Effect of e-waste materials as filler in the flax woven fiber reinforced polymer composite for a sustainable environment

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RESEARCH ARTICLE

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Effect of e-waste materials as filler in the flax woven fiber reinforced polymer composite for a sustainable environment

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Abstract

The main aim of the present investigation is to fabricate waste printed circuit board (WPCB) particles and woven bidirectional flax fiber mat reinforced polymer matrix composite through a hand layup technique followed by vacuum bagging technique and examine its mechanical properties using the Universal Testing Machine (UTM), compression testing machine, and Shore D hardness tester. The WPCB particles with weight percentages of 0, 5, 10, 15, and 20 were used as reinforcement along with five layers of flax fiber mat to improve the adhesion behavior of epoxy resin with reinforcements and thereby improve the properties. The XRF (X-ray fluorescence) investigation of the prepared WPCB particles confirmed the existence of various toxic elements in the processed printed circuit board (PCB). The scanning electron microscopy (SEM) analysis confirmed the presence of WPCB particles in the composite, along with flax fiber and resin. The tensile, compression, impact test shows that that the 15 wt.% WPCB particles reinforced flax fiber polymer composite gave betters properties, and the reduction of properties was seen thereafter. The percentage of water absorption increased with the weight percentage of the WPCB particles from 0% to 20%. Results indicate that the biodegradable flax fiber composites impregnated with WPCB filler can be utilized for many engineering and domestic applications.

KEYWORDS

flax fiber-reinforced polymer matrix composite, vacuum bagging process, waste printed circuit board

1 | INTRODUCTION

The increasing rise of industrial and socioeconomic advancements necessitates greater utilization of accessible materials with desired qualities. Composite materials have emerged in the modern period due to their strength, stiffness, density, cheaper cost, and enhanced sustainability (Abou-Zeid et al., 2015; Chrispin Das et al., 2021; Prabhuram et al., 2021). Despite the introduction of synthetic fibers, fiber-producing plants are still very significant and are increasingly gaining commercial importance in the industry. The researchers have researched the natural fiber reinforcements, including leaf seed, core, bast, sugarcane baggase, grass, reed, wood, and waste (Mohammed et al., 2015). One of the strongest natural fibers is flax fiber, which contains cellulose and is frequently employed in engineering applications. It is obtained from the flax plant through the retting process, in which the skin is stripped of its fibers (Xiong et al., 2018). This use of flax fiber goes as far as replacing wood in the manufacture of furniture. Arun Prasath et al. studied the effect of the addition of basalt fiber as reinforcement in a flax fiber reinforced composite. They studied the low velocity impact performance of the different percentages of basalt fiber reinforced 10-layered flax fiber composite. The result revealed that 10% basalt fiber had enhanced properties compared to flax fiber composite (Arun Prasath et al., 2020). Tronc et al. researched the esterification of blue agave fiber for thermoplastic composite reinforcement. The environmentally friendly composite made of Portland cement and *Agave lecheguilla* has a high tensile strength (Tronc et al., 2007).

Mobile devices, computers, and tablets have swiftly and intensely taken over daily life and become necessary

Mobile devices, computers, and tablets have swiftly and intensely taken over daily life and become necessary. Companies continuously develop new, inventive items that perform better than those produced previously, yet many of them are not built to last. This rapid increase in their disposal is caused by how quickly castoff elements from electronic equipment become garbage. In addition to posing a risk to human health, the effects of particular elements' toxicity on the environment can also have an adverse effect on the health of various ecosystems (Jianzhi et al., 2004). The circular economy is greatly benefited by the careful disposal of electronic trash after its useful life and the recovery of resources. It completes the cycle by taking the trash out of its disposal locations, processing it once more, and adding it back into the manufacturing process. The primary resources of metals and energy can be preserved in this way for the following generation (Kumar, 2020). Printed circuit boards (PCBs), which can be found in computers, cell phones, TVs, and other electronic devices, are inserted into electronic garbage. These boards typically consist of fiber glass and resin, with thin copper layers on top where electronic components are connected. They also contain hazardous heavy elements such as tin, copper, lead, zinc, nickel, antimony, chromium, strontium, barium, and so on (Oguchi et al., 2013; Park & Kim, 2019; Vermeşan et al., 2019). PCBs may differ depending on the type of equipment, although they often include the same components (Szałatkiewicz, 2014). Recyclable PCBs have a diverse composition, which makes recycling methods challenging. But in exchange, the fact that common and valuable metals are present makes it a fascinating source of secondary raw materials (Veit et al., 2002). Based on this, the objective of the research is to recycle the powdered WPCB particles as reinforcement in polymer matrix composites to reduce the availability of PCB in the environment. The authors thought that this was also one way to handle e-waste materials. Therefore, this work involved the infusion of powdered WPCB particles in the flax fiber-reinforced polymer matrix composite and investigating its mechanical and chemical properties.

1.1 | Selection of fibers

Due to the extremely crystalline structure of the secondary cell wall, flax fiber is stiff and sturdy all the way along its length (Scida et al., 2017). Flax fibers crystalline form and amorphous existence cause its qualities, such as stiffness and strength, to vary in the lateral as opposed to the longitudinal direction. Composites made of flax fiber and epoxy has strong tensile strength but poor compressive strength (Perremans et al., 2018). From Exhibit 1 shows, Flax fiber has more tensile strength than other natural fibers. In addition to this the fatigue resistance of flax fiber is higher than that of any other natural fiber. It has been observed that the elastic modulus of flax fibers can either raise or decrease during the course of their fatigue cycles in the fiber direction.

2 | MATERIALS AND METHODS

The processed WPCB particles with an average particle size of 75 μm were reused as reinforcement due to their disposal problems in the atmosphere. The PCBs are the integrated components of many electronic devices such as mobile phones, computers, televisions, and so on. The disposal of these PCBs will release hazardous gases into the environment. However, the technological improvement increased the outcome of PCBs, which are now called e-waste materials. Therefore, the author decided to reuse the PCBs as reinforcement in the polymer matrix composite along with kerf natural fibers. Since flax fiber has a higher strength than other plant-based fibers, it is regarded as the best reinforcement component in the polymer composite. The mat type flax fibers were collected from Anakaputhur in Tambaram, Tamil Nadu, India. Because of the enhanced mechanical features such as high strength, resilience, and toughness, the epoxy resin (LY556) and curing agent (HY559) were employed as the matrix materials, along with flax fiber and WPCB particles. These materials were purchased from a local vendor in Chennai called Shakti Glass.

