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Effect of the sorbitol to glycerol weight ratio and sugarcane bagasse concentration on the physicomechanical properties of wheat starch-based biocomposite

Mohammad Reza Abdollahi Moghaddam^{1*}, Mohammad Ali Hesarinejad^{2*} and Fatemeh Javidi³

Abstract

This study involved fabricating thermoplastic wheat starch-sugarcane bagasse biocomposites through melt mixing method. The effect of sugarcane bagasse concentration at 3 levels of 0 wt.%, 7.5 wt.% and 15 wt.% of wheat starch and sorbitol: glycerol weight ratio at 4 levels of 0:4, 1:4, 2:4 and 4:4 on their physicomechanical properties was evaluated. The results indicated that increasing both of the weight ratio of sorbitol to glycerol and the concentration of bagasse generally led to a significant increase in tensile strength and modulus, but a decrease in elongation at break and equilibrium moisture content. The biocomposite containing the weight ratio of sorbitol:glycerol of 0:4 and bagasse concentration of zero, had the lowest tensile strength (0.22 MPa) and tensile modulus (0.23 MPa), and the highest elongation at break (103.1%) and equilibrium moisture content (30.6%) and conversely The biocomposite containing the weight ratio of sorbitol:glycerol of 4:4 and bagasse concentration of 15, had the highest tensile strength (5.3 MPa) and tensile modulus (371.5 MPa), and the lowest elongation at break (1.5%) and equilibrium moisture content (20.6%). Moisture absorption was also studied using the Peleg model, which showed that samples with lower weight ratios of sorbitol to glycerol and lower bagasse concentrations had higher initial moisture absorption rates and greater moisture absorption capacity. The investigation of thermal behavior of the biocomposites by TGA analysis showed improved thermal stability of the biocomposites by increasing both of the sorbitol:glycerol weight ratio and the bagasse concentration. Finally, the FTIR spectrum revealed an increase in hydrogen and polar bonds in the biocomposites compared to pure starch.

Keywords Biocomposite, Natural fibers, Plasticizer, Thermoplastic starch

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Introduction

Plastic waste, such as disposable packaging containers made of non-biodegradable plastics, is a significant contributor to environmental pollution. As of 2015, approximately 6300 Mtons of plastic waste had been generated, around 9% of which had been recycled, 12% was incinerated, and 79% was accumulated in landfills or the natural environment. If current production and waste management trends continue, roughly 12,000 Mtons of plastic waste will be in landfills or in the natural environment by 2050 [1]. It is well-known that the improper disposal of non-biodegradable plastic waste has led to pollution of soil and groundwater [2]. On the other hand, the primary sources used to produce petroleum-based plastics are finite and non-renewable. Consequently, there is a growing public demand for the production of fully biodegradable or compostable disposable packaging containers, which can significantly diminish the burden on waste management system. To this end, a significant amount of research has been dedicated to discovering alternative solutions, such as the use of plastics derived from renewable, bio-based, and biodegradable resources [3, 4]. A viable solution to this problem is the use of films and containers that possess a high degree of biodegradability, which can be obtained from raw materials sourced from agricultural resources. This approach offers an additional benefit of reducing agricultural waste and providing a new application for such waste, thereby preventing the disposal of materials that could otherwise be recycled or composted.

Biodegradable polymers obtained from renewable natural sources, such as polysaccharides and proteins, are extensively researched due to their economic feasibility, availability, and shorter production process. Among these, starch is particularly attractive compared to other natural biopolymers, because it is readily available, relatively inexpensive, and can be mass-produced easily [5]. Native starch has to be modified by plasticizers to be melt-processed as a thermoplastic material, because the melting temperature (Tm) of pure dry starch is close to 220-240 °C, which is higher than its degradation temperature (220 °C) [6, 7]. When subjected to the melt mixing process with non-volatile plasticizers and without water (or minimal amounts of water), native starch can be converted into thermoplastic starch through mechanical and thermal processes in an equipment, such as an extruder

