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Research Article

Optimization and Characterization of Environmentally Friendly Biocomposites Reinforced with *Solanum muricatum* Wastes

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Abstract – This research aims to produce and thermophysical characterize polyester resin-based biocomposites reinforced by pepino (*Solanum muricatum*). Pepino fruits, thought to be thrown away as waste in the food industry, are evaluated as biomass, and environmentally friendly biocomposites are obtained. During the experimental optimization, dried pepino fruit powder at different ratios (0 wt.%, 2 wt.%, 4 wt.%, 6 wt.%, and 8 wt.%) is mixed homogeneously into unsaturated polyester resin (UPR) and cast into standard molds. According to experimental results, approximately 4 wt.% pepino fruit powder supplementation is the optimum ratio for the obtained biocomposites. At higher ratios, significant decreases occur in the bulk density and hardness of the biocomposite. Thermal analyses show that adding 8 wt.% pepino powder significantly reduces the thermal stability of the biocomposites. Scanning electron microscopy (SEM) analysis shows good interfacial adhesion between the UPR and pepino fruit at the optimum mixing ratio. At higher ratios, both the pore structure and pore distribution of the biocomposite are negatively affected. When Fourier transform infrared spectroscopy (FTIR) spectra have been investigated, it is understood that this interaction is not chemical but a physical interaction. According to these results, by using bio-wastes such as waste pepino fruit in biocomposites, interest in environmentally friendly and low carbon footprint biomaterials will increase in the future.

Keywords – Solanum Muricatum, Polyester Resin, Biocomposite, Experimental Optimization, Thermophysical Characterization.

I. INTRODUCTION

Pepino (*Solanum muricatum*) is a fruit belonging to the *Solanaceae* family, which includes important crops such as tomatoes and potatoes. It is a juicy, aromatic, and sweet fruit that grows in tropical and subtropical regions. Although it is defined as a fleshy, juicy, and sweet fruit, it is also used in salads due to the high acid content in some varieties. It is reported to be phylogenetically similar to tomatoes and potatoes [1-5]. Pepino originates from South America. It grows naturally in regions such as Ecuador, Colombia, and Peru. Native species from South America, more specifically from the Andes region of Peru and Chile, are widely distributed from Colombia to Bolivia. It is still found in its natural habitat in these regions and is consumed by the local people. It is also commercially grown in some other South American countries and in different parts of the world such as New Zealand and Australia. Its fruits, which can reach up to 15 cm, are also called sweet cucumber, tree citron, pear melon, etc. due to their similarity in taste to cucumber and melon. Pepino, one of approximately 1500 species belonging to the genus *Solanum*, has become one of the few species produced for food use [6-10].

Pepino fruits have different physical properties. These properties vary according to the type of fruit. The fruits can be round or long. Their colors vary as green, cream, green with purple stripes or cream with purple stripes. This character, which is usually mentioned as the main quality criterion of the ripening stage, has been reported as an excellent harvest index for pepino. It has been accepted that pepino fruit is not starchy and is a sucrose storage. It is reported that slightly more than 50% of the sweetness of pepino is due to the sucrose content, which increases significantly during ripening. The average soluble solids content values in the fruit vary between 7.8% and 9.6% and even lower values according to some studies between 5.2% and 8.6%. Between 6 and 3 weeks before pepino harvest, the soluble solids content is low and constant. Organic acids are represented by citric acid, which constitutes 91% of the total non-volatile organic acids found in the fruits. It has been reported that the citric acid content in ripe fruits increases by 25% compared to unripe fruits. Pepino contains vitamin C at levels higher than those normally found in most fruits, including citrus fruits (48–68.8 mg/100 g of fresh tissue) [11–17].

As in other foods, the characteristic aroma of pepino is a result of the presence of volatile compounds. The aroma of a pepino fruit has been described as green, fresh and reminiscent of melon and mango. A ripe pepino has an odor reminiscent of melon melon, but when not fully ripe it has a cucumber-like odor. Pepino is quite rich in aroma compounds, which are alcohols, esters, lactones, aldehydes and ketones. A total of 50 aroma compounds were determined in the musky variety pepino, including 12 alcohols, 7 ketones, 3 lactones, 8 aldehydes, 12 volatile acids, 7 esters and 1 terpene. The total amount of aroma compounds was 12,893 μg/kg [18-19]. Among these compounds, acids were determined to be the most dominant, followed by esters and aldehydes, respectively. Esters are important aroma compounds responsible for the fruity aroma. In the miski type pepino, butyl acetate, 4-pentyl acetate and methyl-3-methyl-2butanoate are the prominent ester compounds in terms of quantity, respectively. Having low calories, being rich in minerals such as calcium, phosphorus and potassium, containing vitamins such as thiamine, niacin, riboflavin and ascorbic acid show that it is ideal for antioxidant reactions [20].