The processed WPCB particles with an average particle size of 75 μm were reused as reinforcement due to their disposal problems in the atmosphere

Initially, WPCBs were collected from the local old material market in Chennai, as shown in Exhibit 2a. The mounted electronic devices, such as capacitors, relays, resistors, transistors, and so on, were desoldered from the board using a tool working with the aid of hot air. The necessary safety precautions were followed during the desoldering process, since it produces toxic gases, causing serious health issues. After the proper removal of unwanted materials from the WPCBs, they were pulverized and sieved to get a particle size of 75 μm. Exhibit 2b shows the sieve shaker used after the pulverization process. Finally, the prepared

EXHIBIT 1 Properties of flax fiber (Celino et al., 2014).

Fiber	Density (g/cm^3)	Young's modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)
Flax	1.54	27.5–85	345–2000	1–4
Kenaf	1.2	14–53	240–930	1.6
Hemp	1.47	17–70	368–800	1.6
Jute	1.44	10–30	393–773	1.5–1.8
Sisal	1.45–1.5	9–22	350–700	2–7
Cotton	1.5–1.6	5.5–12.6	287–597	7-8
Bamboo	0.6–1.1	11–17	140–230	–

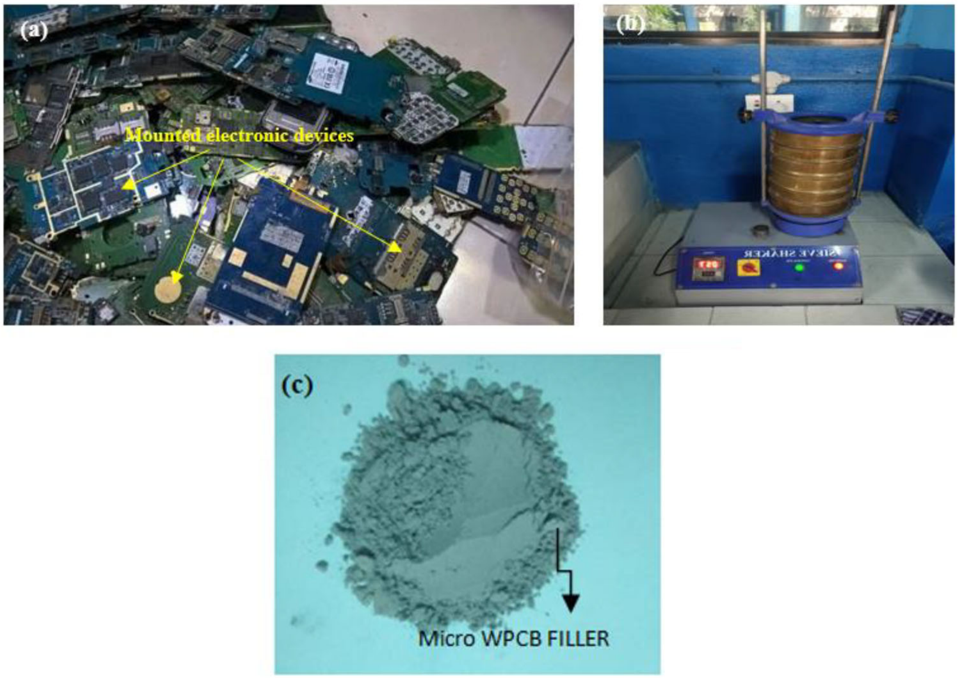

EXHIBIT 2 (a) Collected WPCB for our experimental evaluation; (b) Sieve shaker used to collect the WPCB particles with the dimension of 75 μm; (c) Prepared micron sized WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

micron sized WPCB particles are shown in Exhibit 2c. The SEM image of the prepared particles is shown in Exhibit 3.

XRF (X-ray fluorescence) analysis was performed on the processed WPCB particles to confirm the existence of environmentally hazardous materials. One of the main advantages of XRF is that it can analyze a wide range of elements, from light elements such as carbon and oxygen to heavy elements such as uranium and plutonium, with high sensitivity and accuracy. XRF analyzers identify alloys, detect tramp elements, deliver geochemical data, analyze precious metals, and determine coating weight and plating thickness, to ensure material chemistry specifications. Also XRF can give details as to the chemical composition of a sample (Caporale et al., 2018; Dewi et al., 2018; Oyedotun, 2018). Exhibit 4 shows the outcome of the XRF analysis. It confirmed the huge presence of major heavy elements such as tin (30.5%), copper (17.7%), and iron (8.7%) in the form of oxides (CuO, SnO_2 and Fe_2O_3) and the minimal amount of toxic materials such as Cr (0.36%), Zn (1.26%), Br (22.9%), Pb (10.2%), Sr (0.41%), Mn (0.29%),

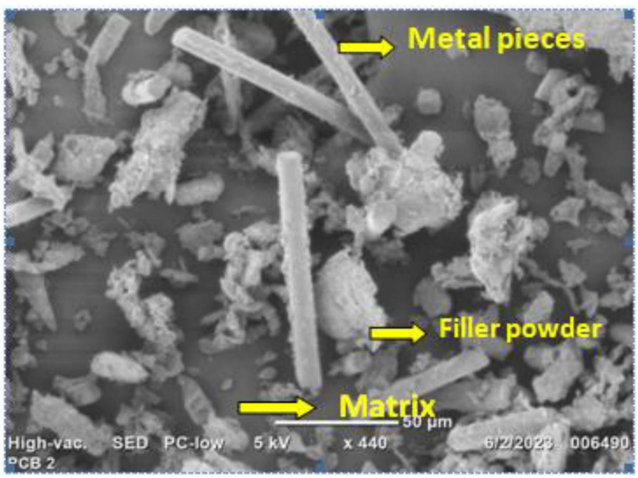

EXHIBIT 3 SEM image of the prepared WPCB particles at 50 μm. [Color figure can be viewed at wileyonlinelibrary.com]

