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Effect of filler particle size on of pine dust-filled recycled HDPE composites

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Abstract

This research investigated the incorporation of pine dust; a residual material from the furniture industry, into recycled high-density polyethylene (HDPE) to form a wood plastic composite (WPc) and analyzed how this integration affects the structure, mechanical properties, and water absorption of the resulting WPc. Here, after necessary required processing, different samples of different wt% (0wt%, 5wt%, 10wt%, 15wt%, 20wt%, 25wt%, and 30wt%) and various sizes (less than 250 μm, 250-500 μm, and 500-1000 μm) of pine dust were mixed into recycled HDPE and fed into a single extrude extruder at 210 ^{0}C. The morphologies of the all-prepared samples were taken via stereoscopy microscopy. The tensile test, impact test, and water absorption quality of all WPc samples were tested. The test results showed that the ultimate load and strength were maximum at 15wt%, 20wt%, and 10wt% of 500-1000 μm, 250-500 μm, and less than 250 μm particle size mixed WPc, respectively. The impact test showed the impact resistance was maximum at 15wt% mixed pine dust WPc in all particle sizes. Similarly, water absorption was found to be increased with the increment of wt% of pine dust of all particle sizes in recycled HDPE.

***Keywords*:** recycled HDPE, pine dust, wood plastic composite.
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1. Introduction

Growing environmental concerns regarding plastic and wood waste are attracting increasing interest due to their significant volume and negative impacts on an atmospheric environment [1]. Non-biodegradable plastic waste stances waste management challenges and adds to plastic accumulation, harming habitats and fauna [2], [3], [4]. Improper management of wood waste leads to the depletion of useable resources and accelerates environmental pollution. Both materials are very useful in manufacturing various products but if not properly managed, the waste generated from them can become a remarkable factor of environmental pollution. Efforts are underway globally, especially in developed countries, to address those waste issues and promote alternative materials [5]. Research into wood and polymer alternatives has gained prominence due to their appealing properties, including durability, low maintenance, competitive pricing, and the use of natural resources [6], [7].

Natural fillers, like wood fibers, plant particles, and agricultural residues, are organic materials from nature [5]. They offer cost savings for thermoplastic composites and help to reduce non-biodegradable natural plastic waste, lessening the dependency on synthetic materials [8], [9]. Furthermore, these additives can enhance composite materials' structural

characteristics and efficacy. WPCs provide advantageous operating parameters, can be crafted using traditional woodworking implements, and are additionally deemed environmentally friendly due to their utilization of recycled plastics and wood industry byproducts [9], [5].

A thermoplastic, also called thermos soft plastic is a form of plastic that becomes malleable when heated. The polymer chains weaken their intermolecular forces at higher temperatures, turning the material into a viscous liquid. In this state, thermoplastics can be reshaped by using various manufacturing techniques like injection molding, compression molding, and extrusion [10], [11]. High-density polyethylene (HDPE), or polyethylene high-density (PEHD), derived from ethylene, offers strength and density balance. This polymer is being used in the manufacturing industries of plastic bottles, pipes, geo-membranes, and plastic lumber [12]. Recycled HDPE exhibits substantial differences in physical properties compared to pure HDPE. The value of Young's modulus, tensile strength, and percent elongation produced from recycled HDPE are found to be lower than pure HDPE [13]. The WPCs made from a mixture of 35%wt wood dust and 65%wt polypropylene granules improved the modulus of rupture, elasticity, and water absorption characteristics. Beyond this %wt of wood dust, the value of these properties starts to decrease. However, the hardness value of the WPCs was found to be increased by up to 40wt% of wood dust content [14].

Incorporating sawdust into HDPE composites through compression molding revealed a polymer-like web structure and cross-linking, enhancing composite properties. Sample-wise, 1.1 to 1.4 mm size sawdust particles with 30wt% ratio by weight and 3wt% compatibilizer exhibited the lowest water absorption, while those with less than 1 mm size particles at 30wt% weight and 7wt% compatibilizer showed the highest tensile strength [15].

