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# Circular Economy of Composite Materials Using Waste Jute Fibers and Recycled Polyester Fibers as a Reinforcement for Packaging Applications

**Tamer Hamouda and Nermin M. Aly ***

*Spinning and Weaving Engineering Department, Textile Research and Technology Institute, National Research Centre, 33 El Bohouth St., Dokki, Cairo, Egypt, P.O.12622*

**Abstract**

Sustainable packaging is an emerging trend that contributes successfully to the development of the packaging industry. The use of waste in the production of fiber reinforced composites for packaging applications is one of the promising approaches to reduce the environmental impacts of using plastics, and assist in preserving wood-based materials. In this study, eight laminated composite panels reinforced with waste jute and recycled polyester fibers in a polypropylene matrix were produced to be used in packaging applications. The influence of changing the reinforcement type and ratio, and hybridization between the reinforcement materials with different stacking sequences on the composite panel's performance was investigated. The mechanical properties of the composite panels such as tensile, flexural and impact strengths, in addition to their physical properties such as density, water absorption, thickness swelling and moisture content were studied. The disintegration behavior of the composite samples was assessed through applying a simulated composting burial test under controlled laboratory conditions for 4 months. The results indicated that the 3-layers polyester composite sample exhibited the highest tensile and impact strengths, as well it showed the lowest water absorption, thickness swelling, moisture content and degree of disintegration compared to the other samples. The hybrid composite sample with a stacking sequence of recycled jute and polyester layers PET/J/PET presented the highest flexural strength and modulus values. Overall, the hybrid composite samples PET/J/PET and J/PET/J revealed improved mechanical and physical performance compared to the pure jute composites and the hybrid integrated jute/polyester composites. Thus, the proposed recycled polyester and hybrid jute/polyester composites with stacking sequence have the potential to be used as ecofriendly and cost-effective panels for packaging boxes applications.

Keywords: Fiber reinforced composites, Biocomposites, Packaging, Waste jute, Recycled polyester, Disintegration degree.

## 1. Introduction

The increasing awareness and environmental concerns have led the way for the development of ecofriendly sustainable plastics as a replacement of petroleum-derived polymers for various industrial applications such as automotive, construction, sporting goods, packaging, etc. [1-3]. Conventional plastics (synthetic polymers) are widely used in many industries due to their excellent characteristics and processing possibilities, although the continuous use of finite oil resources will result in reducing their availability and increasing their costs [2,4,5]. Moreover, the massive amounts of plastic waste landfilled or left in the environment cause serious environmental threats due to the ever-increasing amount of solid waste [4]. Packaging is one of the major industries that plays a crucial role in many sectors that depend on it vastly such as food, electronics, pharmaceutical and chemical industries, etc. The packaging must meet the consumer's requirements including the ability to protect the item from various physical and mechanical damages,

*Corresponding author e-mail: nermin_moh@yahoo.com.; (Nermin M. Aly).
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providing ease during the handling and transportation, and the ability to promote the purchase of the product. There are three categories of packaging; primary packaging where the material is in direct contact with the product, and can be separated from it, secondary packaging that physically protects the product, and tertiary packaging that fulfils the product's requirements for storage and handling [2,5].

Paper and paperboard hold the largest market share for primary and secondary packaging materials [2]. On the other hand, synthetic polymers such as polypropylene, polyethylene, polyester, polyvinyl chloride and polyamide are extensively used in packaging because of their low cost, efficient mechanical performance, heat sealability and good barrier to carbon dioxide, oxygen, anhydride and aroma compounds [2,6-8]. Most of these plastics are recyclable, even though many countries face both technical and economic constraints on recycling this plastic waste. In 2019, the European Union (EU) market showed that paper and paperboard packaging waste material accounted about 32.3 million tonnes, followed by plastics about 15.4 million tonnes, and glass waste about 15.2 million tonnes [9]. In addition, the manufacturers prefer hardwood and plywood packaging boxes over plastic packaging because of their high bearing strength, durability and deformation resistance. This wooden packaging can be reused and employed in building and construction applications [10]. However, wood can be affected by wet and humid conditions and show significant dimensional instabilities like shrinkage and thickness swelling. Also, moisture accumulation can cause growth and proliferation of fungi leading to wood degradation [11].

Waste recycling is one of the paths taken by the European Union in 2018 to move towards the circular economy concept, seeking to minimize the consumption of raw materials. The EU plans to recycle 50% of plastic waste and 25% of wood waste by 2025 which will increase to 55% for plastic and 30% for wood by the end of 2030. All plastic packaging in the EU market should be reusable or recyclable in a cost-effective manner, and the recycled plastics should be used as a valuable feedstock for industries [12-14]. Consequently, there has been a great interest in developing high-performance recyclable and/or biodegradable materials for the sustainable growth of packaging industry [5,8]. Utilizing of waste fibers in composite materials is a significant approach to reduce the environmental impacts of using plastics. Fiber reinforced composites can be suitably used in packaging due to their unique physical and mechanical properties. Various types of synthetic and natural fibers have proved their effective use as reinforcement in enhancing the mechanical performance of composites in various thermoset and thermoplastic matrices [15-23]. Natural fibers such as jute, flax, coir, bamboo, etc. have the potential to be utilized in packaging owing to their excellent properties such as renewability, biodegradability, recyclability, low density, low cost, and good insulation and mechanical performance. Also, they increase the bio-based content within the composite structure [5,24,25]. Furthermore, due to the concepts of environmental sustainability, hybridization between natural and synthetic fibers has rapidly gained a significant market share in various composites applications due to their distinguished properties [26].