or an internal mixer. The resulting thermoplastic starch can be formed into films and sheets for a variety of purposes, including the creation of packaging. These thermoplastic starch-based materials are among the most affordable thermoplastic materials available for disposable applications, particularly in the production of disposable food packaging containers [8] and plastic films used in agriculture [9]. While films and containers made from only various types of thermoplastic starch offer good oxygen and carbon dioxide barrier properties, they tend to have weak tensile strength and modulus, moderate elongation at break, high water vapor permeability, and are sensitive to ambient humidity. This sensitivity to moisture can cause a loss of mechanical integrity and barrier properties of them in environments with moderate to high humidity levels and make them unsuitable for packaging applications [10-13]. Various methods have been employed to address the aforementioned limitations, such as chemically modifying starch, melt mixing of thermoplastic starch with non-biodegradable petroleum-based polymers or biodegradable polymers, blending it with fillers and reinforcing materials, and creating nanocomposites based on thermoplastic starch [14].

Incorporating bioresourced materials such as agroindustrial wastes as fillers or reinforcements in the composites formulation based on biodegradable polymers is a beneficial approach to decrease the cost of the final product while maintaining or enhancing its eco-friendliness [3]. Previous research has demonstrated that adding lignocellulosic fillers to the starch matrix has increased its tensile strength while simultaneously decreased its flexibility, water vapor permeability, and sensitivity to moisture [15–19].

Sugarcane bagasse, which is a type of lignocellulosic material, has been utilized as a reinforcing filler for creating composites based on both petroleum-based and biodegradable polymers [20-22].

One research project involved preparing biocomposites of thermoplastic starch and treated sugarcane bagasse fibers with soda, and their morphological properties, thermal stability, X-ray diffraction, and water absorption were analyzed [23]. In addition, another study aimed to create plastic film for food packaging using a potato peels starch-sugarcane bagasse biocomposite and examining its tensile properties, oxygen barrier, and procity [24]. The impact of gamma ray radiation on sugarcane bagasse fibers and how it affects the physical and mechanical properties of waste polypropylene-treated sugarcane bagasse composite were also evaluated [20]. Up until now, no studies have looked into how the weight ratio of sorbitol to glycerol as a plasticizer affects the physical and mechanical properties of thermoplastic starchsugarcane bagasse biocomposites. To address this, we conducted a study, where we prepared thermoplastic wheat starch–sugarcane bagasse biocomposites using a melt mixing method, and assessed how varying the concentration of sugarcane bagasse and the weight ratio of sorbitol to glycerol affected their physical and mechanical properties.

Materials and methods

Materials

Wheat starch was obtained from Toos Nemune Glucose Company (Mashhad, Iran). According to the company's statement, It had 10.1 wt.% moisture, a trace amount of fat, and a maximum of 0.8 wt.% protein and 0.3 wt.% ash. Glycerol and sorbitol with laboratory purity were purchased from Dr. Mojallali Company (Tehran, Iran). Sugarcane bagasse was obtained from a commercial company located in Ahvaz (Iran) and according to the company's statement, its composition by weight was cellulose, 44.7%, hemicelluloses, 26.5%, lignin, 21.2%, ash, 2.9%, moisture, 3.8% and wax, 0.9%. Commercial zinc stearate as an external lubricant was donated by Behzist Danesh Narvan Co. (North East Food Tech Park, Mashhad, Iran). Magnesium Nitrate was supplied by Merck Company (Germany).

Methods

Preparation of thermoplastic wheat starch-sugarcane bagasse biocomposite

Sugarcane bagasse fibers were washed well with lukewarm water and after dewatering, they were dried in a vacuum oven at 80 °C for 5 h. Then, the dried bagasse fibers were ground and passed through a standard sieve with 60 mesh and the obtained powder was kept in polyethylene bags until further process. To prepare biocomposite sheets, to investigate the effect of the weight ratio of sorbitol to glycerol and sugarcane bagasse concentration on their physicomechanical properties, wheat starch was first dried in a vacuum oven at 80 °C for 5 h. After cooling in a desiccator containing silica gel, it was mixed well with 2 phr zinc stearate and a mixture of glycerol and sorbitol plasticizers (40% by weight of thermoplastic starch) with different weight ratios of sorbitol:glycerol (S:G) equal to 0:4, 1:4, 2:4 and 4:4 manually. The resulting mixture was kept in aluminum bags for 24 h to penetrate the glycerol into the starch granules. The mixture obtained was mixed well with different levels of bagasse powder (0%, 7.5% and 15% by weight of starch) manually and then melt mixed by an internal mixer (Iranian Polymer and Petrochemical Research Institute, Tehran) with the blades speed of 60 rpm at 130 °C for 10 min. The obtained biocomposite was cooled and then milled. A certain amount of the obtained biocomposite powder was placed in a steel mold with dimensions of $1 \times 200 \times 200$