In one study, the highest antioxidant activities of various pepino extracts were reported as 22.11 μg/mL for 70% ethanol; 23.81 μg/mL for ethyl acetate; 28.31 μg/mL for water; 30.06 μg/mL for chloroform; 38.92 μg/mL for petroleum ether and hexane [21]. The phenolic content of pepino fruit was found to be much higher than vitamin C, indicating that the bioactive content of pepino may have an important role [22,23]. Pepino and its species have been traditionally used in the treatment of diabetes mellitus, hypertension and some tropical diseases. In addition to its remarkable morphological properties, pepino has also been reported to have antitumor, anti-inflammatory, antidiabetic and antioxidant activities in various studies. Therefore, it is a food product that can contribute to dietary antioxidant intake [24-29].

In addition, *Solanum muricatum* has been investigated for its potential to improve symptoms of osteogenesis imperfecta, as it has been found to promote osteogenic differentiation [30]. However, a study has also highlighted that pepinone may aggravate alcohol-induced liver damage [31]. The phenolic profile and biological activities of pepino fruit have also been investigated, emphasizing its increasing importance as an edible and juicy fruit native to the Andean region [32]. These findings suggest that pepino peels may be potentially useful in the development of natural antioxidant agents, supplements, and possibly in the treatment of bone-related conditions. However, caution should be exercised in consuming amounts in cases of liver damage.

This study aims to produce and characterize biocomposites using *Solanum muricatum* powders as organic fillers in order to contribute to the development of sustainable materials in line with increasing environmental concerns. Pepino fruit, which is widely used as waste in agriculture and food industry, has been evaluated as a low-cost and environmentally friendly biomass source. These biocomposites prepared with UPR matrix offer an alternative material for various structural and insulation applications, combining advantages such as lightness, thermal insulation and low carbon footprint. The bulk density, Shore D hardness, surface morphology, thermal conductivity coefficient and thermal stability of biocomposites produced with different ratios of pepino powder reinforcement were investigated comprehensively. This research determines the optimum filler ratio by revealing the effect of organic filler ratio on the physical and thermal properties of the biocomposite and provides valuable information for the evaluation of food industry wastes such as pepino as a sustainable source in biocomposite production.

II. MATERIAL AND METHOD

In this study, optimization and characterization of orthophthalic based unsaturated polyester resin (UPR) based biocomposites reinforced with *Solanum muricatum* (pepino) wastes were carried out. In order to prepare the composites, firstly pepino wastes were subjected to drying and grinding processes and reduced to certain particle sizes. While unsaturated polyester resin was used as matrix, methyl ethyl ketone peroxide (MEKP) was added as hardener and cobalt octoate (Co Oc) was added as accelerator. Resin, hardener and accelerator were carefully weighed in certain ratios and mixed until a homogeneous mixture was obtained. Then, pepino waste particles were added to the resin mixture in certain ratios and mechanical mixing was applied in order to provide a homogeneous distribution. The obtained mixture was poured into appropriate molds and left to cure at room temperature. At the end of the curing period, biocomposite samples were analyzed by various characterization techniques such as thermal decomposition and scanning electron microscopy (SEM) in order to evaluate thermal stability and surface properties. In addition, bulk density, Shore D hardness and thermal conductivity coefficient of the biocomposite were determined. This method approach provided a comprehensive evaluation of the structural and performance properties of environmentally friendly biocomposites reinforced with pepino wastes. Figure 1 shows the dried and ground powder structure of *Solanum muricatum*.