Plastic recycling, essential for global sustainability, was explored for producing plastic lumber from recycled HDPE alone or in wood composites. The materials made from recycled HDPE have a lower value of mechanical properties and diminished load capacity. This is due to the porosity formation during the cooling system [16]. Despite this, WPCs provide advantageous machining, shaping with standard tools, and sustainability by reusing plastics and wood waste. WPCs are easily recyclable and versatile for molding, even into complex shapes, albeit generally with lower strength and stiffness compared to wood [17].

Previous research emphasizes the merits of natural organic fibers as eco-friendly reinforcements in composites. Pine dust and recycled HDPE provide sustainable waste management solutions, reducing environmental impact. However, the beneficial properties of composite materials manufactured by adding pine dust into recycled HDPE have not yet been sufficiently studied. Therefore, further exploration seems to be needed to study the mechanical behavior and adhesion of HDPE with pine dust. Thus, this study aims to investigate the mechanical properties, different morphologies and their effect on these properties, and water absorption quality of the composites made by mixing various particle sizes of pine dust in different weight percentages with recycled HDPE.

In this experimental study, a composite material was made using different sizes of pine dust as a filler material in recycled HDPE and explored the impact of dust size, proportion of dust, and integration of the dust on the morphology and physical characteristics of the composite materials. A single-screw extrusion method is used to fabricate composite materials. The choice of utilizing both base materials, pine dust and recycled HDPE stems from their availability as local waste products from nearby industries. This experiment offers an eco-friendly method for creating composite materials by efficiently reusing waste materials and advocating for environmentally sustainable practices.

2. Material and methods

2.1. Material

The recycled HDPE and wood dust were obtained from the plastic manufacturing industry and local sawmills, respectively.

2.2. Processing of pine-dust

Solar energy was utilized to pre-heat the collected pine dust, eliminating moisture. Subsequently, a home sieving process ensured uniform sizing. Grinding and screening techniques were applied to get the different particle sizes of pine dust. Finally, microwave heating was used to remove the moisture from dust.

After processing pine dust, eighteen samples were prepared by mixing pine dust of three distinct sizes at various proportions with recycled HDPE. The samples of prepared composites are shown in table 1.

%Weight of Pine Dust /Weight of Recycled HDPE	425-1000 micrometer		212-425 micrometer		Less than 212 micrometers	
	Pine Dust	Recycled HDPE	Pine Dust	Recycled HDPE	Pine Dust	Recycled HDPE
	(in gm)					
5	35	665	35	665	35	665
10	70	630	70	630	70	630
15	105	595	105	595	105	595
20	140	560	140	560	140	560
25	175	525	175	525	175	525
30	210	490	210	490	210	490
Total	735	3465	735	3465	735	3465

Table 1. Samples of different sizes and proportions of pine dust in recycled HDPE

2.3 Sample Processing

The prepared samples were fed into the single screw extruder through a hopper, mixed, and heated in an extruder at 210 ºC. The specimens were extracted in a die of rectangular cross-section 50 cm × 20 cm. The die is then cooled in water and solidified. Finally, the composite was extracted using thrust by a mandrel in a clamper.

The resulting products were re-shaped using different cutting and grinding tools to specific dimensions to test various mechanical properties of the composite.

2.4 Mechanical Testing

2.4.1 Tensile Test

Tensile experiments were executed at room temperature using AMI-652-1 UTM and the test speed was 10 mm/min. The samples were firmly secured onto the testing apparatus with a gauge length of 170 mm. Tensile test data in different loads were obtained from the universal testing machine and then analyzed to calculate the percentage of elongation, ultimate strength, and yield strength of the composite.

2.4.2 Impact Test

The assessment was performed employing a Charpy Impact Testing instrument. Specimens measuring 50 mm × 10 mm × 10 mm with a notch depth of 2 mm inclined at a 45-degree angle were utilized and tested at room temperature.

2.4.3 Water Absorption

Following the guidelines outlined in the ASTM D570 procedure, the specimens underwent a 24-hour drying duration in an oven at 105 °C and were promptly weighed. Then, they were immersed in water at ambient temperature for another 24 hours. Following immersion, the specimens were removed and re-weighed, and the water absorption percentage was evaluated using the provided equation;

$$\text{Water absorption \%} = \frac{\text{wet weight} - \text{dry weight}}{\text{dry weight}} \times 100\ \%$$

2.4.4 Morphological Observation

A stereo microscope with a 100x optical magnification was employed to study the particle dispersion and morphology in the prepared composites.