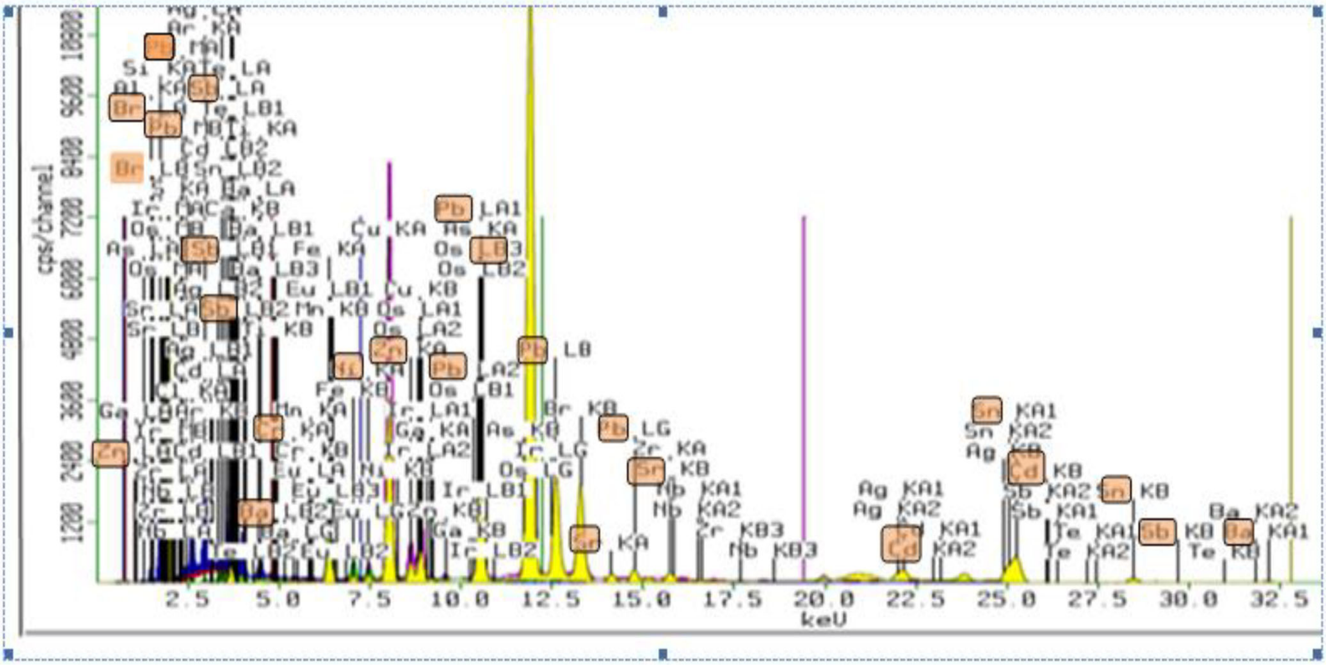

EXHIBIT 4 XRF pattern of prepared WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

EXHIBIT 5 XRF elemental composition of processed WPCB particles.

Compound	SnO_2	CuO	Br	PbO	Fe_2O_3	BaO	ZnO	NiO	Sb_2O_3	Cr_2O_3	SrO	MnO
Wt. (%)	30.5	17.7	22.9	10.2	8.7	5.9	1.26	0.87	0.55	0.36	0.41	0.29

and Ni (0.87%) in the form of oxides (Cr_2O_3, ZnO, PbO, and NiO). Only the available hazardous materials in WPCB powder are calculated in percentages which are measured through XRF are tabulated in Exhibit 5.

After placing the peel-ply sheet, the resin coating was applied. Then flax fiber mat was placed over the resin coating, and this process was repeated for five layers of flax fiber mat. Finally, a breather cloth was included to remove the unused resin from the mold. After bagging, the sides were sealed with tape. Finally, a vacuum pump was used to suck the unneeded epoxy resin inside the mole. The vacuum bag was sealed off, and the composite was removed. Exhibit 6 shows the process of making the composite using the vacuum bagging process. The five composites are fabricated by varying the weight percentage of WPCB particles along with an equal proportion of flax fiber, and the composition of all five combinations is tabulated in Exhibit 7.

To determine the tensile strength of the material, specimens were prepared (Exhibit 8a and 8b) as per ASTMD3039 ($120 \times 20 \times 3$ mm^3) in an UTM (universal testing machine) by Dak System Inc., make 7200Series. Three specimens for each WPCB filler concentration were calculated, and the average value was noted.

The compressive measurement was performed on the fabricated polymer composite samples using a compression testing machine (Dak System Inc., Make, 7200Series) as per ASTM D3410 standards. The three samples were tested with dimensions of $120 \times 25 \times 3$ mm at a speed of 2 mm/min under a load of 100 kN (Exhibits 8c and 8d.

Flexure test was conducted as per ASTM D- 790 standards in three point bending test machine. The size of specimens used are 125 mm in length, 12.7 mm in breadth and 3.2 mm in thickness as shown in Exhibit 9a and 9b. The load capacity of the fabricated WPCB-reinforced polymer composite was studied through the impact test analysis in the Izod impact test as per the ASTM D256 standard. A load of 10 kJ was applied to break the composite specimens (64mmx12.7mmx3.2mm) using a vertically mounted pendulum hammer(as shown in Exhibit 9c and 9d), and the impact energy was examined in J/m.

Mostly, the hardness of the fiber-reinforced composites is measured through the Shore D hardness test. This was measured using a shore durometer machine as per the ASTM D2240 standard. The reading scale is from 0 to 100. Higher value shows high hardness.

The water absorption capacity of the fabricated composite was investigated to examine the expansion of fiber in the water environment. This leads to poor strength and dimensional characteristics through the formed micro cracks. The specimens of size 2″ in diameter by 0.25″ in thickness were sliced from each composite specimen to examine the water absorption behavior as per ASTM D570 standards. The low temperature preheating was done to remove the moisture content in the composite, which was weighted using a precision