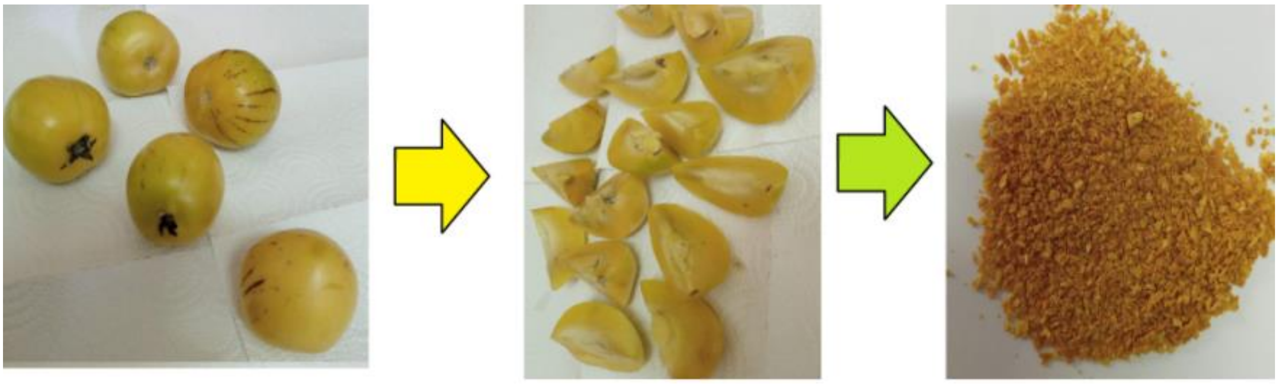

Figure 1. *Solanum muricatum* fruit, dried and ground powder structure

Figure 2 shows the scheme of obtaining biocomposite with organic fillers added into orthophthalic-based unsaturated polyester resin. Composite production with methyl ethyl ketone peroxide (MEKP), cobalt octoate and unsaturated polyester resin (UPR) is a process carried out with careful measurements. First, 100 g of UPR determined according to the final composite amount is taken into a suitable mixing container. UPR is mixed homogeneously with a certain amount of organic filler for 5 min. MEKP is used as a catalyst at approximately 1.5 wt.% (1.5 g) of the resin, and cobalt octoate (Co Oc) is used as an accelerator at 0.5 wt.% (0.5 g). In the first stage, Co Oc is added to the resin and mixed homogeneously at low speed for 2 min. Then MEKP is added and the mixture is mixed for another 1 minute to make it completely homogeneous. The resulting mixture is slowly poured into the mold to prevent air bubbles and left to cure for approximately 24 h at room temperature. If desired, the composite can be cured at 40 °C for 24 h for higher durability and thermal stability. This procedure requires the correct adjustment of the amount of each component, as incorrect application of the proportions may adversely affect the mechanical properties of the composite [33-35].

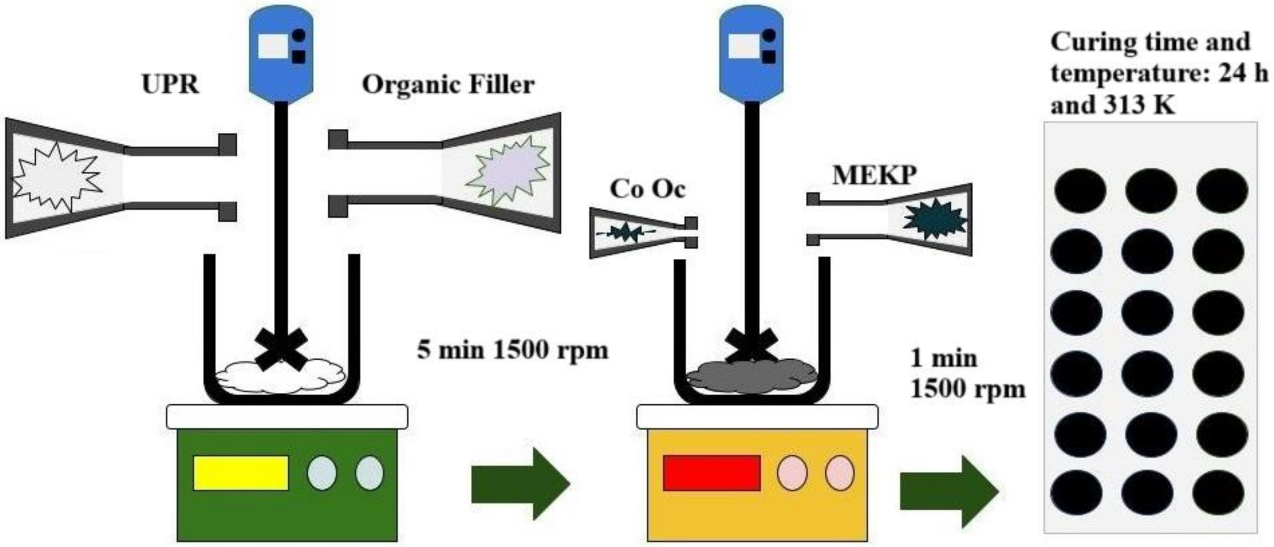

Figure 2. Scheme of obtaining biocomposite by adding organic fillers to orthophthalic based UPR