Several properties must be considered to determine the suitability of composite materials for certain packaging applications [27]. Mechanical properties are important to investigate the behavior of materials when subjected to various loads during manufacturing operations, and throughout their entire service life. Physical properties such as water absorption, moisture content and thickness uniformity are essential properties that will further affect the service life of the finished products. Moreover, the durability or long-term performance of composites in an open environment can be assessed through real-time observations [1]. Several studies have investigated the biodegradability and disintegration of fiber reinforced composites in various environments. Martín del Campo et al. [28] investigated the influence of using agave and coir waste fibers on the abiotic and composting degradation of PLA-based biocomposites. Both fibers showed a significant influence on biocomposites degradation. Ochi [29] studied the biodegradability of kenaf/PLA composites by composting for 4 weeks and found that the weight of the composites decreased. Chee et al. [30] studied the impacts of soil burial and accelerated weathering on the thermal and biodegradability properties of bamboo/kenaf-reinforced epoxy composites. Soil burial was found to show more prominent degradation compared to accelerated weathering. On the other hand, a time of degradation is not always desirable. It is also a positive side of the slow degradation of composites used in long-term applications such as packaging and transportation of goods, where the material can be used for extended times and therefore reduce costs [3].

In order to be aligned with the circular economy direction, in the present study, eight laminated composite panels were produced from waste jute fibers and recycled polyester fibers as a reinforcement in a polypropylene matrix. The influence of changing the reinforcement type and ratio, and hybridization between the reinforcing materials on the composite panels' performance were investigated by characterizing their physical and mechanical properties along with their disintegration behavior to assess their long-term durability for potential use in packaging boxes applications.

## 2. Experimental

### 2.1. Materials

In this work, different types of waste fibers in nonwoven preforms were used as the reinforcing materials in manufacturing of the laminated composite samples namely; Jute (800 g/m$^2$), Polyester (800 g/m$^2$), and Hybrid integrated jute/polyester (80:20%) of (1200 g/m$^2$). The hybrid integrated jute/polyester sample is composed of two layers of jute and polyester fibers bonded together. The nonwoven fabrics were produced by the needle punching technology, where the fibers are randomly oriented due the utilization of the cross lapper during manufacturing of the fabric. The recycled nonwoven fabrics were provided from Egyptex Company in Giza, Egypt. The thickness of the three nonwovens was; 8.7 mm for jute fabric, 9.2 mm for polyester fabric, and 9.65 mm for the hybrid jute/polyester (80:20%) fabric. Spunponded nonwoven polypropylene fabric of (80 g/m$^2$) was used as the matrix material in manufacturing of the composite samples.

### 2.2. Fabrication of the composite samples

The three types of nonwovens were used separately to produce six composite panels with changing the number of the reinforcement layers. Then, two hybrid composite samples were produced from jute and polyester fabrics stacked at various layers' configuration alternately. Polypropylene (matrix) was used with a constant weight ratio inserted in between the reinforcement layers of each sample. The prepared laminated composites layers' structure is illustrated in Figure 1. The compression molding technique was used in producing the laminated composite panels using a hydraulic press machine equipped with stainless steel plates. The temperature was adjusted to 195ºC, then the stack of fabric layers for each sample was placed between the two stainless steel plates, and preheated for 2 min. under a compression pressure of 5MPa. Then the pressure was set to 10MPa and applied to the sample that thermally molded for 3 min. at 195ºC. After that, the composite sample was cooled under pressure for 5 min. Table 1 shows the description of the prepared composite samples.

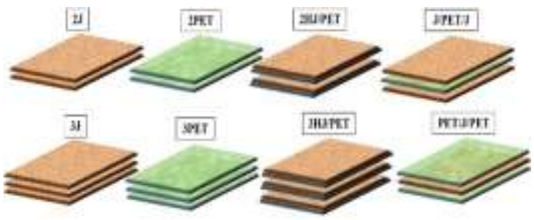


**Figure 1.** Schematic diagram of the laminated composite samples layers' structure prepared from jute and polyester nonwovens.

### 2.3. Testing

#### 2.3.1. Mechanical properties

**Tensile strength**

The tensile properties of the laminated composite samples were measured in accordance with ASTM D638. The test was performed using a Universal testing machine (Galdbini-Quasar 600 KN, Italy) at a crosshead speed of 20 mm/min. until fracture of the sample. The tensile strength, modulus and elongation at break were determined.

**Flexural strength**

The flexural strength and modulus properties of the laminated composite samples were determined using three-point bending test according to ASTM D790. The test was performed using a Universal testing machine (Galdbini-Quasar 600 KN, Italy) at a crosshead speed of 20 mm/min, and the span length was set to 50 mm. Each sample was subjected to bending load until fracture happened.

**Impact strength**

The impact strength of the laminated composite samples was measured using the Izod impact testing device (CSI-137 Pendulum impact tester) according to ASTM D256. The composite sample was subjected to an impact load applied with one pendulum swing. The impact energy required to fracture the sample was recorded to determine the sample's impact resistance and toughness.