Page 4 of 12

mm³, and then it was preheated with a 30-ton manual hot press machine (SPH-300, Santam Company, Tehran, Iran), for 3 min at 140 °C. Then, it was pressed at 35 MPa and 140 °C for 7 min. After that, it was cooled to ambient temperature by the same device for 3 min at the same pressure. The obtained sheet was separated from the mold by a cutter. The resulting sheet was placed in a desiccator containing a saturated solution of Magnesium Nitrate for 7 days to be conditioned in 53% RH at 25 °C. The samples were punched from the mentioned sheets by a 2-ton manual press machine (SPH-20, Santam Company, Tehran, Iran) to perform tensile tests. The formulation of thermoplastic wheat starch–sugarcane bagasse biocomposites is tabulated in Table 1.

Tensile properties

The tensile properties of the samples, including the tensile strength and elongation at break, were measured using an Universal Test Machine (STM-5, Santam Company, Tehran, Iran) and according to the ASTM D638-02a (2002) standard [25]. A load cell of 200 N was used, and the distance between the two jaws was 115 mm and the upper jaw movement speed was set at 10 mm/min. The slope of the linear region of the stress–strain curve was calculated as the tensile modulus and the average values of the obtained tensile properties were reported. The test was performed in 5 repetitions.

Moisture absorption

The equilibrium moisture content of the samples was measured according to the method of Angles and Dufresne (2000) with some modifications [26]. A sample with dimensions of $10 \times 40 \text{ mm}^2$ was separated from a

Table 1 Formulation of thermoplastic wheat starch-sugarcanebagasse biocomposites

Sample	Code	S:G weight ratios	Sugarcane bagasse concentration (%)
1	4g-0B	0:4	0
2	4g-1s-0B	1:4	0
3	4g-2s-0B	2:4	0
4	4g-4s-0B	4:4	0
5	4g-75B	0:4	7.5
6	4g-150B	0:4	15
7	4g-1s-75B	1:4	7.5
8	4g-1s-150B	1:4	15
9	4g-2s-75B	2:4	7.5
10	4g-2s-150B	2:4	15
11	4g-4s-75B	4:4	7.5
12	4g-4s-150B	4:4	15

biocomposite sheet with a thickness of 1 mm and dried in an oven with an air circulation system at a temperature of 105 °C for 5 h and its weight was measured with an accuracy of 0.0001 g (W_0). Then, the sample was conditioned in a desiccator containing a saturated solution of NaCl with a RH 75% at 25 °C for 9 days. The weight of the sample was measured every day until it reached a constant weight (W). The test was done with 4 repetitions. The equilibrium moisture content of the samples was calculated from the following equation:

$$EMC = \left(\frac{W - W_0}{W_0}\right) \times 100 \tag{1}$$

In addition, to predict the moisture absorption behavior of biocomposites, the moisture absorption values at different times were fitted by Peleg's mathematical model [42] (Eq. 2):

$$M(t) = M(0) + \left(\frac{t}{\mathbf{k}\mathbf{1} + (\mathbf{k}\mathbf{2} \times t)}\right)$$
(2)

where M(t) is the moisture content at time t (g_{water}/g_{solids}), M(0) is the initial moisture, and k₁ and k₂ are Peleg rate constant and Peleg capacity constant, respectively.