III. RESULTS AND DISCUSSION

The physical and thermal properties of *Solanum muricatum* (pepino) reinforced unsaturated polyester resin (UPR) based biocomposites were evaluated within a wide analysis framework depending on the filler ratio. Firstly, it was observed that the addition of organic filler caused a significant decrease in the bulk density of the biocomposite (Figure 3). Since pepino wastes provide a lower density structure, the addition of filler at the ratios of 2 wt.%, 4 wt.%, 6 wt.%, and 8 wt.% reduces the overall density of the composite and provides a lightweight structure. Low density may allow the biocomposite to be preferred in areas requiring lightweight materials, especially providing savings in transportation and energy costs [36-39]. When evaluated in terms of Shore D hardness, a gradual decrease in the hardness value occurred with the increase in pepino filler ratio (Figure 4). This decrease is due to the fact that the filler is not distributed homogeneously in the matrix and the bond between the matrix and the filler is weakened at higher filler ratios [40-43]. Therefore, although the decrease in the hardness of the biocomposite provides advantages in applications requiring more flexible and soft properties, it may be a limiting factor in areas requiring structural durability. In order to provide the balance between hardness and density at the optimum filler ratio, 4 wt.% filler ratio was determined as ideal. Thermal conductivity coefficient and thermal stability of the biocomposite also vary depending on the filler ratios [44-46]. A significant decrease occurred in the thermal conductivity coefficient with the increase in the amount of pepino filler (Figure 5). The organic filler increases the thermal insulation property by interrupting the heat conduction paths within the composite, which enables the biocomposite to be used in energy efficient insulation applications. However, in terms of thermal stability, exceeding the optimum level caused some disadvantages. According to the thermal analysis results, while the thermal stability of the composite structure remained high at 4 wt.% filler ratio, a decrease in the thermal resistance capacity of the structure was observed due to the increased porosity at 6 wt.% and 8 wt.% organic filler ratios. High filler ratios limit the heat resistance of the biocomposite due to the micropores and rough surface morphology that occur as a result of the insufficient integration of the filler with the matrix. In SEM images, significant irregularities and pore structures were observed on the surface in fillers at 6 wt.% and 8 wt.% ratios; This is a factor that reduces the mechanical and thermal strength of the composite and increases its brittleness. As a result, 4 wt.% filler ratio for UPR biocomposites with pepino powder addition provides optimal performance in terms of both thermal stability and mechanical strength, while losses in surface integrity and thermal resistance are observed at higher ratios [47-49].

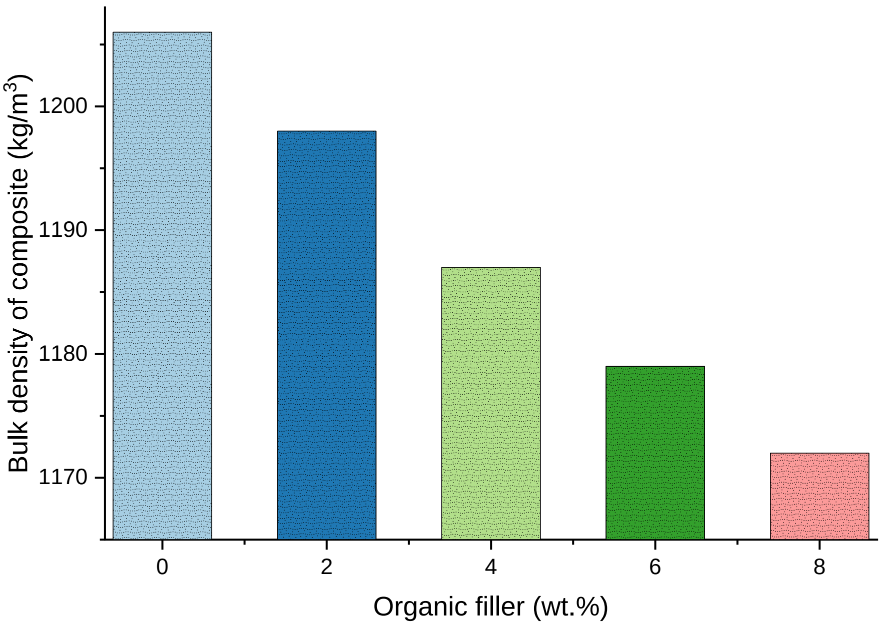

Figure 3. Effect of *Solanum muricatum* powder reinforcement on bulk density of UPR based composite