3. Results and discussion

3.1 Morphology

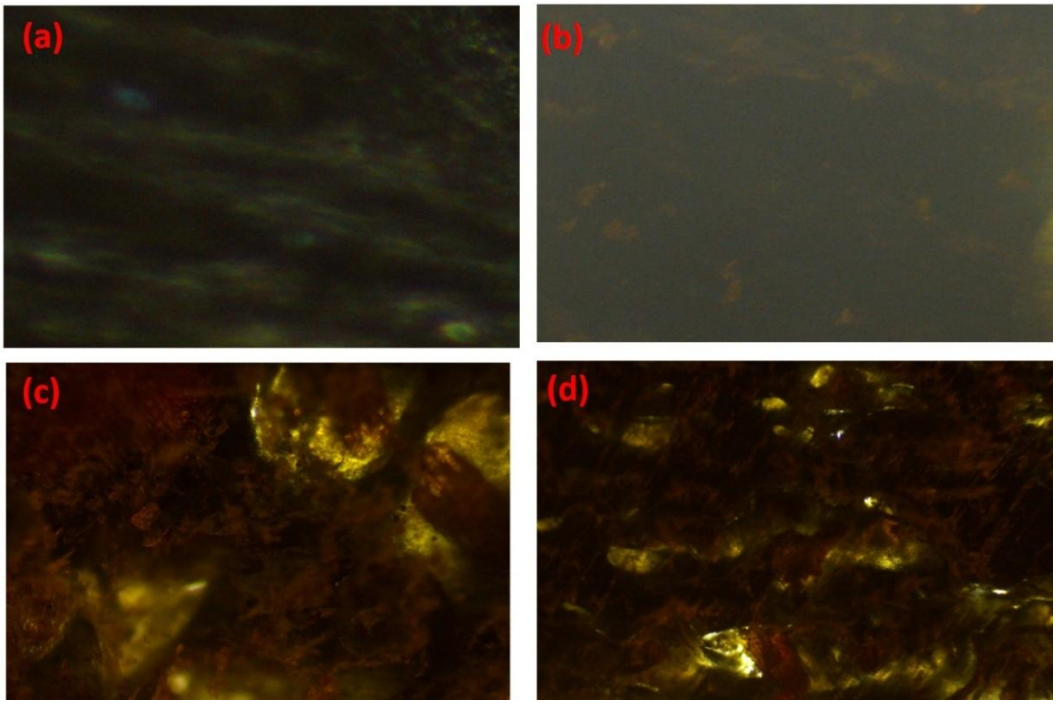

Figure 1. Morphology of (a) Recycled HDPE, composite with 10% by weight of pine dust of size (b) 200 μm - 500 μm, (c) 500 μm- 1000 μm, and (d) less than 250μm

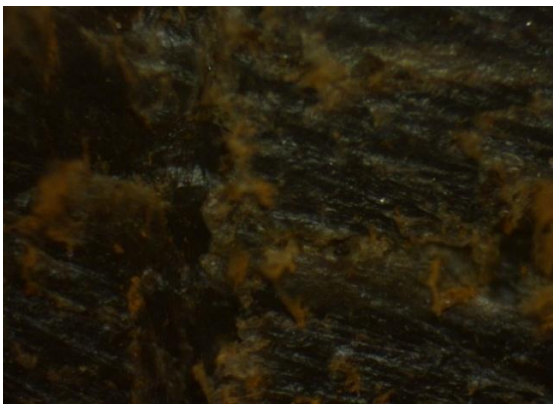

Figure 2. Composite with 25wt% by weight of pine dust of size less than 250 μm

The detailed morphological study using a stereoscopic microscope has exposed complicated dynamics in the interaction of pine dust with recycled HDPE. Initially, the uniform distribution of pine dust particles throughout the recycled HDPE polymer improved the ultimate strength of prepared composites. However, in a higher proportion of pine dust,

distinct clustering has occurred, diminishing the composite's ultimate strength, and notifying the necessity of sustaining uniform particle dispersion to preserve structural integrity.

Furthermore, focusing on smaller additive particles, especially those smaller than 250μm, uncovered a pivotal discovery. In this specific size bracket, clustering intensified, exacerbating detrimental effects on ultimate strength.