Fourier transform infrared spectroscopy (FTIR spectroscopy)

Starch, sugarcane bagasse, 4g-1s and 4g-1s-150B samples were properly blended with potassium bromide (KBr) powder and the resulted mixture was pressed into a small tablet. FTIR spectra was recorded using a FTIR spectrometer Paragon 1000 (Perkin Elmer, Akron, OH, USA) in the transmittance mode, with the resolution of 4 cm⁻¹ in the range of 4000–400 cm⁻¹ wavenumber.

Thermogravimetric analysis (TGA)

The thermal stability of thermoplastic wheat starch samples without sugarcane bagasse fiber and glycerol plasticized wheat starch filled with different amounts of sugarcane bagasse fiber was assessed using a thermogravimetric analyzer (TGA/DSC1, Mettler Toledo, Switzerland). TGA was performed at a temperature rate of 10 °C/min from 23 °C to 600 °C under N₂ atmosphere.

Preparation of food packaging container from biocomposite sheet

Using the sample sheet 4g-2s-150B, a food packaging container in the form of a plate was prepared by a laboratory vacuum thermoforming device (Adrina model, Sizan Smart Machines, Kashhan, Iran).

Statistical analysis

Minitab software version 18 was used for statistical analysis of data. The effect of sugarcane bagasse concentration and weight ratio of sorbitol to glycerol on the physicomechanical properties of biocomposites was investigated with a factorial test in a completely randomized design. Means were compared with Tukey's method and at the 5% probability level (P<0.05). Each measurement was replicated at least 3 times.

Results and discussion

Tensile properties

The changes in tensile strength, tensile modulus and elongation at break of biocomposites by changing the weight ratio of sorbitol to glycerol and the concentration of sugarcane bagasse are shown in Fig. 1. As can be seen, for each concentration of sugarcane bagasse, with an increase in the weight ratio of sorbitol to glycerol, the tensile strength and tensile modulus of the biocomposite increased (with the exception of the tensile strength of the biocomposite with bagasse concentration of 7.5) and its elongation at break was accompanied by a decrease. These changes were significant in most cases (P < 0.05). For example, the biocomposite containing the weight ratio of sorbitol:glycerol of 0:4 and bagasse concentration of 15, had a tensile strength of 1.4 MPa, tensile modulus of 12.6 MPa, and elongation at break of 13.5%, and the sample containing sorbitol:glycerol weight ratio of 4:4 and bagasse concentration of 15 had tensile strength, tensile modulus and elongation at break of 5.3 MPa, 371.5 MPa, and 1.5%, respectively. Sorbitol, having a larger molecular length and a higher molecular weight than glycerol, and having more structural similarity to the glucose unit of starch than glycerol, is able to create more entanglement with starch chains, which results in more interactions with starch chains than glycerol. It causes less mobility and flexibility and more stiffness of the starch chains, which is associated with an increase in the tensile strength and tensile modulus and a decrease in the elongation at break of the biocomposite [27]. In similar studies, thermoplastic corn starches containing 42 wt.% of plasticizer were prepared and investigated the effect of different weight ratios of sorbitol:glycerol (0:42, 14:28, 28:14, and 42:0) on their tensile properties. The obtained results showed that with the increase in the weight ratio of sorbitol to glycerol, the tensile strength and tensile modulus increased and the elongation at break was accompanied by a decrease [28]. Similar results have been reported by other researchers for being more rigid and less flexible of thermoplastic films based on various types of starch and hydrocolloids plasticized with sorbitol compared to glycerol [29-32].

In addition, as shown in Fig. 1, for each weight ratio of sorbitol to glycerol, with the increase in bagasse concentration, the tensile strength and tensile modulus of the biocomposite increased, and the elongation at break was accompanied by a decrease. These changes were significant in most cases (P < 0.05). As an example, the biocomposite with the weight ratio of sorbitol:glycerol of 1:4 and bagasse concentration of 7.5, had tensile strength, tensile modulus and elongation at break of 1.7 MPa, 7.1 MPa and 28.7%, respectively, and the sample with the weight ratio of sorbitol:glycerol of 1:4 and bagasse concentration of 15 had tensile strength, tensile modulus and elongation at break of 2.4 MPa, 27.6 MPa and 9.6%, respectively.