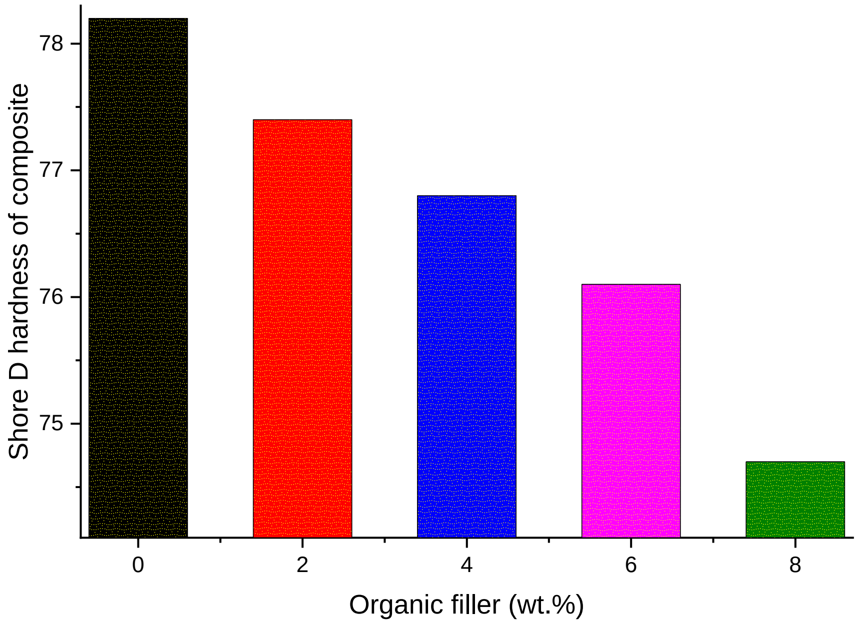

Figure 4. Effect of *Solanum muricatum* powder reinforcement on hardness of UPR based composite

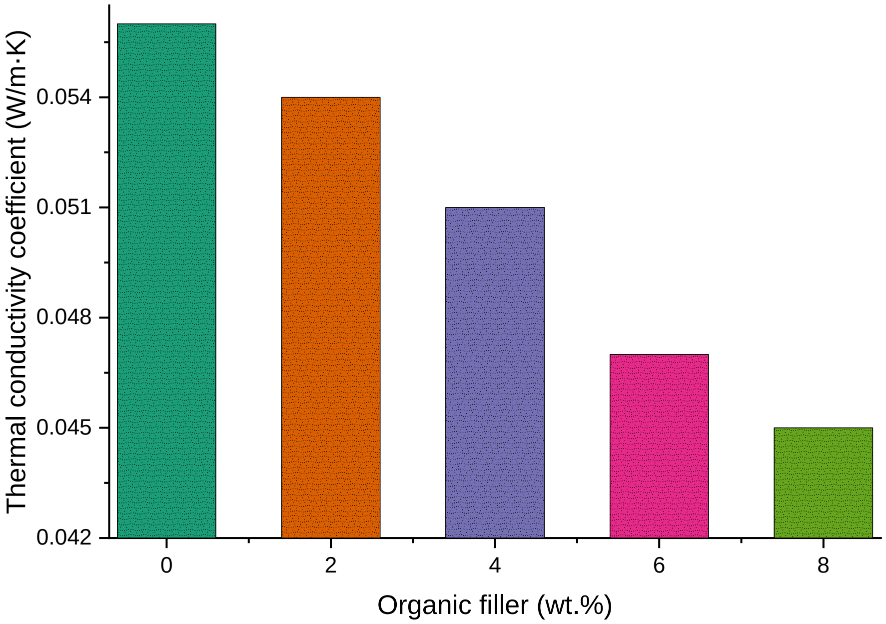

Figure 5. Effect of *Solanum muricatum* powder reinforcement on thermal conductivity of UPR based composite