3.2 Tensile Test

The impact of additive size and ratio on composite mechanical attributes of each specimen was investigated based on loading vs elongation data obtained which was further analyzed to calculate the ultimate load, ultimate strength, and elongation percentage of each sample:

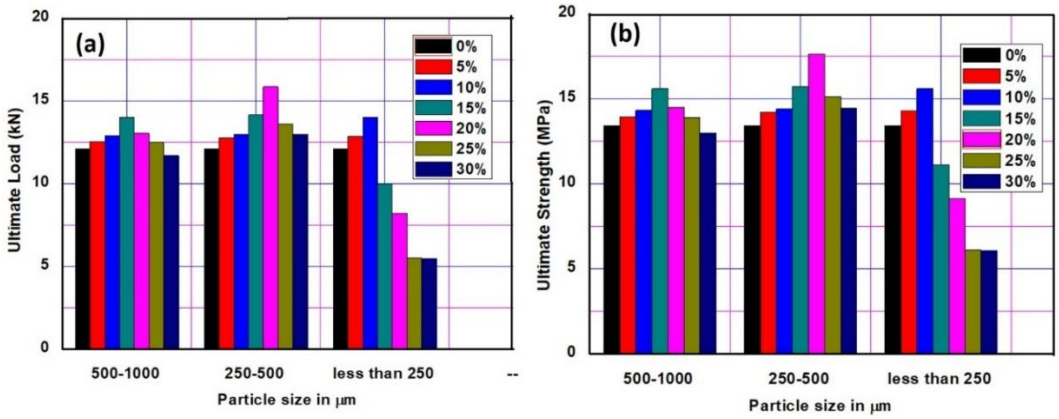

Figure 3. Ultimate load (a) and ultimate strength (b) of the composite at 0wt% to 30wt% of pine dust

Figure 3 shows the ultimate load and strength of pure recycled HDPE and different wt% pine dust mixed composite for various particle sizes**.** The ultimate strength initially increases up to 15wt% pine dust but gradually declines beyond this point in the 500 μm – 1000 μm size range. However, even at 20wt% and 25wt% of pine dust, WPc offered higher value in mechanical properties compared to pure recycled HDPE. In the 250μm - 500μm size range, ultimate strength shows a similar trend up to 20wt% pine dust than a decreasing trend, though, 25wt% and 30wt% surpass the ultimate strength of pure recycled HDPE. For composites containing pine dust particles smaller than 250 μm, the peak ultimate strength was recorded at a 10wt% of pine dust, with a noticeable decrease beyond this point. Here, increasing pine dust wt% of every size up to a certain value in pure recycled HDPE, ultimate load, and ultimate strength increase. After the addition of hard filler pine dust to the flexible HDPE, the free movement of the HDPE will be hindered and stiffness will increase which enhances the ultimate strength of the composites [18], [19]. However, these properties of the composites decreased upon the increase of the filler wt% of every particle size, mainly due to the high stress of the complex transfer through the interface, weak interfacial adhesion between pine dust and HDPE, and the possibility of aggregate formation in higher wt% of filler materials [20].

The proportion of pine dust that offered the best ultimate strength from all three size ranges was selected for comparison among themselves and also with recycled HDPE. Figure 4 shows the additives of size (250 – 500 μm) with 20wt% of pine dust exhibit the highest ultimate strength among all composites. However, the best ultimate strength of high (500-1000 μm) and low (less than 250) sizes pine dust blended WPc was observed in low wt% blended composites compared to the medium size pine dust blended WPc. Such results might be due to the weak interfacial adhesion between HDPE and dust particles in case of larger size particles, and the possibility of aggregation in case of small-sized particles on the flexible HDPE [21]**.**

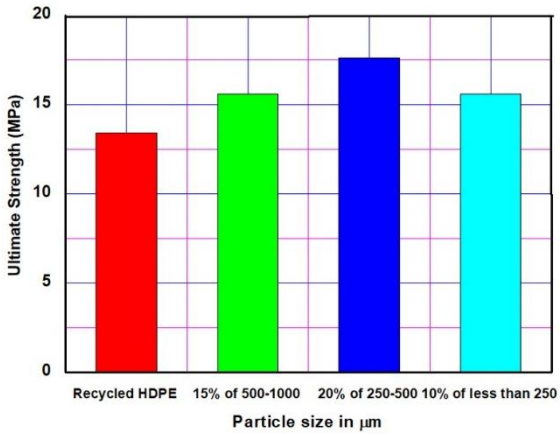

Figure 4. Comparison of ultimate strength of specimen exhibiting greatest from each size