Adding hard bagasse fibers (having 44.7 wt.% cellulose, 26.5 wt.% hemicellulose and 21.2 wt.% lignin) to the semi-flexible matrix of thermoplastic starch increases the rigidity and reduces the flexibility of the biocomposite [33]. In previous studies, biocomposites based on thermoplastic corn starch reinforced with bagasse fibers treated with water-ethanol solution were prepared. According to the results with the increase of bagasse concentration up to 15 wt.% of starch, the tensile strength and tensile modulus increased and the elongation at break of the biocomposite decreased [34]. Other researchers have also reported similar results regarding the changes in tensile properties of biocomposites based on different types of thermoplastic starch filled with bagasse or other lignocellulosic fillers with increasing filler concentration [33, 35, 36].

Equilibrium moisture content and kinetics of moisture absorption

Changes in the equilibrium moisture content of biocomposites according to the weight ratio of sorbitol to glycerol and the concentration of bagasse are shown in Fig. 2. For each weight ratio of sorbitol to glycerol, with increasing bagasse concentration, the equilibrium moisture content of biocomposite decreased. For example, the biocomposite with the weight ratio of sorbitol:glycerol of 1:4 and the bagasse concentration of 7.5 had an equilibrium moisture content of 24.5%, and the biocomposite with the weight ratio of sorbitol:glycerol of 1:4 and the bagasse concentration of 15 had the equilibrium moisture content of 22.5%. The reason for the decrease in the equilibrium moisture content of the biocomposite with the increase in bagasse concentration can be attributed to the lower hygroscopicity of bagasse compared to starch due to the presence of waxy materials and lignin on the surface of bagasse fibers [37]. In addition, the strong hydrogen interactions between bagasse and starch reduce the capacity of the starch matrix to interact with water and absorb moisture [38, 39]. It has been reported previously that the water absorption of biocomposite based on thermoplastic potato starch reinforced with bagasse decreased steadily with the increase of bagasse concentration up to 15 wt.% of starch, so that thermoplastic potato starch had water absorption of 20.3% and



Fig. 1 Changes in the tensile strength (**a**), tensile modulus (**b**), and elongation at break (**c**) of biocomposites containing different sorbitol-to-glycerol weight ratios and different concentrations of bagasse. Different small letters on the bars with the same bagasse concentration indicates the significance of the effect of the weight ratio of sorbitol to glycerol on the measured parameter of the biocomposite. Different big letters on the bars with the same weight ratio of sorbitol to glycerol indicates the significance of the effect of bagasse concentration on the measured parameter of the biocomposite



Fig. 2 Changes in the equilibrium moisture content of biocomposites containing different weight ratios of sorbitol to glycerol and different concentrations of bagasse. Different small letters on the bars with the same bagasse concentration indicates the significance of the effect of the weight ratio of sorbitol to glycerol on the measured parameter of the biocomposite. Different big letters on the bars with the same weight ratio of sorbitol to glycerol indicates the significance of the effect of bagasse concentration on the measured parameter of the biocomposite.

biocomposite with 15 wt.% bagasse had water absorption of 9.1% [37]. Other similar results regarding the reduction of water absorption or the equilibrium moisture content of biocomposites based on various types of thermoplastic starch filled with bagasse or other lignocellulosic fillers by increasing the concentration of fillers have been reported by other researchers [40–44].