The surface morphology of *Solanum muricatum* (pepino) powder reinforced orthophthalic based unsaturated polyester resin (UPR) composites was analyzed in detail by scanning electron microscopy (SEM) at different filler ratios (0 wt.%, 2 wt.%, 4 wt.%, 6 wt.%, and 8 wt.%). In the pure UPR sample, it is seen that the surface has a homogeneous, smooth and non-porous structure; this structure reflects the pure and unfilled form of the epoxy matrix and no phase separation or irregularity is observed on the surface. In this case, the UPR matrix presents a full-density structure without a filler effect. With the addition of 2 wt.% pepino waste, it is observed that the filler particles are homogeneously distributed on the surface and a good harmony is achieved between the matrix and the filler. Thanks to the low filler ratio, no large pores are formed on the surface and the surface integrity of the composite is preserved. This ratio provides a structure where the matrix-filler compatibility is sufficient and the filler affects the surface properties at a minimum level. The 4 wt.% filler ratio was determined as the optimum ratio in this study and it is seen that the interface compatibility between the matrix and the filler is high in SEM images (Figure 6). This ratio represents a structure where the filler particles are distributed homogeneously and evenly, and minimum pores or voids are formed on the surface. It was observed that the filler particles were well integrated within the matrix and a smooth surface morphology was provided in the composites obtained with a 4 wt.% filler ratio. However, when the filler ratio was increased to 6 wt.%, distinct porous structures and irregularities began to appear on the surface with the increase in the filler amount. At this ratio, the gaps between the filler particles increase, and the interface fit between the filler and the matrix weakens. Clusters of filler material and microscopic voids are observed in the matrix, which increases the surface roughness of the composite and presents a structure that can negatively affect mechanical strength. At a filler ratio of 8 wt.%, these effects become more pronounced; SEM images show that a high filler ratio significantly deteriorates the surface morphology (Figure 7). This ratio indicates a structure where the filler particles cannot show a homogeneous distribution within the matrix, filler clusters are formed, and the interface fit between the matrix and the filler is seriously weakened. The increase in pores and irregularities negatively affects the integrity on the surface and weakens the structural strength of the composite [50-53]. The phase separation observed at these rates increases the brittleness of the composite and leads to deterioration of the surface morphology. In general, while the surface morphology remains homogeneous and smooth at 0 wt.% to 4 wt.% filler rates, the increased porous structure and irregularities at 6 wt.% and 8 wt.% filler rates negatively affect the surface integrity. These analyses reveal that pepino powder reinforcement creates different effects on the surface morphology depending on the filler ratio and that 4 wt.% filler rate offers the most suitable structure for optimal performance.

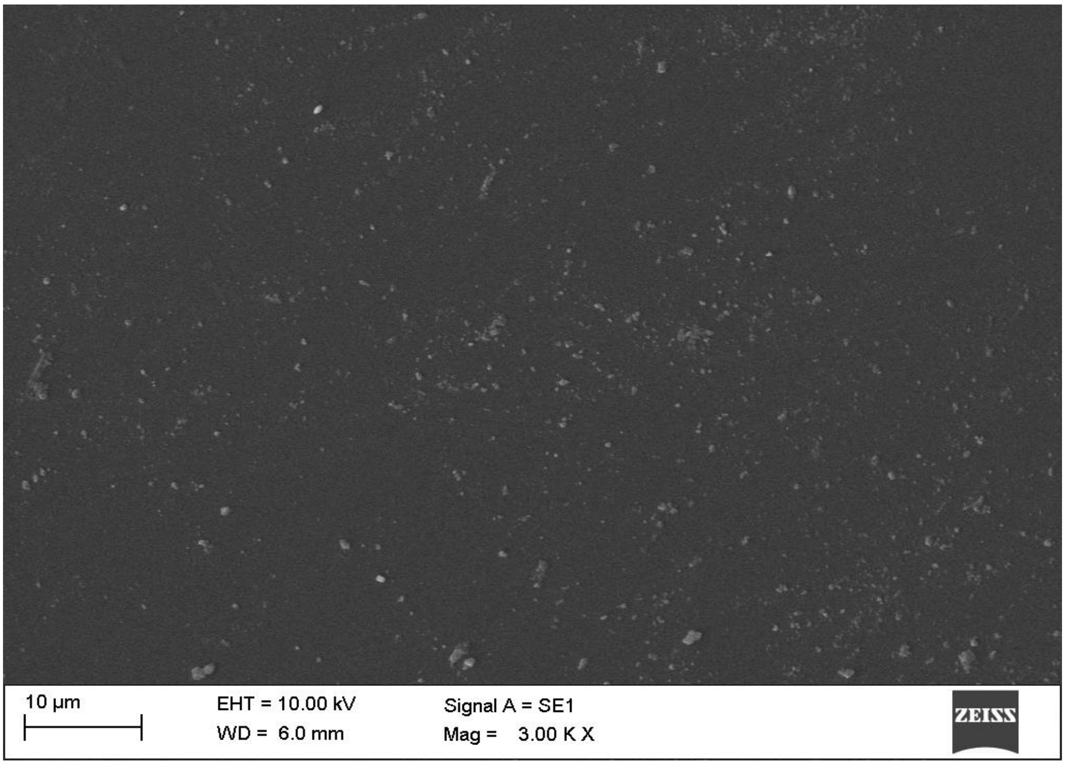

Figure 6. SEM image of UPR based composite with 4 wt.% *Solanum muricatum* powder addition