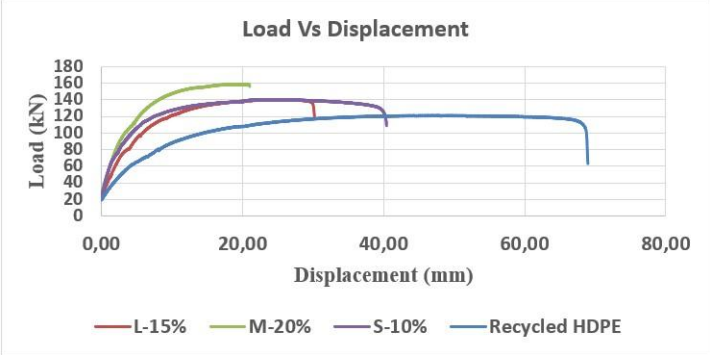

Figure 5. Comparison of load and displacement of the specimen from each size exhibiting the greatest ultimate strength

Figure 5 shows the load Vs displacement curve of 15wt% (500-1000 μm), 20wt% (250-500 μm) and 10wt% (less than 250 μm) pine dust WPc. The displacement of the composite decreases as the filler content increases. This is because as the pine dust wt% increased, composite became highly reinforced and the degree of stiffness increased. Thus, failures occur at higher loading [22], [23].

Figure 6 shows the elongation percentages of different WPc. As the amount of pine dust rises, a downward trend is noted in the elongation property of the composites. Here, the higher wt% pine dust decreases the molecular ability by increasing the matrix composites which adversely affects its ductility and thus, the elongation characteristic diminished [24]. Although a slight enhancement was noticed with pine dust particles smaller than 250 μm at a 5wt% inclusion, further escalating the pine dust proportion results in a declining elongation trend.

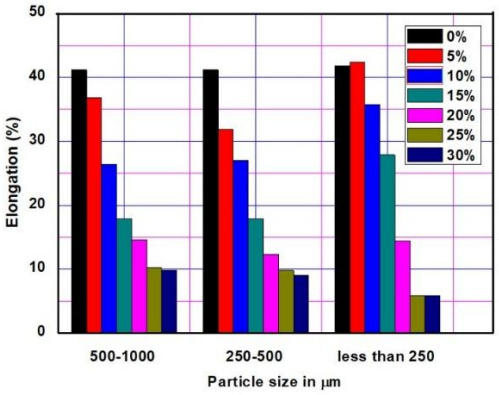

Figure 6. Elongation percentage of different composites

3.3 Impact Test

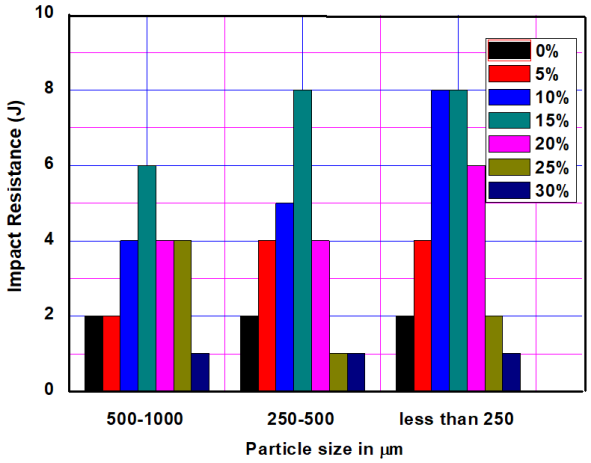

Figure 7. Energy absorbed by different WPc

The composite of 250 μm - 500 μm and 500 μm – 1000 μm pine dust, 15wt% inclusion exhibits the highest energy absorption characteristics. In the specimens size less than 250 μm pine dust range 10wt% and 15wt% inclusion both exhibit the highest energy absorption characteristics [25].