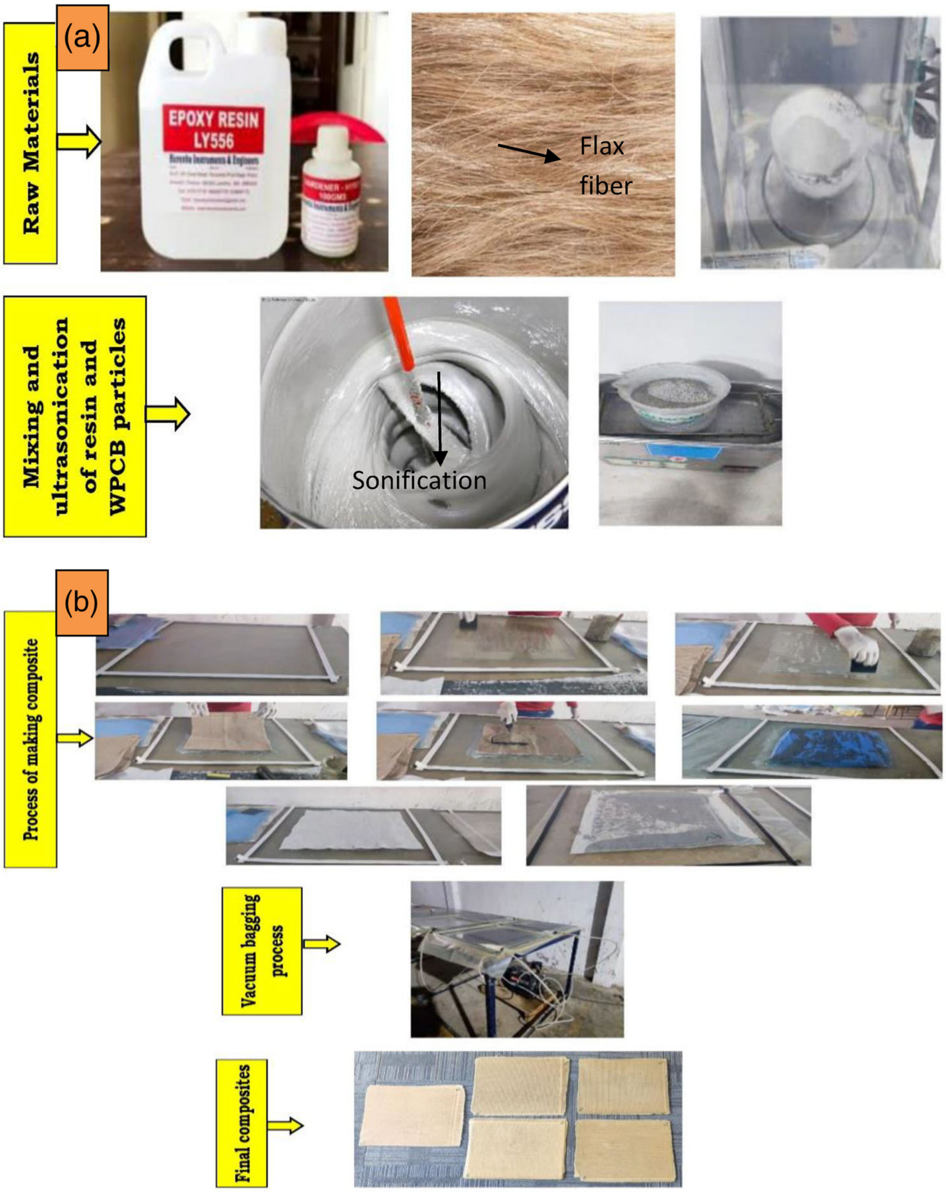

EXHIBIT 6 Fabrication of process - (a) Raw materials, resins and sonification (b) Making, vacuum bagging and cured laminate boards [Color figure can be viewed at wileyonlinelibrary.com]

EXHIBIT 7 Weight fraction of fiber layer and WPCB particles.

Sl. no.	Laminates	Amount of filler used (%)	Woven flax fiber weight per layer (gm)	Amount of WPCB filler (gm)
1	S0	0	31 + 33 + 32 + 32 + 31 = 159	0
2	S5	5	33 + 32 + 31 + 32 + 32 = 160	8
3	S10	10	32 + 32 + 33 + 31 + 33 = 161	16.1
4	S15	15	33 + 31 + 32 + 33 + 32 = 161	24.15
5	S20	20	33 + 32 + 32 + 31 + 33 = 161	32.2

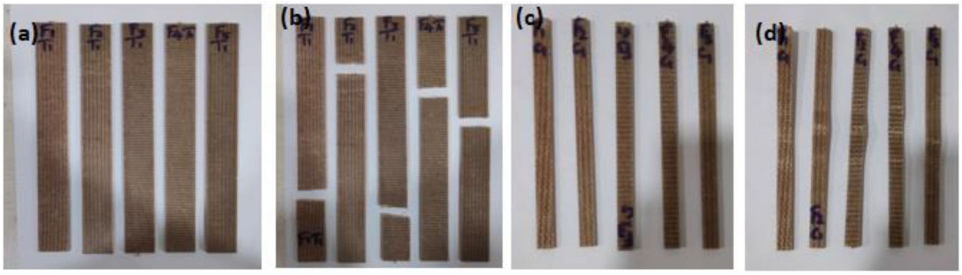

EXHIBIT 8 Tensile test specimens (a) Before test (b) after test. Compressive test specimens (c) Before test (d) after test. [Color figure can be viewed at wileyonlinelibrary.com]

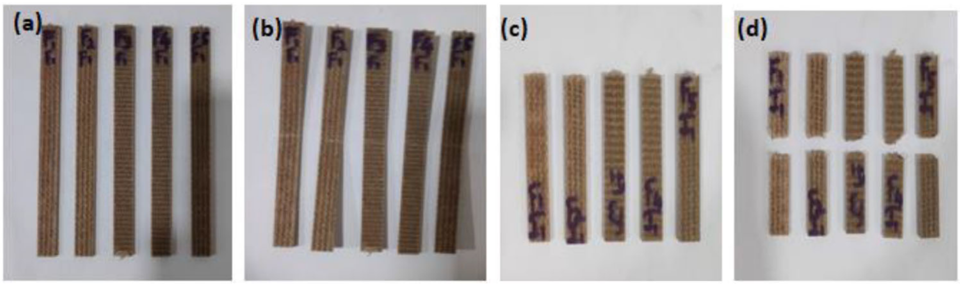

EXHIBIT 9 Flexure test specimens (a) Before test (b) after test. Impact test specimens (c) Before test (d) after test. [Color figure can be viewed at wileyonlinelibrary.com]

weighing machine. Then the samples were dipped in the water over a period of 24 hours at room temperature. After that, the immersed samples were taken out of the water and weighted to measure the weight after the immersion in water. The percentage of water absorption was measured by the weight measured before and after the experiment using the Equation (1).

$$\% \text{ of water absorption} = \frac{(w_a - w_b)}{w_b} \times 100 \tag{1}$$

3 | RESULT AND DISCUSSIONS

The SEM, mechanical properties (tensile strength, compression strength, flexural strength, impact strength, and shore D hardness), and percentage of water absorption of the fabricated WPCB particles and flax fiber-reinforced polymer matrix composite are discussed briefly in the upcoming sections.