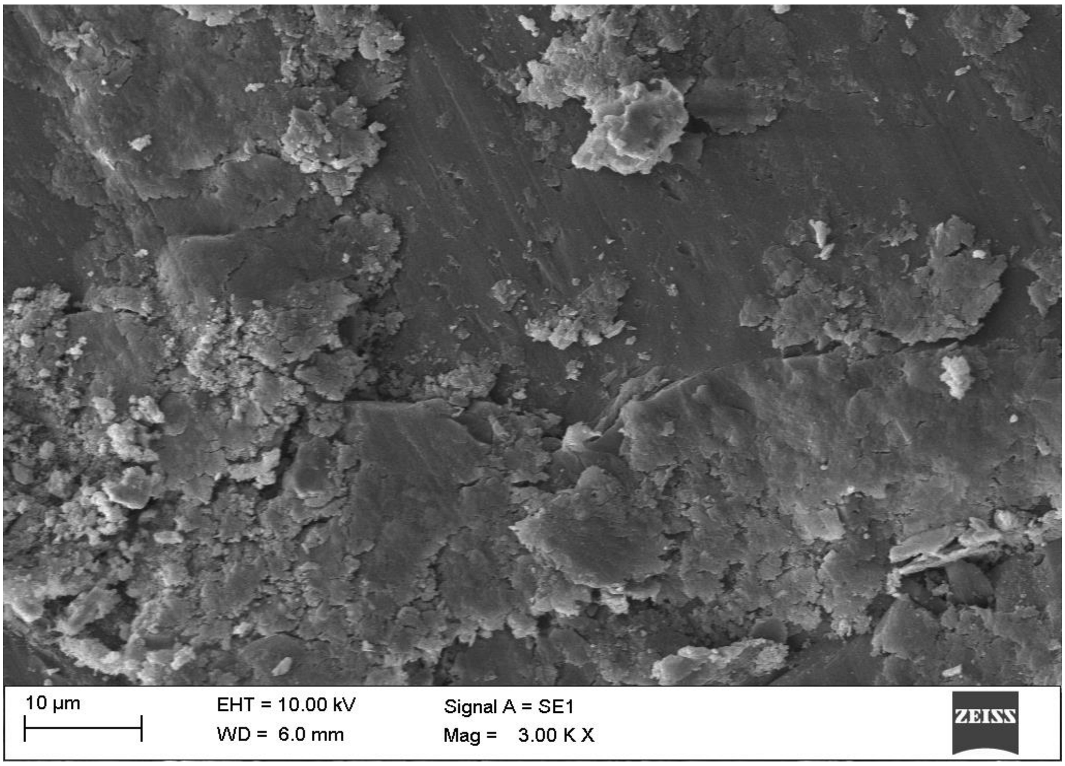

Figure 7. SEM image of UPR based composite with 8 wt.% *Solanum muricatum* powder addition

Fourier transform infrared spectroscopy (FTIR) spectra of orthophthalic based unsaturated polyester resin (UPR) reinforced with *Solanum muricatum* (pepino) waste provide important information in terms of understanding the structural properties of the composite and the interactions between the reinforcement material and the matrix (Figure 8). FTIR analysis allows us to understand whether there is any chemical change in the polyester resin structure with the addition of pepino waste and how the reinforcement material interacts with the matrix. The characteristic functional groups of UPR are largely preserved even when pepino reinforcement is added, indicating that there is no chemical change in the main structure of the composite. This reveals that pepino reinforcement is integrated into the polyester matrix with a physical bond and no chemical bonding occurs. Typical FTIR bands belonging to UPR are observed around 1720 cm^{-1} for carbonyl (C=O) group, approximately 1100-1250 cm^{-1} for C–O stretching vibration and around 1500 cm^{-1} for aromatic C=C stretching vibration. When pepino wastes are added, these bands are basically preserved and there is no significant change in their peak positions or intensities. This confirms that pepino wastes are physically integrated into the structure and no chemical bonding occurs. The presence of pepino wastes in the FTIR spectrums can be manifested by a broad OH stretching vibration observed in the range of 3300-3500 cm^{-1}. This peak represents the hydroxyl groups naturally found in pepino wastes and indicates a physical bonding between the matrix and the filler. In addition, slight changes in C–H stretching vibrations in the range of 2800-3000 cm^{-1} can be observed in the FTIR spectra when pepino wastes are added [54-57]. These changes may indicate that organic compounds on the surface of pepino wastes are in physical interaction with the matrix. As the filler amount increases, slight increases in the intensity of OH and C–H stretching vibrations can be observed, but these increases do not indicate a new chemical bond, but are only considered as an indicator of physical reinforcement. These FTIR findings indicate that pepino wastes function as a physical filler material in the UPR matrix, do not chemically react with the polymer matrix, but provide physical integration in the structure. This physical interaction leads to significant changes in the mechanical and thermal properties of the composite depending on the filler amount, and FTIR analyses stand out as an important tool in understanding the nature of these interactions [58,59].