**Table 1.** Description of the laminated composite samples

| Samples code | Reinforcement type | Matrix | Composite samples structure (stacking sequence)* | Composite samples thickness (mm) |
|---|---|---|---|---|
| **2J** | Two layers of jute fabric | **Polypropylene** | PP/J/PP/J/PP | 2.60 |
| **3J** | Three layers of jute fabric | | PP/J/PP/J/PP/J/PP | 3.63 |
| **2PET** | Two layers of polyester fabric | | PP/PET/PP/PET/PP | 2.27 |
| **3PET** | Three layers of polyester fabric | | PP/PET/PP/PET/PP/PET/PP | 3.21 |
| **2HJ/PET** | Two layers of hybrid integrated jute/polyester (80:20%) fabric | | PP/HJPET/PP/HJPET/PP | 5.06 |
| **3HJ/PET** | Three layers of hybrid integrated jute/polyester (80:20%) fabric | | PP/HJPET/PP/HJPET/PP/HJPET/PP | 7.30 |
| **J/PET/J** | Two layers of jute fabric and one layer of polyester fabric | | PP/J/PP/PET/PP/J/PP | 3.23 |
| **PET/J/PET** | Two layers of polyester and one layer of jute fabric | | PP/PET/PP/J/PP/PET/PP | 3.08 |

*J: Jute, PET: Polyester, HJPET: Hybrid Jute/Polyester, PP: Polypropylene.

**2.3.2. Physical properties**

**Reinforcement weight fraction**

The weight fraction of the reinforcing fibers in the prepared composite samples were determined according to equation (1).

$$\mathbf{W_f = W_c - W_m / W_C} * 100 \quad \mathbf{(1)}$$

Where; $\mathbf{W_f}$ is the weight of the reinforcing fibers (g), $W_c$ is the weight of the composite sample (g), and $W_m$ is the weight of matrix (g).

**Density**

The density of the laminated composites was measured according to BS EN-323. The weight of each sample was measured using an analytical weighting balance, and the volume was obtained by measuring the sample's dimensions using digital Vernier caliper.

**Water absorption and thickness swelling**

Water absorption (WA) and thickness swelling (TS) tests were carried out on the laminated composite samples in accordance with ASTM D-570 and BS EN-317. The composite samples were submerged in distilled water at room temperature for different time durations; 2, 24, 48, 72, 96 and 120 hours. The composite samples were taken out from water at these time intervals, wiped with clean tissue paper to remove excess surface water, and then the samples' weight and thickness were measured. Water absorption (%) is the increase in the sample's weight after immersion in water compared to its original dry weight, and it is calculated according to equation (2).

$$\mathbf{WA\% = W_t - W_o / W_o * 100} \quad \mathbf{(2)}$$

Where; **WA** is the water absorption (%), $W_t$ is the wet weight of the specimen at immersion time in water (g) and $W_o$ is the initial weight of the dry specimen (g).

Thickness swelling (%) is the increase in the sample's thickness after immersion in water compared to its original dry thickness, and it is calculated according to equation (3).

$$\mathbf{TS\% = t2 - t1 / t1 * 100} \quad \mathbf{(3)}$$

Where; **TS** is the thickness swelling (%), $t_2$ is the thickness of the specimen after immersion in water (mm) and $t_1$ is the initial thickness of the dry specimen (mm).

**Moisture content**

The moisture content in the laminated composite samples was determined according to BS EN-322. Each sample was weighted at its state time of sampling by using an analytical weighting balance, and then dried in a laboratory oven at 103°C (±2° C) until reaching a constant mass. The constant mass is considered when two successive weighting operations results of the tested sample do not differ by more than 0.1% carried out at an interval of 6 hours. The moisture content % is calculated according to equation (4).

$$MC\% = m_H - m_o / m_o * 100 \quad (4)$$

Where; **MC** is the moisture content (%), $m_H$ is the original weight of the test specimen (g); and $m_o$ is the weight of the test specimen after drying (g).

### 2.3.3. Disintegration test in composting conditions

Disintegration is defined as the physical breakdown of the material into very small fragments. The disintegration behavior of the laminated composite samples was assessed under controlled simulated composting conditions in a laboratory-scale test according to ISO 20200 standard [31]. The dimensions of the tested composite samples were determined based on their thickness as stated in the standard. Samples of thickness <5 mm were cut into 2.5 x 2.5 $cm^2$ and samples of thickness > 5mm were cut into 1.5 x1.5 $cm^2$. To simulate the compost soil, a solid synthetic waste was prepared by mixing different components with specified quantities as listed in Table 2. The compost medium consisted of 55 %wt. distilled water and 45 %wt. synthetic solid waste.

**Table 2.** Composition of the synthetic solid waste [31].

| Material | Dry mass (%) |
|---|---|
| Sawdust | 40 |
| Rabbit feed | 30 |
| Ripe compost | 10 |
| Corn starch | 10 |
| Saccharose | 5 |
| Corn seed oil | 4 |
| Urea | 1 |
| Total | 100 |

The samples were dried, weighted and buried in the compost medium in a reactor box perforated with two holes (5mm) to provide gas exchange between the inner atmosphere and the outside environment, see Figure 2. The reactor box was weighted and incubated in a laboratory oven under controlled temperature 58°C ±2°C for a period of 120 days (4 months). During the test, the aerobic conditions were guaranteed through mixing the compost manually and periodical addition of water to adjust the weight of the reactor as described in the standard requirements. The samples were taken out from the reactor at different time intervals (60, 90 and 120 days), cleaned, dried and weighted. Photographs were taken for the samples at different stages of incubation for visual inspection. The degree of disintegration (biodegradation) is calculated according to equation (5).

$$D\% = m_i - m_r / m_i * 100 \quad (5)$$

Where, D is the degree of disintegration (%), $m_i$ is the initial dry mass of the sample (g); and $m_r$ is the dry mass of the residual sample after the test (g).