Exhibit 10 shows the SEM images taken on the surface of the WPCB and flax fiber-reinforced polymer matrix composite fabricated through the vacuum bagging route. It confirmed the existence of woven bidirectional flax fiber with micron-sized WPCB particles. Exhibit 6a shows the polymer composite surface that is free from surface damages like microcracks and fiber breakage. Exhibit 6b shows an enlarged image of the fabricated composite in the presence of WPCB particles.

Exhibit 11 shows the line graph plotted for the tensile test outcome of the 0, 5, 10, 15, and 20 wt.% WPCB particles reinforced flax fiber polymer matrix composite. The graph showed the improvement of the tensile strength unto 15 wt.% WPCB particles reinforced flax fiber composite and it showed the maximum value of 41.13 MPa for the S15 sample. Further, it showed the immediate decrease in the tensile strength with 20 wt.% WPCB reinforced flax polymer composite (S20), which the less than the flax fiber reinforced polymer composite.

Exhibit 12 shows the line graph plotted for the compression test outcome of the 0, 5, 10, 15, and 20 wt.% WPCB particles reinforced flax fiber polymer matrix composite. The compression line graph followed almost the same pattern as the tensile graph. The graph displayed the improved compression strength at 10 and 15 wt.% WPCB particles reinforced flax fiber polymer composites, with the maximum compression strength at sample S15 (46.47 MPa). However, the S20 polymer sample showed less compression strength than the S10 and S15 samples. Moreover, the S0 and S5 samples were considered non-beneficial for the compression-based application due to their lowest compression strengths. This is due to the reduction of the effective cross section and enhanced stress concentration. On the other hand, a lack of interfacial adhesion between the matrix (epoxy resin) and reinforcements (flax fiber and WPCB particles) brought about a drop in the tensile strength of polymer composites because of the significant surface variations. Yang et al. (2007) discovered a comparable outcome in their investigation of rice husk flour and wood flour using HDPE and LDPE matrixes.

Exhibit 13 shows the line graph plotted for the flexural test outcome of the 0, 5, 10, 15, and 20 wt.% WPCB particles reinforced flax fiber polymer matrix composite. Here, the S0 sample showed less flexural

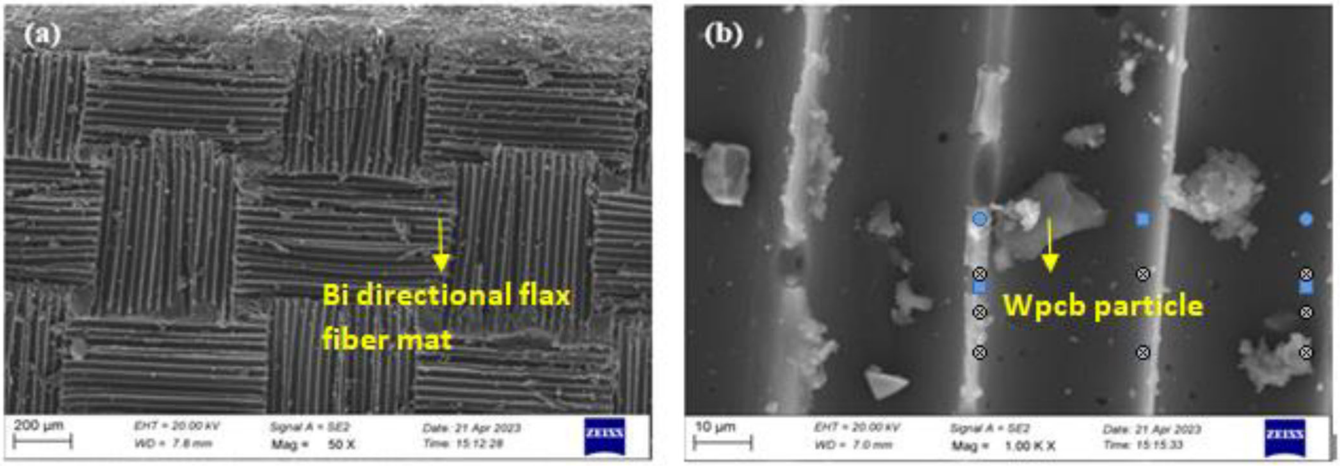

EXHIBIT 10 (a) SEM image of the WPCB and flax fiber reinforced polymer matrix composite at 200 μm; (b) Enlarged view of the fabricated composite at 10 μm. [Color figure can be viewed at wileyonlinelibrary.com]

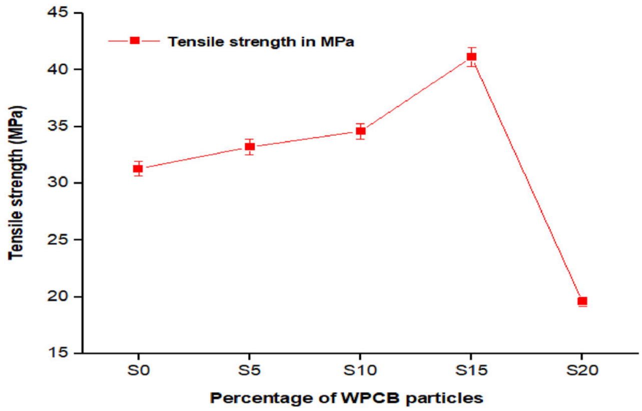

EXHIBIT 11 Tensile strength values of the fabricated composite with varied level of WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