In addition, as shown in Fig. 2, the equilibrium moisture content of the biocomposite decreased with the increase in the weight ratio of sorbitol to glycerol in each bagasse concentration (P > 0.05). It was observed that the biocomposite sample with the weight ratio of sorbitol:glycerol 0:4 and the bagasse concentration of 7.5 had an equilibrium moisture content of 27.8% and the biocomposite with the weight ratio of sorbitol:glycerol 4:4 and the bagasse concentration of 7.5 had an equilibrium moisture content of 21%. The reason for the decrease in the equilibrium moisture content of thermoplastic starch with the increase in the weight ratio of sorbitol to glycerol is due to the greater structural similarity of sorbitol to the glucose unit of starch compared to glycerol and the greater number of hydroxyl groups of sorbitol compared to glycerol (6 vs. 3). This leads to the increase of interactions and intermolecular forces between starch and sorbitol compared to glycerol in thermoplastic starch, which in turn reduces the capacity of starch and sorbitol to absorb water and hence reduces the hydrophilicity of thermoplastic starch plasticized with sorbitol [27, 44]. In another study, the effect of different weight ratios of sorbitol:glycerol (0:30, 10:20, 20:10 and 30:0) on the equilibrium moisture content of thermoplastic corn starches containing 30 wt.% plasticizer was investigated. Similar to the present study, they also reported that the equilibrium moisture content of thermoplastic starch decreased with the increase in the weight ratio of sorbitol to glycerol [27]. Other similar results have been reported by other researchers for the lower equilibrium moisture content or water absorption of thermoplastic films based on starch and other hydrocolloids plasticized with sorbitol compared to glycerol [30, 31, 45, 46].

The moisture absorption curves of biocomposites are shown in Fig. 3. As can be seen, for all samples, the rate of moisture absorption was higher at the beginning of the test, and with the passage of time, less water was absorbed, and finally the moisture content reached its equilibrium and constant value. This behavior may be attributed to more hydroxyl groups present on starch and plasticisers molecules at the beginning of the test for interacting with water molecules. The parameters of the Peleg model $(k_1 \text{ and } k_2)$ as well as coefficient of determination (R^2) and Root mean square error (RMSE) for the samples are tabulated in Table 2. The values of R^2 and RMSE indicate that the Peleg model describes well the behavior of moisture absorption with time for all samples. The constant k_1 is related to mass transfer and a lower k₁ indicates a higher initial moisture absorption rate. Constant k₂ corresponds to the maximum moisture absorption capacity and lower k2 indicates more moisture



Fig. 3 Moisture absorption curves of biocomposites

 Table 2
 Peleg model parameters for biocomposites with different formulations

Formulations	Parameters					
	k ₁	k ₂	R ²	RMSE		
4g-0B	1.652	0.024	0.99	0.884		
4g-1s-0B	2.165	0.025	0.99	0.642		
4g-2s-0B	3.056	0.026	0.99	0.237		
4g-4s-0B	3.721	0.028	0.99	0.764		
4g-75B	2.080	0.026	0.99	0.702		
4g-1s-75B	2.617	0.027	0.99	0.595		
4g-2s-75B	3.124	0.030	0.99	0.230		
4g-4s-75B	5.383	0.031	0.99	0.667		
4g-150B	2.104	0.028	0.99	0.662		
4g-1s-150B	2.977	0.029	0.99	0.351		
4g-2s-150B	3.239	0.032	0.99	0.330		
4g-4s-150B	5.768	0.034	0.99	0.917		

absorption capacity. As can be seen in Table 2, biocomposites with a lower weight ratio of sorbitol to glycerol had lower k_1 and k_2 values. This shows that these biocomposites had a higher initial moisture absorption rate and a higher moisture absorption capacity, so that 4g-0B had k_1 and k_2 of 1.652 h/(g_{water}/g_{solid}) and 0.024 g_{solid}/g_{water} ,

respectively, and 4g-4s-0B had k_1 and k_2 of 3.721 h/(g_{water}/g_{solid}) and 0.028 g_{solid}/g_{water} , respectively. In addition, 4g-150B had k_1 and k_2 of 2.004 h/(g_{water}/g_{solid}) and 0.028 g_{solid}/g_{water} , respectively, and 4g-4s-150B had k_1 and k_2 of 5.768 h/(g_{water}/g_{solid}) and 0.034 g_{solid}/g_{water} , respectively.

Other scientists have investigated the effect of replacing glycerol with sorbitol on the moisture absorption behavior of agar-based films at a RH of 53%. They reported that the film plasticized by glycerol, plasticizer mixture with the weight ratio of glycerol:sorbitol 4:1, and sorbitol had k_1 and k_2 (0.07 and 0.06), (0.09 and 0.06) and (0.83 and 0.1), respectively [47].