3.4 Water absorption test

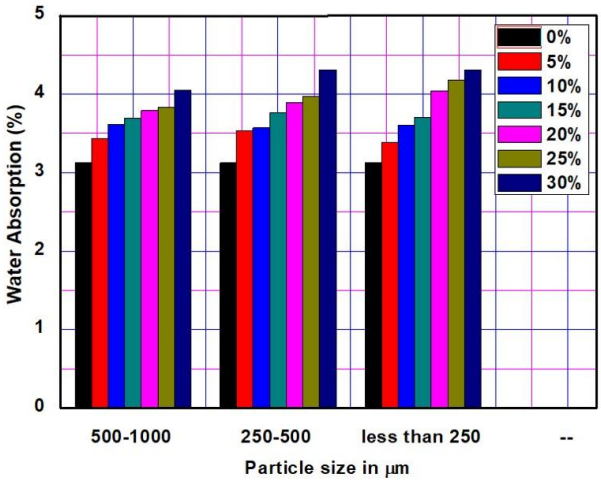

Figure 8. Water absorption test.

The water absorption tendencies indicate that higher proportions of pine dust in WPc and smaller sizes result in increased water absorption behavior of the WPc. Specifically, maximum water absorption of 4.305% was observed in composites with pine dust particles smaller than 250 μm at a 30wt% proportion in recycled HDPE. The pine dust contains high hydrophilic content like cellulose and hemicellulose which are mostly responsible for water absorption. Similarly, poor bonding between pine dust and HDPE matrix causes void space which leads to higher water absorption quality [26].

Thus, homogeneous pine dust distribution revealed critical parameters for enhancing WPc mechanical properties. Decreasing the size of pine dust exacerbated clumping, resulting in further weakening of strength. Therefore, utilizing pine dust of appropriate sizes up to a certain wt% as a filler material into recycled HDPE not only allows for the efficient use of local waste materials but also enhances the mechanical properties of the produced product and helps to decrease the environmental pollution from the plastics and wood waste.

4. Conclusion

When examining the influence of pine dust on tensile properties, it was found that increasing the proportion of pine dust enhanced ultimate load up to a certain point, followed by a decreasing trend across all sizes of pine dust. Relative examination revealed that composites repeatedly excelled base material in ultimate strength. Among all specimens, the composite of sizes 250μm - 500 μm with a 20wt% incorporation exhibited the highest ultimate strength. Despite this, several specimens still exceeded the ultimate strength of the base material, indicating that integrating pine dust enhances the ultimate strength of the composite.

Regarding elongation properties, a negative correlation was observed with increasing proportions of pine dust. Higher pine dust content showed a lower ductile property of the composite material.

From the Impact test, it was found that in the 500 μm – 1000 μm and 250 μm - 500 μm pine dust ranges, 15wt% samples exhibited the highest energy absorption characteristics. For specimens with pine dust particles smaller than 250 μm, both 10wt% and 15wt% pine dust added samples demonstrated the maximum energy absorption of 8 Joules, markedly exceeding the pure recycled HDPE. These findings highlight the capacity for enhancing the energy absorption properties of recycled HDPE pine dust composites.

Water absorption examinations revealed that increasing the ratio of pine dust in recycled HDPE led to a proportional augmentation in the water absorption qualities of the composite. Moreover, diminishing the dimensions of the composite further contributed to enhanced water absorption qualities.

The examination of composite morphology involving pine dust and recycled HDPE carried out through stereoscopic microscopy, provided insights into their complex interactions. The uniform dispersion of pine dust particles within the recycled HDPE matrix led to a notable enhancement in ultimate strength, confirming its capacity to strengthen recycled HDPE. However, with the escalation of pine dust proportion, a noticeable agglomeration occurred and the clusters of dust particles were formed in the composite and subsequent declines in ultimate strength. This emphasizes the significance of preserving a uniform distribution of pine dust within the recycled HDPE matrix. Furthermore, the analysis of smaller pine dust particles, particularly those measuring less than 250 μm, accentuated the agglomeration effect, exacerbating the decrease in ultimate strength and jeopardizing the overall structural integrity of the composite material.

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Authors' Declaration

The authors declare no conflict of interests regarding the publication of this article.

Competing interests

All authors have no conflict of interest regarding the publication of this article.

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