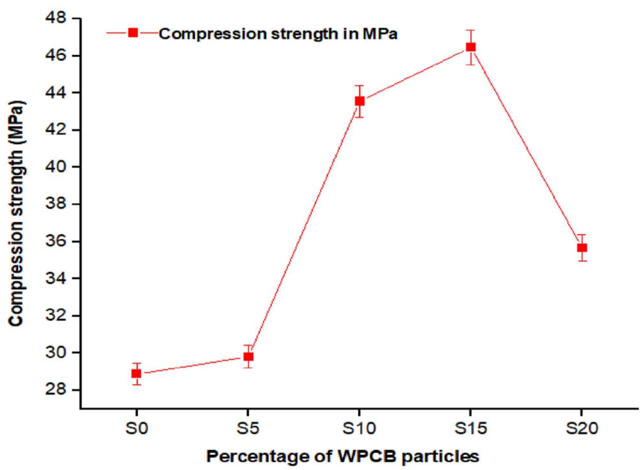

EXHIBIT 12 Compression strength values of the fabricated composite with varied level of WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

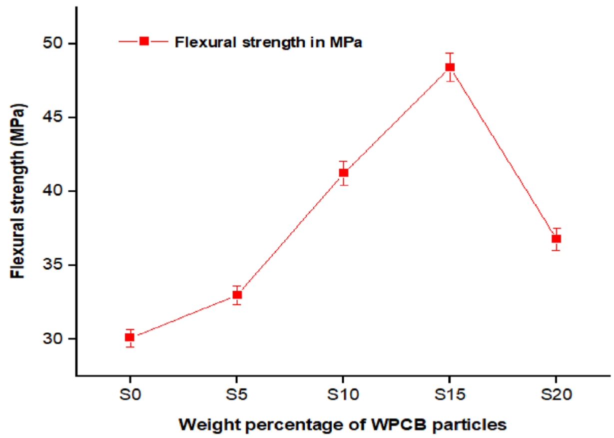

EXHIBIT 13 Flexural strength values of the fabricated composite with varied level of WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

strength, which is less than the flexural strength of the remaining samples. This could be due to the improper bonding between the flax fiber and the epoxy resin. Further, the S15 sample showed a maximum compression strength value of 48.8 MPa. Here, the included optimum percentage of WPCB particles formed efficient bonding between the matrix and reinforcement and thereby increased the flexural strength to 15 wt.%. At the S20 sample, the higher amount of particles breaks the bonding between the matrix and the flax fiber and decreases the flexural strength (ShahinoorAlam & Chowdhury, 2020).

Exhibit 14 shows the line graph plotted for the impact test outcome of the 0, 5, 10, 15, and 20 wt.% WPCB particles reinforced flax fiber polymer matrix composite. Normally, the impact strength depends on the addition of reinforcement materials to the polymer composite in the form of fibers or particles. The increase in reinforcement content increases the bonding between fiber and matrix, which in turn increases the impact strength. Because of the increased bonding, it requires more energy to break the bond between matrix and

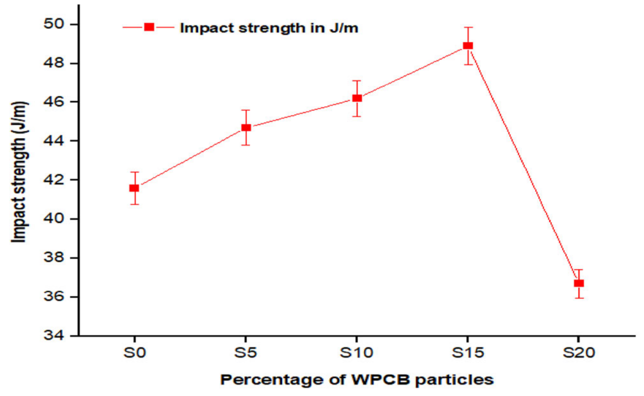

EXHIBIT 14 Impact strength values of the fabricated composite with varied level of WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

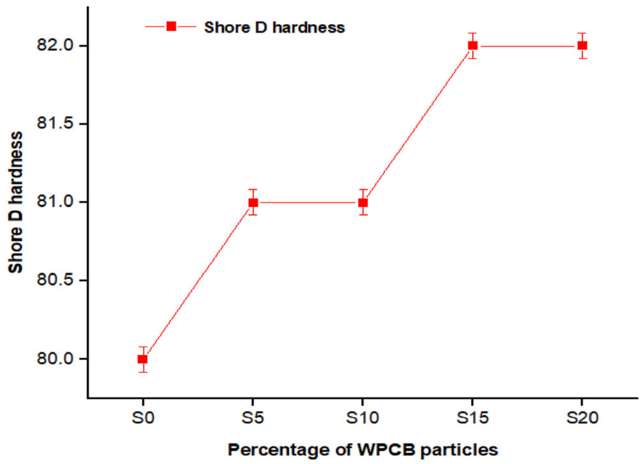

EXHIBIT 15 Shore D hardness values of the fabricated composite with varied level of WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

reinforcements. The graph clearly revealed that the increase in reinforcement enhanced the Izod impact strength of the WPCB and flax fiber polymer composite up to 15 wt.%, with the S15 showing a maximum impact strength of 48.9 J/m, which is less than all the remaining samples. However, a fall in impact strength was identified after the 15% reinforcement. This could be due to the poor adhesion behavior between the resin matrix and the reinforcement materials (Dalbehera & Acharya, 2016).

Exhibit 15 shows the line graph plotted for the shore D hardness outcome of the 0, 5, 10, 15, and 20 wt.% WPCB particles reinforced flax fiber polymer matrix composite. The WPCB-reinforced polymer composite samples showed enhanced hardness compared to the unreinforced samples. Moreover, S5 and S10 showed the same hardness value of 81, and S15 and S20 showed a hardness of 82. This increased hardness is due to the addition of WPCB reinforcement particles present in the polymer composite. Normally, the improper wettability

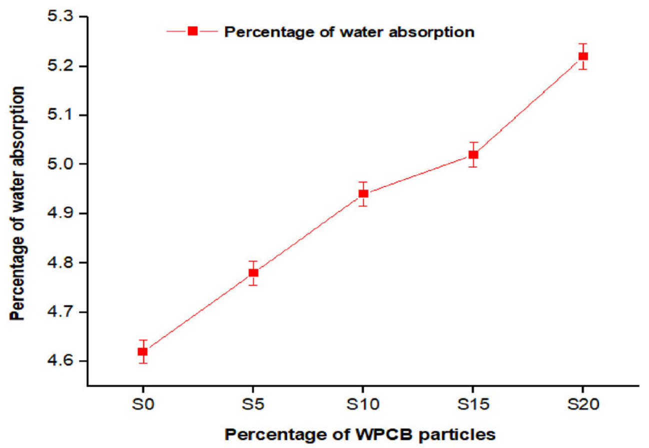

EXHIBIT 16 Percentage of water absorption of the fabricated composite with varied level of WPCB particles. [Color figure can be viewed at wileyonlinelibrary.com]

and the poor bonding between resin matrix and fiber create voids during the fabrication of polymer composite and thereby decreases the hardness (Prasad et al., 2022). In this study, the addition of WPCB micron-sized particles resisted the hardness due to its hard nature, thereby attaining the increased hardness.