**Figure 2.** The compost reactor box.

## 3. Results and discussion

### Mechanical properties

### 3.1.1. Tensile strength

The tensile behavior of fiber reinforced composites is highly influenced by the reinforcement fibers' strength and modulus, the fabric arrangements, and the interfacial bonding between the fibers and the matrix [32]. Figure 3 shows the tensile strength results of the laminated composite samples. It is observed that the polyester composite sample 3PET exhibited the highest tensile strength of 20.43 MPa compared to all other samples owing to the high strength of polyester fibers compared to jute fibers [33,34]. On the other hand, the hybrid integrated jute/polyester (80:20%) composites 3HJ/PET and 2HJ/PET showed the lowest tensile strength of 7.6 MPa and 7.25 MPa, respectively. This could be attributed to the incorporation of high content of jute fibers with high thickness leading to poor interfacial bonding between the fibers and the matrix, which accordingly reduced the strength of the composites. Also, it is found that increasing the number of reinforcement layers improved the tensile strength of the pure jute composites by 54.35%, the pure polyester composites by 17.21% and the hybrid integrated jute/polyester (80:20%) composites by 4.83%. The hybrid samples J/PET/J and PET/J/PET with different stacking sequence of layers showed higher tensile strength values of 17.9 and 16.34 MPa, respectively compared to the jute composites and the hybrid integrated jute/polyester (80:20%) composites, which indicated that the hybridization with different reinforcement types and stacking sequences improved the laminated composites strength.

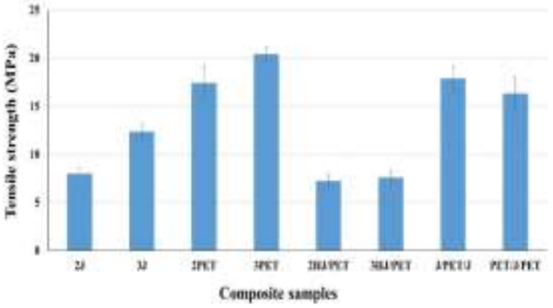


**Figure 3.** Tensile strength results of the laminated composite samples.

The tensile modulus of the prepared laminated composites is depicted in Figure 4. It is observed that the pure jute composite sample 2J achieved the highest tensile modulus of 378.31MPa compared to all samples due to the high modulus of jute fibers [33]. Also, the hybrid integrated jute/polyester (80:20%) composite sample 2HJ/PET showed the lowest tensile modulus value of 43.55 MPa and with increasing the number of layers, the modulus increased by 44.66%. The tensile modulus of the pure jute composites and pure polyester composites decreased by 63.74% and 30.61% respectively, with increasing the number of reinforcement layers. This may be attributed to increasing the stiffness of the samples by increasing the reinforcement layers. As well, it is indicated that the hybrid composite samples J/PET/J and PET/J/PET showed higher values of tensile modulus compared with the hybrid integrated jute/polyester (80:20%) composite sample. This could be related to the sandwich structure of different stacking sequence of jute and polyester fabrics which enhanced the samples' performance to bear the tensile load.

Figure 5 displays the elongation at break results of the laminated composite samples. It is found that the pure polyester composites showed higher elongation values compared to the pure jute composites due to the high elongation property of polyester fibers and the low elongation of jute fibers [33, 34]. Increasing the number of reinforcement layers caused an improvement in the elongation of the pure jute composites and the hybrid integrated jute/polyester (80:20%) composites by 8.55% and 28.18% respectively, whereas the elongation of the pure polyester composites decreased to some extent by 3.4%. The other hybrid composite sample J/PET/J achieved the highest elongation value of 14.1% compared with all other samples. This could be related to using polyester nonwoven fabric in the core layer which enhanced the elongation properties of the composite structure during applying load. Also, the hybrid composite sample PET/J/PET showed higher elongation values compared to pure jute composites.

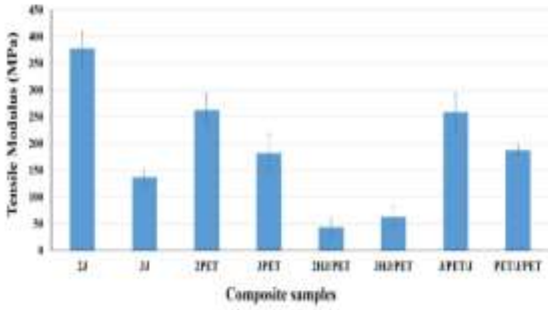


**Figure 4.** Tensile modulus results of the laminated composite samples.

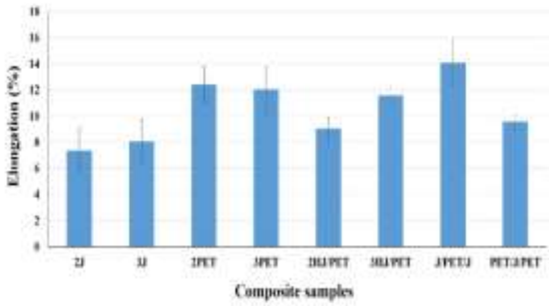


**Figure 5.** Elongation at break results of the laminated composite samples.

### 3.1.2. Flexural strength

The flexural strength and modulus properties of the laminated composites are illustrated in Figures 6 and 7. It is observed from Figure 6 that the hybrid composite samples PET/J/PET and J/PET/J achieved the highest flexural strength values of 16.68 MPa and 14.54 MPa, respectively compared to all samples, due to their sandwich structure of different stacking sequence of jute and polyester fibers and the enhancement of the core layer in resisting the bending load. The pure polyester composites had higher flexural strength values compared to pure jute composites owing to the high strength of polyester fibers. Additionally, increasing the number of reinforcement layers caused an improvement in the flexural strength of the jute and the hybrid integrated jute/polyester (80:20%) composites samples by 24.76% and 22.2%, respectively. Although the pure polyester composite samples' flexural strength decreased by 5.7%.