It can also be seen in Table 2 that the biocomposites with lower bagasse concentration had lower k1 and k2 values, which indicates that these biocomposites had higher initial moisture absorption rate and higher moisture absorption capacity. In such a way that 4g-0B had k₁ and k₂ 1.652 and 0.024, and 4g-150B had k₁ and k₂ 2.104 and 0.028, respectively. In addition, 4g-2s-0B sample had k_1 and k_2 of 3.056 and 0.026, respectively, and 4g-2s-75B sample had k₁ and k₂ of 3.124 and 0.030, respectively. According to the results obtained for composite films based on thermoplastic cassava starch containing cassava fibers, it was reported that the film without cassava fibers had k_1 and k_2 of 17.7 and 2.83, respectively. The film with the content of cassava fibers of 10 wt.% of starch also had k_1 and k_2 of 25.10 and 4.45, respectively. The film with the cassava fibers content of 20 wt.% of starch had k₁ and k₂ of 39.80 and 4.92, respectively [48].

FTIR spectroscopy

The FTIR spectroscopy diagram of starch, bagasse, thermoplastic starch (4g-1s-0B), and biocomposite (4g-1s-150B) samples is shown in Fig. 4. FTIR spectrum for thermoplastic starch has been reported by many researchers [49, 50]. The diagrams show the type of bonding of the materials in the composite. Since the chemical structure of the major part of starch and bagasse fiber is similar and consists of glucose, the observed peaks are very similar and no new peak was observed. The observed peaks in the range of 1020–1040 cm⁻¹ are related to the C–O bonds of the C–O–C group in the anhydroglucose ring, and the peaks in the range of 1075-1155 cm⁻¹ are related to the C-O bonds of the C-O-H group of glucose. In addition, the range of wavenumbers 1400-1450 cm⁻¹ is related to O-H bonds. The peak around 1650 cm^{-1} is related to water bonds in starch. In addition, a small peak at 1720 cm⁻¹ has appeared in the biocomposite spectrum, which may be due to the stretching of C=O acetate groups in hemicellulose and cellulose fiber [51, 52]. Wavenumbers in the range of $2840-3000 \text{ cm}^{-1}$ indicate C-H bonds. The broad peak observed in the wavenumbers 3200–3500 cm⁻¹ is related to the hydrogen



Fig. 4 FT-IR spectrum of bagasse, starch, 4g-1s-0B and 4g-1s-150B

bonds of the hydroxyl group. These hydroxyl groups have the ability to create intramolecular and intermolecular hydrogen and polar bonds. When the amount of these types of polar and hydrogen bonds in a substance increases, the wavenumbers related to these bonds tend slightly towards lower wavenumbers. These types of bonds can affect the physical, thermal, and mechanical properties of biocomposites [35, 53]. These wavenumbers can be seen in Fig. 4. As can be seen, the wavenumber of the hydroxyl group has decreased from 3355 cm⁻¹ for native starch to 3349 cm^{-1} for thermoplastic starch, and then to 3343 cm⁻¹ for biocomposite. This indicates the increase of hydrogen and polar bonds between bagasse, wheat starch and plasticizers in biocomposite. In addition, by comparing native and thermoplastic starch, it shows that there are more hydrogen bonds in thermoplastic starch, which indicates the improvement of mechanical and thermal properties in thermoplastic starch compared to native starch. Similar results have been reported by some other researchers [41, 54].

Thermal stability

Some thermogravimetric parameters of 4g-0B, 4g-1s-0B, 4g-2s-0B and 4g-4s-0B samples are shown in Table 3. $T_{10\%}$ is defined as the temperature for 10% weight loss and is utilized as onset temperature of thermal degradation. As can be seen 4g-0B, 4g-1s-0B, 4g-2s-0B and 4g-4s-0B samples had $T_{10\%}$ of 190.6 °C, 207.4 °C, 235.6 °C and 242.2 °C, respectively. In addition $T_{50\%}$ the temperature for 50% weight loss, for 4g-0B, 4g-1s-0B, 4g-2s-0B and 4g-4s-0B samples was 312.8 °C, 319.4 °C, 325.6 °C

Table 3 Thermogravimetric parameters of 4g-0B, 4g-1s-0B, 4g-2s-0B,4g-4s-0B, 4g-75B and 4g-150B samples