Exhibit 16 shows the line graph plotted for the percentage of water absorption outcome of the 0%, 5%, 10%, 15%, and 20% WPCB particles reinforced flax fiber polymer matrix composite. It showed an increasing trend of water absorption percentage from S0 to S20, with maximum water absorption of 5.22% at the S20 sample. This could be due to the fact that the gap between the resin and the fiber is the cause of the water absorption, along with the fiber content. Epoxy, unsaturated polymer resin gel, AESO (acrylated epoxidized soybean oil), and other coatings assist prevent delamination and decrease water absorption because natural fibers absorb more water than synthetic fibers do. Chemical treatment is now possible because to advances in technology, and this allows for the capacity for water absorption to be reduced (Bachchan et al., 2022). When exposed to climatic conditions, bio-based coatings, particularly PFA, can considerably cut the amount of moisture that fiber-reinforced composites absorb while maintaining the structural integrity of the materials (Mokhothu & John, 2017).

3.1 | Morphological examination

Exhibit 17 shows the SEM image taken from the fractured surface of the 15 wt.% reinforced composite's tensile specimen. It demonstrates the breakage of flax fiber from the matrix surface. Even though, the flax fiber is breaking, the restriction toward breakage was shown by the optimal WPCB particle-reinforced composite. In addition, it clearly defined the proper bonding between the flax fiber and the epoxy resin matrix.

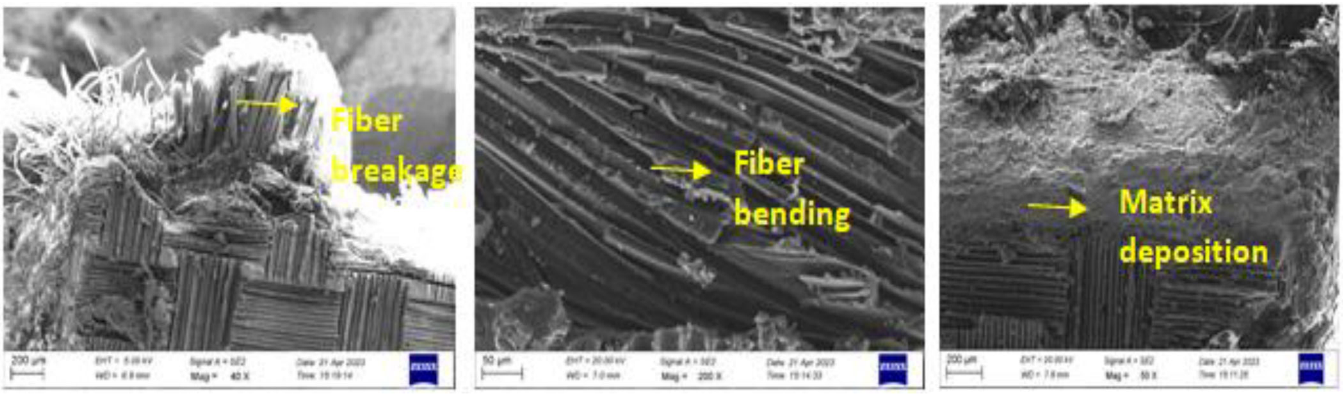

EXHIBIT 17 SEM image of the fractured tensile location of the 15 wt.% reinforced composite. [Color figure can be viewed at wileyonlinelibrary.com]

4 | CONCLUSION

- The XRF analysis confirmed the presence of toxic metals in the fabricated WPCB particles, and the SEM analysis confirmed the presence of WPCB particles in the flax fiber-reinforced polymer matrix composite.
- The mechanical properties such as tensile strength, compression strength, flexural strength, and impact test confirmed that the increase in WPCB particles increased the respective properties up to 15 wt.% due to the proper adhesion between the matrix and reinforcement particles. Further addition of WPCB particles decreased the properties due to the excess addition of fillers.
- The hardness test revealed that the addition of WPCB particles had a small effect on the shore D hardness due to the formation of voids during the formation process.
- The percentage of water absorption increased with the weight percentage of the WPCB particles. This is due to the water accumulation in the gap between the reinforcements, such as WPCB particles and flax fiber.
- Flax fiber composites impregnated with WPCB filler show an increase in value when added up to a particular concentration level. For 15% of the filler, 24.15 g of WPCB filler is added. And the laminate gives nearly equivalent values that are given by the synthetic fiber composites.
- Instead of dumping e-waste into landfills, which causes environmental pollution and human health problems, these hazardous materials can be better utilized by adding them as filler to maintain a sustainable environment.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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REFERENCES

Abou-Zeid, R. E., El-Wakil, N. A., & Fahmy, Y. (2015). Thermoplastic composites from natural reed fibers. *Egyptian Journal of Chemistry*, *58*(3), 287–298.

Arun Prasath, K., Arumugaprabu, V., Amuthakkannan, P., Manikandan, V., & Deepak Joel Johnson, R. (2020). Low velocity impact, compression after impact and morphological studies on flax fiber reinforced with basalt powder filled composites. *Materials Research Express*, *7*(1). https://doi.org/10.1088/2053-1591/ab611e

Bachchan, A. A., Das, P. P., & Chaudhary, V. (2022). Effect of moisture absorption on the properties of natural fiber reinforced polymer composites: A review. *Materials Today: Proceedings*, *49*, 3403–3408. https://doi.org/10.1016/j.matpr.2021.02.812

Caporale, A. G., Adamo, P., Capozzi, F., Langella, G., Terribile, F., & Vingiani, S. (2018). Monitoring metal pollution in soils using portable-XRF and conventional laboratory-based techniques: Evaluation of the performance and limitations according to metal properties and sources. *Science of the Total Environment*, *643*, 516–526. https://doi.org/10.1016/j.scitotenv.2018.06.178

