increases surface area and breaks the cell walls that make the organic substrate more readily available for microorganisms to decompose [61,62]. Normally, the enzyme activity of cellulolytic microbes in probiotics cause degradation and break of bonded lignin with the cell wall of rice straw [63]. Mostly, degradability of the RSF increases through the enzyme treatment [64].

In this study, the degradability of the biopolymer composites from TPS and PBS reinforced with RSF using biodegradation under environmental conditions, soil burial method (according to the ISO 846) and is estimated by the sample weight loss revealed that the biodegradation of the composites increased with increasing % RSF content and duration of burying. The weight loss of the composites increased significantly ($p < 0.05$) with increasing RSF content and duration of soil buried treatment. The 35 % RSF composite buried in soil for 60 days exhibited the highest weight loss, indicating the highest biodegradation. In contrast, the lowest biodegradation was found in the 0 % RSF composite buried in soil for 7 days (**Figure 10**). It could state that the RSF content of the composites should be a maximum of 35 %. However, this is not significant different from 30 %.

This result is in agree with high amount of cellulose is found to boost the rate of biodegradability of cellulose-PE composite films [38]. Addition of rice

straw nanofibers increases the degradability of bioplastics [48]. In addition, the integration of the apple waste into the bioplastic promotes biodegradability, evident from the maximum weight loss after 4 weeks of biodegradation test [65]. Furthermore, cellulose-based bioplastic possesses degradability as it is totally decomposed within 105 days after soil burring [35]. The RSF are enrich carbohydrate content, cellulose, hemicelluloses and lignin [55,66] that can be degraded and consumed by a variety of microorganisms [66], thus the higher RSF, the higher biodegradation occurred.

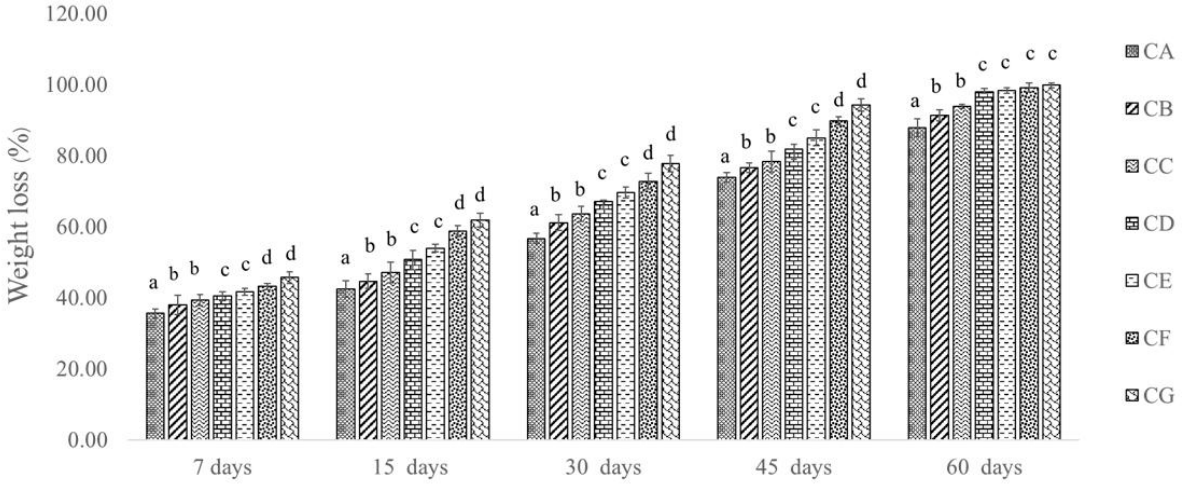

Figure 10 Weight loss (%) of the polymer composites developed from various ratios among TPS and PBS reinforced with RSF; CA = 0 % RSF, CB = 10 % RSF, CC = 15 % RSF, CD = 20 % RSF, CE = 25 % RSF, CF = 30 % RSF, and CG = 35 % RSF, Data are shown as mean ± SD for 5 replications. Bars having different letters are significantly different at $p < 0.05$.

Conclusions

This study was aimed to develop the biodegradable polymer composites with the high performance to replace the petroleum-based plastics. The composites were prepared from TPS and PBS reinforced with various % rice straw fibers (0, 10, 15, 20, 30, and 35 % weight percent) by melt-mixing method followed by compression molding process.

The biopolymer composite reinforced with rice straw fibers found to improve the mechanical properties, morphology and biodegradability of the composites. Increasing rice straw fiber increased tensile strength, tensile modulus, flexure modulus and hardness, but decreased elongation at break and impact strength of the composites. The composite reinforced with 30 % RSF provided the better crucial parameter requirement in terms of tensile/flexural strength/modulus, hardness, morphology and biodegradability. The study highlights the utilization of the rice straw fibers as a reinforcement in biopolymer plastics and can be adopted for application in agricultural field as the growing substrate, seedling bags/pots, and flower pots. Additionally, the achievement of this study possibly minimizes the impacts on environment and human health from rice stubble burning and eliminating the synthetic plastic utilization and also provides low-cost of bioplastic production with high-performance, biodegradable, eco-friendly, and more sustainable as well as value-added in the rice crop cultivation.

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