Sample code	Τ _{10%} (°C)	Τ _{50%} (°C)	Residual wt.% at 600 ℃
4g-0B	190.6	312.8	9.14
4g-1s-0B	207.4	319.4	8.87
4g-2s-0B	235.6	325.6	8.11
4g-4s-0B	242.2	328.2	7.63
4g-75B	197.1	324.4	9.50
4g-150B	212.2	328.3	10.04

and 328.2 °C, respectively. In addition, the sample 4g-0B with higher glycerol content and absorbed moisture than other samples had a greater weight loss at the same temperature than other samples, so that weight loss for 4g-0B, 4g-1s-0B, 4g-2s-0B and 4g-4s-0B samples at 290 °C (the boiling point of glycerol) was 41.2%, 35.3%, 24.1% and 22.7%, respectively. The weight loss of thermoplastic starch below 100 °C is related to the evaporation of water [27, 55, 56]. Weight loss at temperatures between 100 °C and starch degradation temperature (about 330 °C), is related to weight loss of water and plasticizers [29]. Due to the stronger interactions of sorbitol with starch compared to glycerol and also the lower volatility of sorbitol than glycerol, increasing the weight ratio of sorbitol to glycerol in thermoplastic starch increases thermal stability and thus $T_{10\%}$ and $T_{50\%}$ [29]. Other researchers have reported similar results for increasing the thermal stability



Fig. 5 Sample sheet 4g-1s-150B (a), plate-shaped packaging container (b)

of thermoplastic starches by increasing the weight ratio of sorbitol to glycerol [27, 30].

Also some thermogravimetric parameters of 4g-0B, 4g-75B and 4g-150B samples are shown in Table 3. As can be seen 4g-0B, 4g-75B and 4 g-150B samples had $T_{10\%}$ of 190.6 °C, 197.1 °C and 212.2 °C, respectively. In addition $T_{50\%}$ for 4g-0B, 4g-75B and 4g-150B samples was 312.8 °C, 324.4 °C and 328.3 °C, respectively. Increasing sugarcane bagasse concentration, led to an increase in $T_{10\%}$ and $T_{50\%}$ and thus thermal stability of the biocomposites due to the greater thermal stability of cellulosic substances than starch and more probable number of created hydrogen bonds between molecular chains of starch and sugarcane bagasse [57-59]. Similar results have been reported by other researchers for the improvement of thermal stability of thermoplastic starch-based composites by increasing the lignocellulosic filler content [40, 60, 61].

The food packaging container made from the biocomposite

Schematic of a food packaging container in the form of a plate prepared from sample sheet 4g-1s-150B is shown in Fig. 5.

Conclusion

Increasing the concentration of sugarcane bagasse and the weight ratio of sorbitol to glycerol increased the stiffness and decreased the moisture absorption of the biocomposite based on thermoplastic wheat starch. The biocomposite with sugarcane bagasse concentration of 15 wt.% of wheat starch and sorbitol:glycerol weight ratio of 2:4 had balanced stiffness and flexibility so making a packaging container from it by vacuum thermoforming method was possible. The results of FTIR analysis showed that there was no considerable interaction between sugarcane bagasse and wheat starch or plasticizers. Therefore, by physical or chemical treating of sugarcane bagasse and de-ligninizing it, it is possible to use higher concentrations of bagasse in the preparation of biocomposite, which in turn will reduce the price of containers made from the biocomposite. In the end, it was observed that the combination of bagasse, as agricultural waste and filler in the thermoplastic starchbased biocomposite formula, led to the production of biocomposite with the ability to produce containers by vacuum thermoforming method, which can be a beneficial approach to reduce the cost of the final product while maintaining or enhancing its eco-friendliness.

Author contributions

MRAM. Conceptualization, methodology, formal analysis, data curation, writing—original draft, software, writing—review and editing; MAH: methodology, formal analysis, data curation, writing—original draft; FJ: formal analysis.

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Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

This article does not contain any studies with human or animal subjects.

Consent for publication

All authors have read and agreed to the published version of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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