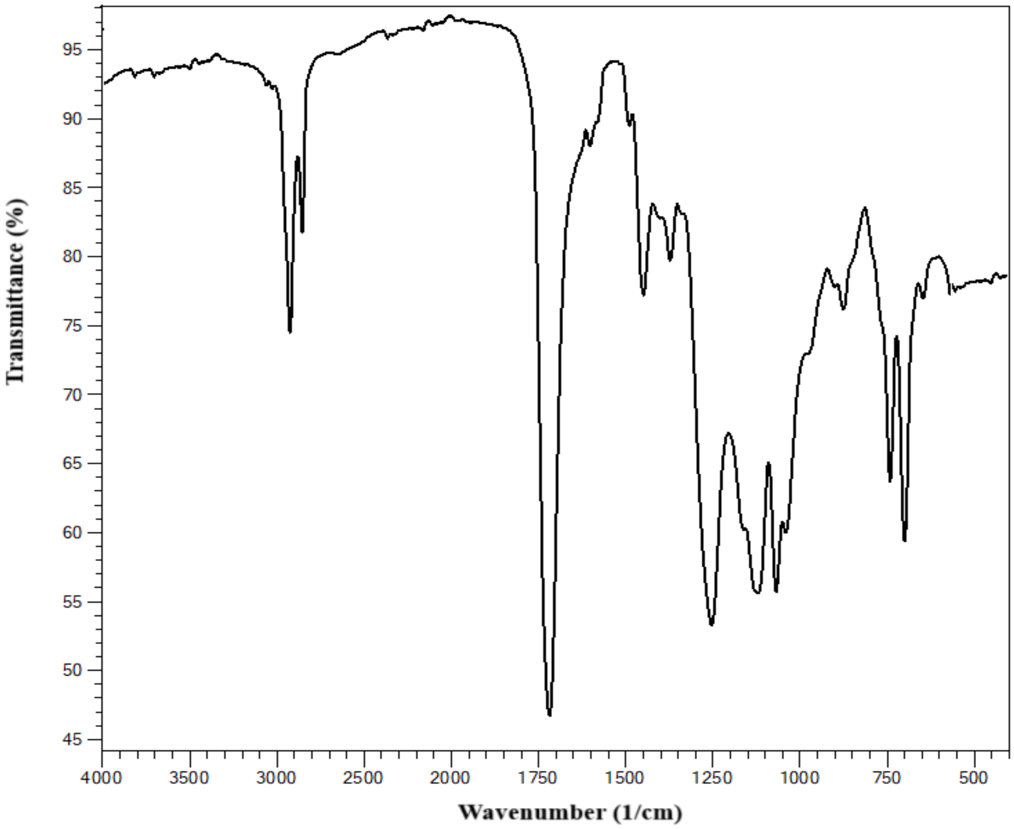

Figure 8. FTIR spectra of UPR based composite with 4 wt.% *Solanum muricatum* powder addition

IV. CONCLUSIONS

This study demonstrates that incorporating pepino (*Solanum muricatum*) waste as an organic filler in unsaturated polyester resin (UPR) matrices produces viable biocomposites with environmentally favorable properties. The addition of pepino powder effectively reduces the bulk density, Shore D hardness, and thermal conductivity coefficient of the biocomposites, contributing to their lightweight nature and potential for thermal insulation applications. However, as the filler content increases beyond the optimized 4 wt.% ratio, adverse effects on both surface morphology and thermal stability become evident. Specifically, biocomposites with higher filler concentrations exhibit increased porosity and uneven pore distribution, which compromises their structural integrity and mechanical resilience. Thermal stability at 8 wt.% pepino powder, suggesting limitations in the heat resistance of these biocomposites under excessive filler loadings. Additionally, FTIR spectroscopy reveals that the interaction between UPR and pepino particles is primarily physical, not chemical, reinforcing that optimal filler levels are crucial to maintaining the material's properties. Overall, this research highlights the potential of using pepino waste in biocomposites as a sustainable approach to developing low-carbon footprint materials, though careful filler optimization is essential to preserve performance characteristics.

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