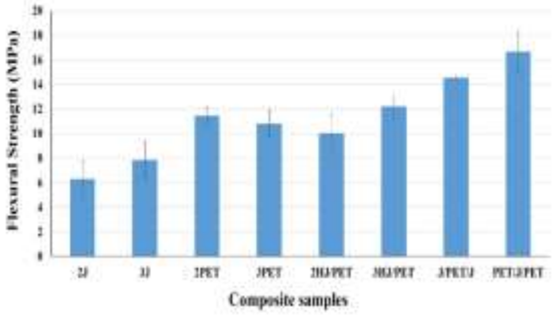


**Figure 6.** Flexural strength results of the laminated composite samples.

The flexural modulus refers to the material's stiffness during exposure to bending load [15]. From Figure 7, it is revealed that the hybrid composite sample PET/J/PET displayed the highest value of 584.82 MPa due to the increased stiffness of the sample with using polyester fabric in the skin layers and jute in the core layer which is characterized by its high modulus. The hybrid integrated jute/polyester (80:20%) composite samples showed the lowest values of flexural modulus of 113.74 and 114 MPa, respectively. The polyester composite samples recorded higher flexural modulus values compared to the jute composites and the hybrid integrated jute/polyester (80:20%) composites. Increasing the number of reinforcement layers caused a decrease in the flexural modulus of the jute and polyester composites by 47.6% and 10.61%, respectively. The hybridization with different stacking sequence of fabric layers in the composite samples caused an improvement in their flexural modulus compared to that of the hybrid integrated jute/polyester (80:20%) composite samples.

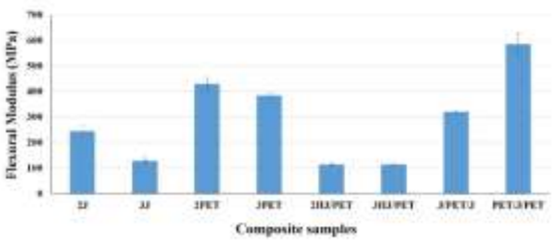


**Figure 7.** Flexural modulus results of the laminated composite samples.

#### 3.1.3. Impact strength

Figure 8 presents the impact strength results of the laminated composites. The pure polyester composites 3PET and 2PET showed the highest impact strength values of 37.5 $KJ/m^2$ and 34.2 $KJ/m^2$ respectively, compared to all samples due to the high strength of polyester fibers. Although the hybrid integrated jute/polyester (80:20%) composite samples 2HJ/PET and 3HJ/PET recorded the lowest impact strength values of 16.4 $KJ/m^2$ and 11.3 $KJ/m^2$. The impact strength of jute composites improved by 37.9% and polyester composites by 15.8% with increasing the number of reinforcement layers, while caused a decrease in the impact strength of the hybrid integrated jute/polyester (80:20%) composites by 31.1%. The hybridization with different stacking sequence caused an increase in the impact strength of the hybrid composite samples J/PET/J and PET/J/PET compared with the pure jute samples and the hybrid integrated jute/polyester (80:20%) composites.

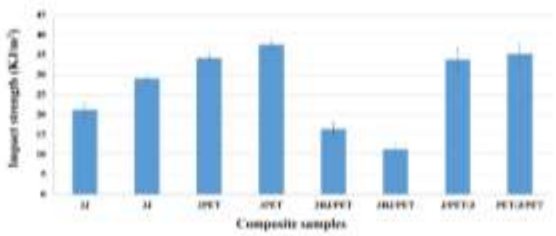

**Figure 8.** Impact strength results of the laminated composite samples.

### 3.2. Physical properties

#### 3.2.1. Reinforcement weight fraction

Table 3 shows the weight fractions of the reinforcing fibers in the composite samples. It is found that the fibers weight fractions ranged between 86.96% - 91.84% of the total composite samples' weight which shows the high fiber content in each composite sample, which in turn affected the permeability of matrix. The hybrid integrated jute/polyester (80:20%) composites showed the highest fiber weight fractions compared with the other samples, although they displayed the lowest mechanical properties due to their composition and the mechanical bonding technique used for interlacing the fibers (needle punching) in the jute and polyester nonwoven layers. Additionally, it is observed that the hybrid jute and polyester composite samples with different stacking sequences showed similar results of fiber weight fractions.

**Table 3.** The weight fractions of the reinforcing fibers in the composite samples

| **Samples code** | **Fibers weight Fraction (%)** |
|---|---|
| **2J** | 86.96 |
| **3J** | 88.24 |
| **2PET** | 86.96 |
| **3PET** | 88.24 |
| **2HJ/PET** | 90.91 |
| **3HJ/PET** | 91.84 |
| **J/PET/J** | 88.24 |
| **PET/J/PET** | 88.24 |

### 3.2.2. Density

The density has a significant role in determining the dimensional stability of the produced fiber reinforced composites [35]. Figure 9 shows the density values of the produced laminated composites. It is revealed from the results that the polyester composites' density values are higher than the jute composites. This could be related to the low thickness of the polyester composite samples, where the polypropylene matrix penetrates in the low voids between fibers during the compression molding process which in turn leads to increase their density. As well, the hybrid integrated jute/polyester (80:20%) composites recorded the lowest density values compared with the other samples due to their structure of integrated jute and polyester fibers with high thickness and the presence of more air voids between the jute fibers. Whereas increasing the number of reinforcement layers leads to increasing the density of pure jute composites by 4.56%, pure polyester composites by 11.31%, and hybrid integrated jute/polyester (80:20%) composites by 6.43%. Also, it is found that the hybrid composite samples with different stacking sequence J/PET/J and PET/J/PET showed higher density values than the hybrid integrated jute/polyester (80:20%) composites and pure jute composites.