Celino, A., Freour, S., Jacquemin, F., & Casari, P. (2014). The hygroscopic behavior of plant fibers: A review. *Frontiers in Chemistry*, *1*, 43. https://doi.org/10.3389/fchem.2013.00043

Chrispin Das, M., Athijayamani, A., Arun Vasantha Geethan, K., Santhosh, D., & Prathap Singh, S. (2021). Effects of length and content of natural cellulose fiber on the mechanical behaviors of phenol formaldehyde composites. *Materials Today: Proceedings*, *45*(2), 516–521. https://doi.org/10.1016/j.matpr.2020.02.111

Dalbehera, S., & Acharya, S. (2016). Effect of cenosphere addition on the mechanical properties of jute-glass fiber hybrid epoxy composites. *Journal of Industrial Textiles*, *46*(1), 177–188. https://doi.org/10.1177/1528083715577936

Dewi, R., Agusnar, H., Alfian, Z., & Tamrin (2018). Characterization of technical kaolin using XRF, SEM, XRD, FTIR and its potentials as industrial raw materials. *Journal of Physics: Conference Series*, *1116*, 042010. IOP Publishing. https://doi.org/10.1088/1742-6596/1116/4/042010

Jianzhi, L., Shrivastava, P., & Hong, C. Z. (2004). Printed circuit board recycling: A state-of-the-Art survey. *Ieee Transactions on Electronics Packaging Manufacturing*, *27*, 33–42.

Kumar, A. (2020). *Characterization of the non-metal fraction of waste printed circuit boards to promote recycling* (Ph.D. Thesis). University of British Columbia, Vancouver, BC, Canada.

Mohammed, L., Ansari, M. N. M., Pua, G., Jawaid, M., & Saiful Islam, M. (2015). A review on natural fiber reinforced polymer composite and its applications. *International Journal of Polymer Science*, *2015*, 15. https://doi.org/10.1155/2015/243947

Mokhothu, T. H., & John, M. J. (2017). Bio-based coatings for reducing water sorption in natural fibre reinforced composites. *Scientific Reports*, *7*(1), 13335. https://doi.org/10.1038/s41598-017-13859-2

Oguchi, M., Sakanakura, H., & Terazono, A. (2013). Toxic metals in WEEE: Characterization and substance flow analysis in waste treatment processes. *Science of the Total Environment*, *463*, 1124–1132. https://doi.org/10.1016/j.scitotenv.2012.07.078

Oyedotun, T. D. T. (2018). X-ray fluorescence (XRF) in the investigation of the composition of earth materials: A review and an overview. *Geology, Ecology, and Landscapes*, *2*(2), 148–154. https://doi.org/10.1080/24749508.2018.1452459

Park, H. S., & Kim, Y. J. (2019). A novel process of extracting precious metals from waste printed circuit boards: Utilization of gold concentrate as a fluxing material. *Journal of Hazardous Materials*, *365*, 659–664. https://doi.org/10.1016/j.jhazmat.2018.11.051

Perremans, D., Verpoest, I., Dupont-Gillain, C., & Van Vuure, A. W. (2018). Investigation of the tensile behavior of treated flax fibre bio-composites at ambient humidity. *Composites Science and Technology*, *159*, 119–126.

Prabhuram, T., Elilraja, D., Singh, P., & Durairaj, I. (2021). Investigation of mechanical and chemical properties of the coir fiber and wood powder reinforced hybrid polymer composite. In S. Vijayan, N. Subramanian, K. Sankaranarayanasamy (Eds.). *Trends in manufacturing and engineering management. Lecture notes in mechanical engineering*. Springer. https://doi.org/10.1007/978-981-15-4745-4_26

Prasad, L., Singh, V., Patel, R. V., Yadav, A., Kumar, V., & Winczek, J. (2022). Physical and mechanical properties of Rambans (Agave) fiber reinforced with polyester composite materials. *Journal of Natural Fibers*, *19*(13), 6104–6118. 10.1080/15440478.2021.1904481

Scida, D., Bourmaud, A., & Baley, C. (2017). Influence of the scattering of flax fibres properties on flax/epoxy woven ply stiffness. *Materials & Design*, *122*, 136–145. https://doi.org/10.1016/j.matdes.2017.02.094

ShahinoorAlam, M. d., & Chowdhury, M. A. (2020). Characterization of epoxy composites reinforced with CaCO3-Al2O3-MgO-TiO2/CuO filler materials. *Alexandria Engineering Journal*, *59*(6), 4121–4137. https://doi.org/10.1016/j.aej.2020.07.017

Szałatkiewicz, J. (2014). Metals content in printed circuit board waste. *Polish Journal of Environmental Studies*, *23*, 2365–2369.

Tronc, E., Hernández-Escobar, C. A., Ibarra-Gómez, R., Estrada-Monje, A., Navarrete-Bolaños, J., & ZaragozaContreras, E. A. (2007). Blue agave fiber esterification for the reinforcement of thermoplastic composites. *Carbohydrate Polymers*, *67*(2), 245–255. https://doi.org/10.1016/j.carbpol.2006.05.027

Veit, H. M., De Pereira, C. C., & Bernardes, A. M. (2002). Using mechanical processing in recycling printed wiring boards. *JOM: the Journal of the Minerals Metals and Materials Society*, *54*, 45–47.

Vermeşan, H., Tiuc, A. E., & Purcar, M. (2019). Advanced recovery techniques for waste materials from IT and telecommunication equipment printed circuit boards. *Sustainability*, *12*(1), 74. https://doi.org/10.3390/su12010074

Wu, C. M., Tsai, H. T., Yang, K. H., & Wen, J. C. (2012). How reliable is X-ray fluorescence (XRF) measurement for different metals in soil contamination? *Environmental Forensics*, *13*(2), 110–121. https://doi.org/10.1080/15275922.2012.676603<./bib>

Xiong, X., Shen, S. Z., Alam, N., Hua, L., Li, X., Wan, X., & Miao, M. (2018). Mechanical and abrasive wear performance of woven flax fabric/polyoxymethylene composites. *Wear*, *414–415*, 9–20. https://doi.org/10.1016/j.wear.2018.07.010

Yang, H. S., Wolcott, M. P., Kim, H. S., & Kim, H. J. (2007). Effect of different compatibilizing agents on the mechanical properties of lignocellulosic material filled polyethylene bio-composites. *Composite Structures*, *79*, 369–375.

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