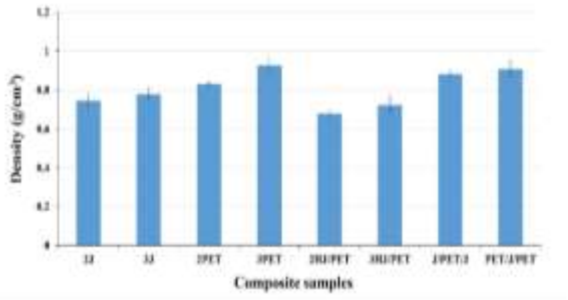


**Figure 9.** Density of the laminated composite samples.

### 3.2.3. Water absorption

The water absorption behavior of the laminated composites after immersion in water for 120 hours is presented in Figure 10. The highest water uptake rate for the composite samples was observed in the first 2 and 24 hours, then it decreased gradually during the test period. The hybrid integrated jute/polyester (80:20%) composite samples 2HJ/PET and 3HJ/PET showed the highest values of water absorption 117% and 101.8% respectively, followed by the pure jute composite samples 2J and 3J which recorded 65.52% and 62.46% respectively. This behavior could be related to the capability of jute fibers to absorb water because of their hydrophilic nature and their tendency to trap water in the air gaps between the fibers, in addition to their low density due to the presence of air voids inside the composite panel structure. This tendency of water trapping increased with increasing the fiber layers [36]. Also, the permeation of water in the air voids in the composite structure occurred due to the hydrolytic breakdown of the interfacial adhesion between the fiber and resin, so water is soaked up by the fiber/matrix interface [37].

It is worth mentioning here that the composite samples 3PET and 3HJ/PET reached their saturation points after 48 h, the samples 2J and J/PET/J reached their saturation points after 96 hours, while the samples 3J, 2PET, 2HJ/PET, and PET/J/PET reached their saturation after 72 hours. On the other hand, the pure polyester composite samples 2PET and 3PET achieved the lowest values of water absorption 21.82% and 21.5% respectively, due to their hydrophobic nature. The hybridization of jute and polyester fabrics with different stacking sequences has significantly reduced their water uptake compared to the pure jute composites and hybrid integrated jute/polyester (80:20%) composites. The sample J/PET/J displayed higher water absorption of 39.6% compared to the sample PET/J/PET which recorded 32.64% due to using jute fibers in the skin layers of the composite structure.

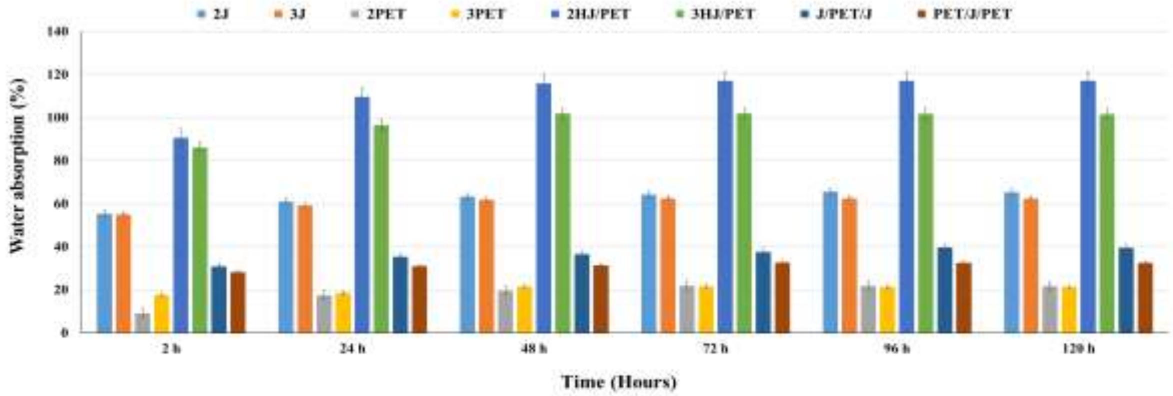


**Figure 10.** Water absorption behavior of the laminated composite samples.

### 3.2.4. Thickness swelling

The thickness swelling behavior of the laminated composites after immersion in water for 120 hours is illustrated in Figure 11. The thickness swelling of all the composite samples significantly increased in the first 24 hours. It is found that the pure polyester composites 2PET and 3PET showed the lowest thickness swelling of 0.65% and 0.28%, respectively. They reached their saturation point after 48 hours' immersion in water, after that no increase in the samples' thickness was recorded. The hybrid integrated jute/polyester (80:20%) composite samples 2HJ/PET and 3HJ/PET showed the highest values of thickness swelling 47.65% and 48.33%, they reached their saturation point after 72 hours, followed by the pure jute composite samples 2J and 3J which recorded 30.51% and 30.86% respectively, due to the high tendency of jute fibers to absorb water which mitigated the fiber/matrix interfacial bonding. The hybrid samples J/PET/J and PET/J/PET showed improved behavior by reducing their thickness swelling compared to the pure jute composites and the hybrid integrated jute/polyester (80:20%) composites. The sample PET/J/PET thickness swelling was 13.2% and reached its saturation point after 48 hours, while the sample J/PET/J showed thickness swelling of 24.35% and reached its saturation point after 48 hours.

### 3.2.5. Moisture content

Figure 12 illustrates the moisture content % of the laminated composites after drying. The pure polyester composites 2PET and 3PET exhibited the lowest amount of moisture content of 0.26 % and 0.22% compared to all samples, followed by the hybrid composite sample PET/J/PET which recorded a moisture content of 1.16%. This result is similar to water absorption and thickness swelling properties. Additionally, the hybrid integrated jute/polyester (80:20%) composite samples 2HJ/PET and 3HJ/PET showed the highest moisture content values of 3.66% and 2.49%, respectively, followed by the pure jute composites 2J and 3J which recorded 2.84% and 2.92%. The hybrid composite sample J/PET/J showed improved performance compared to pure jute composites and hybrid integrated jute/polyester (80:20%) composites due to using polyester fibers in the core layer, where the sample recorded 2.25% moisture content.

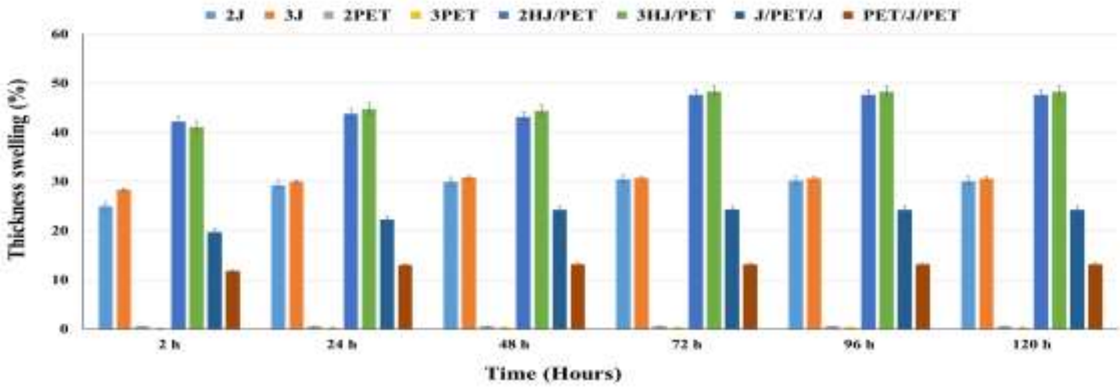


**Figure 11.** Thickness swelling behavior of the laminated composite samples

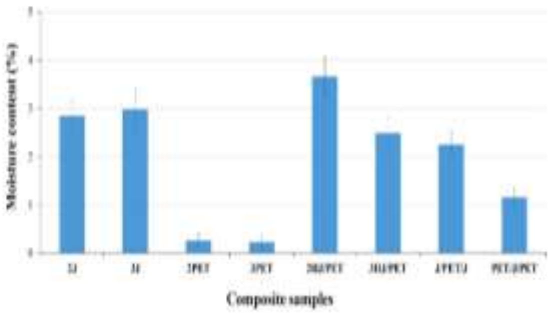


**Figure 12.** Moisture content of the laminated composite samples.

### 3.3. Disintegration test in composting conditions

The disintegration behavior of the laminated composite samples under lab-scale composting conditions was evaluated based on the weight loss of the samples as presented in Figure 13. During the first two weeks, the composting waste changes due to the occurrence of the microorganisms and their adaptation to the environment. The weight loss of samples at different times (60, 90 and 120 days) was monitored and recorded during the test period. It was observed that the weight loss increased significantly by time for the hybrid integrated jute/polyester (80:20%) composite samples 2HJ/PET and 3HJ/PET followed by the pure jute composite samples. Increasing the number of reinforcement layers increased the disintegration behavior of the composite samples to some extent especially for the pure jute and the hybrid integrated jute/polyester (80:20%) composite samples. The sample 3HJ/PET showed the highest disintegration value after 60 days of 1.34% compared to all samples, then increased to 3.44% after 120 days of burial time, followed by the samples 2HJ/PET and 3J which recorded 2.52% and 1.94% after 120 days of burial. This could be attributed to the high content of jute fibers in the composite samples and presence of air voids which ease the access of microorganisms to the sample. Since the presence of lignocellulosic fibers enhances the microbial attack by promoting biofouling and the adhesion of microorganisms to the sample's surface [38].

The pure polyester composite samples showed the lowest degree of disintegration during 120 days due to their synthetic nature. The samples 2PET and 3PET recorded disintegration values of 0.11% and 0.42% respectively after 120 days. Moreover, it was indicated that the hybrid samples composed of jute and polyester fibers with different stacking sequence of layers showed slowed disintegration rate compared to the hybrid integrated jute/polyester (80:20%) composites and pure jute composite samples. Also, the sample PET/J/PET showed better behavior compared to the J/PET/J sample due to presence of polyester fibers in the skin layers which act as barriers that hinder the disintegration process, it recorded 0.85% disintegration value, while the sample J/PET/J recorded 1.8%. Generally, the laminated composite samples showed good performance and resistance to disintegration which indicates their potential for long-term use in packaging.

Figure 14 shows photographs of the laminated composite samples before and after disintegration during burial in the composting conditions for 90 and 120 days. It is indicated from the visual appearance of the composite samples that the color of the samples changed with increasing the burial time, but their dimensions remained almost the same. The hybrid integrated jute/polyester samples and the pure jute samples showed signs of disintegration at their edges that became rougher compared to the pure polyester samples. This may be attributed to the presence of air voids in these composite samples which facilitate the access of microorganisms. Whereas, the hydrophobic nature of polyester fibers and the good interfacial bonding between the fibers and the polypropylene matrix in the pure polyester samples assist to resist the disintegration process.

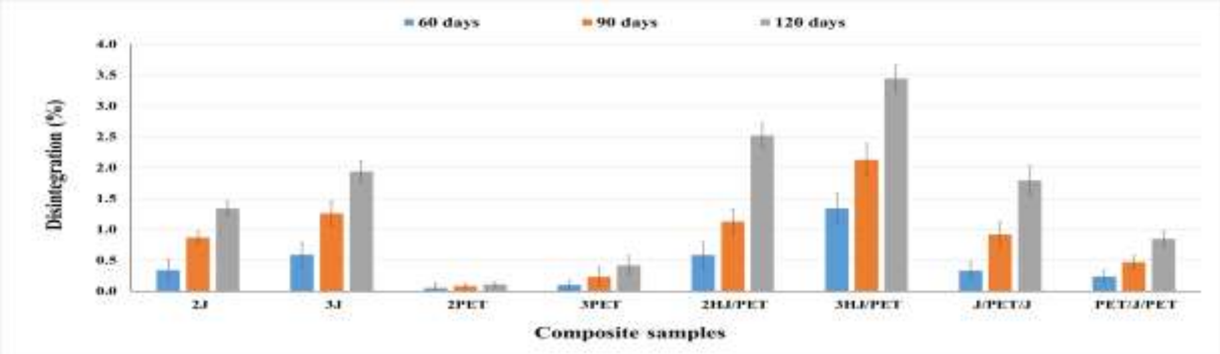


**Figure 13.** Disintegration of the laminated composite samples under composting conditions.

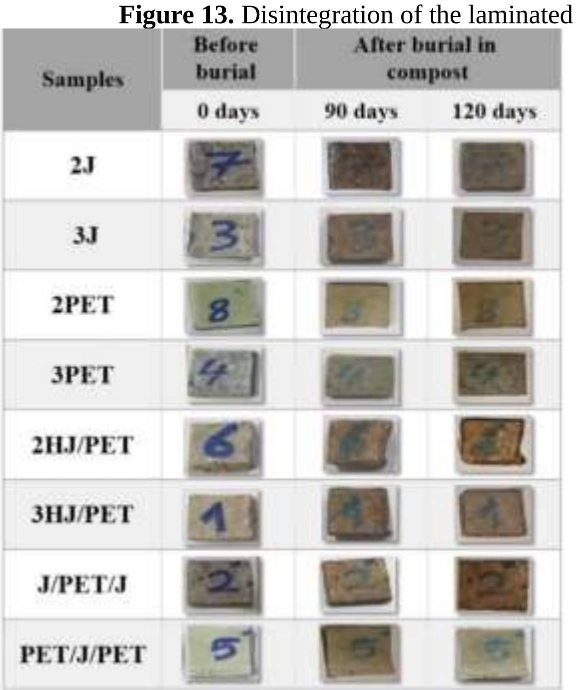


**Figure14.** Photographs of the composite samples before the burial test and after disintegration during burial in the composting conditions for 90 and 120 days

**4. Conclusion**

Circular economy concepts can achieve sustainability through reducing consumption of raw materials, reusing waste and recycling. In this study, the mechanical, physical and disintegration properties of eight laminated composite panels reinforced with waste jute fibers and recycled polyester fibers were investigated to be used in packaging applications. The influence of changing the reinforcement type and ratio, and hybridization between the reinforcement materials with different stacking sequences on the composite panels' performance was studied. Based on the experimental results, the following conclusions can be drawn:

- The polyester composite samples 3PET achieved the highest tensile and impact strengths values. While the jute composite sample 2J exhibited the highest tensile modulus, and the hybrid J/PET/J showed the highest elongation (%).
- The hybrid composite sample PET/J/PET achieved the highest flexural strength and modulus.
- The polyester composite samples 2PET and 3PET exhibited the best physical properties including the lowest water absorption (%), thickness swelling (%), and moisture content (%) compared to all samples. As well, the samples showed the lowest degree of disintegration during burial under composting conditions for 120 days.
- On the other hand, the hybrid integrated jute/polyester (80:20%) composites recorded the lowest mechanical properties such as tensile strength and modulus, flexural modulus and impact strength, in addition to displaying the highest water absorption, thickness swelling, moisture content and disintegration rate.
- Increasing the number of reinforcement layers improved the tensile strength, elongation and flexural strength of the pure jute and the hybrid integrated jute/polyester (80:20%) composite samples. Also, it caused an increase in the tensile modulus, flexural modulus and impact strength of the pure jute and pure polyester composite samples.
- Hybridization of jute and polyester fabrics with different stacking sequence in the composite samples J/PET/J and PET/J/PET resulted in an improvement in the tensile strength and modulus, flexural strength and modulus, and impact strength properties, in addition to the physical properties such as water absorption, thickness swelling, moisture content and disintegration behavior

compared to the pure jute and hybrid integrated jute/polyester (80:20%) composites.

Accordingly, the proposed polyester and hybrid jute/polyester composites reinforced with waste fibers have good potential to be used in packaging boxes as economical and efficient value-added products that are also recyclable, which can assist in reducing the consumption of paperboard and wooden-based materials used in packaging applications.

## 5. Conflicts of interest

There are no conflicts to declare.

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