DOI: 10.31276/VJSTE.2025.0049

Green energy generation from industrial wood waste: Pellet production from carbonised *Eucalyptus saligna* sawdust

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Received 25 August 2025; revised 14 September 2025; accepted 5 October 2025

Abstract:

This study investigated the potential of pellet production from carbonised *E. saligna* sawdust, processed at varying particle sizes (0.6 mm, 1.18 mm, and 2.36 mm) and utilising different organic binders. Proximate and ultimate analyses of charcoal pellets were investigated using standard test methods. *E. saligna* sawdust was carbonised using a cylindrical barrel metal kiln, and pelletised with a manual press machine using molasses, cow dung, and fruit waste as binding agents. The proximate and ultimate analyses of charcoal pellets were determined using American Society for Testing and Materials (ASTM). Binding agents significantly influenced moisture content, volatile matter, fixed carbon, ash content, calorific value, and sulphur content ($p<0.001$), while particle size had a moderate effect on select parameters, particularly fixed carbon and ash content. The highest fixed carbon (44.02%) and calorific value (4980 cal/g) were observed in cow dung-bound pellets, while fruit waste-bound pellets exhibited the lowest ash (3.82%) and sulphur content (0.12%), highlighting their environmental advantages. The interaction between binding agents and particle size was significant for moisture content and volatile matter but not for fixed carbon or calorific value. This research demonstrates an innovative approach to valorise plant waste materials and underscores the potential of local biomass for sustainable energy solutions.

Keywords: **binding agents, biomass, charcoal pellet, *Eucalyptus saligna*, fuelwood.**

Classification numbers: **2.3, 3.5, 5.3**

1. Introduction

Biomass is a promising alternative renewable energy source [1, 2], and upon sustainable utilisation, it brings significant advantages for the environment, society and economy as it taps into the potential of wood waste whilst minimising the negative impacts of waste disposal on human and environmental health [3].

According to various reports, more than three billion people depend on wood fuels for household cooking and other energy needs [4]. In Ethiopia, more than 94% of the population relies on woody biomass energy sources such as firewood and charcoal for domestic purposes [5, 6].

Reusing sawdust and other wood waste generated by sawmill industries for different applications has become increasingly practical worldwide, as wood is one of the most recyclable materials available today [7]. Numerous studies have confirmed that recycling wood waste to produce new materials is economically feasible [8]. Recycling waste is part of the circular economy approach that minimises energy consumption and resource depletion [9]. Sawdust serves as an alternative raw material for energy production globally. For instance, Canada has exported more than one million tonnes of sawdust pellets, which can substitute for fossil fuels in power plants [10]. In Nigeria, 8,012.8 m^3 of wood sawdust is generated annually, representing an energy potential of 31,298 GJ [11].

The Eucalyptus tree belongs to the Myrtaceae family (sub-family Myrtideae) and includes approximately 900 species and an unknown number of hybrids and variants. Eucalyptus provides numerous socioeconomic and environmental benefits [12]. For instance, it is among the most widely used tree species for timber production and biofuel manufacture. In Ethiopia, approximately 72 different Eucalyptus species are extensively distributed across the country [13]. Large areas of land are covered by Eucalyptus plantations, which now account for more than 54% of Ethiopia's total forested area [12, 14].

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A large volume of sawdust is discharged from Eucalyptus sawmill industries each year. However, the potential sawdust from these industries is not efficiently converted into value-added materials such as biofuels. The volume of sawmill residues, including *Eucalyptus saligna* sawdust, is estimated to exceed 25 million kilograms annually [15]. Nevertheless, the utilisation of sawdust in its raw form faces several challenges, such as low energy content, limited bulk density, high moisture content, and hydrophilic nature [16]. These inherent properties affect its effective utilisation and economic value [17], resulting in its disposal in landfills or accumulation in neglected piles that ultimately decay due to the limited application of alternative biomass conversion technologies. Hence, woody biomass must be processed using economically feasible and environmentally friendly conversion mechanisms [18, 19].

The densification of lignocellulosic biomass into solid fuels such as pellets and briquettes results in standardised physical attributes, consistent combustion behaviour, enhanced energy content, increased density, and reduced moisture content. It also mitigates problems associated with handling, transportation, and storage [20, 21].

The deficiency in binding capability within lignocellulosic biomass gives rise to substandard pellets characterised by low strength, dustiness, and unsuitability for practical use. Consequently, several studies have explored ways to improve inter-particle binding efficiency within biomass pellets. Various parameters affect the fuel quality and production process of pellets, including biomass particle size [22], biomass moisture content [23], pretreatment methods of biomass feedstock [24], and types of binders [25]. These factors significantly contribute to improving the overall fuel properties of pellets and protecting production equipment from wear by acting as bridges or matrices that facilitate robust inter-particle bonding [26, 27].

Numerous studies have examined the impact of different binding agents on pellet quality. In addition to binder selection, modern carbonisation processes have emerged as promising techniques to enhance pellet energy density [28]. Carbonisation increases the calorific value, enhances hydrophobicity, and improves resistance to microbial degradation, offering a significant improvement over the 15 MJ/kg exhibited by raw biomass [29]. This dual enhancement in energy density and physical properties positions carbonisation as a valuable approach.

This study aims to elucidate the pellet production process using lab-scale pelletising machinery, focusing on carbonised *Eucalyptus saligna* sawdust with binding agents such as cow dung, molasses, and fruit waste. By systematically investigating the influence of binding agents and particle size on the physicochemical attributes of pellets, this research seeks to highlight the potential of sustainable binding agents and optimised particle dimensions for producing high-quality pellets.

2. Materials and methods

2.1. Sample collection

Samples of *E. saligna* stems with diameters ranging from 3 to 4 cm were collected from the Oromia region, located 174 km from Addis Ababa. The samples were then transported to the Forest Products Innovation Centre of Excellence laboratory for further processing.

Fig. 1. Stages of sample preparation. Source: Authors' research results.

The stems of the specified species were manually chopped into small strips using a cutting blade to facilitate the milling process. The strips were spread out on a fabric sheet and allowed to dry naturally under shade for two weeks until the moisture content reached 10-12% (Fig. 1). The particle size of the dried samples was reduced to 0.6 mm, 1.18 mm, and 2.36 mm using a milling machine, following the standard method described by [30]. Sieve size is also a key factor influencing the quality of densified solid biofuels [31]. The particle size was determined in accordance with the ASTM standard described by [32].

2.2. Carbonisation of Eucalyptus saligna sawdust

Carbonisation increases the energy content of biomass compared with raw biomass [29]. A locally crafted cylindrical metal kiln equipped with a chimney was used for the carbonisation process. This kiln was constructed from a drum with dimensions of approximately 1.2 metres in height and 90 centimetres in diameter. The *E. saligna* sawdust samples with various particle sizes (0.6 mm, 1.18 mm, and 2.36 mm) were carbonised in an oxygen-deficient environment at a heating rate of 7°C per minute. Key parameters such as carbonisation temperature and residence time were monitored to ensure consistent carbonisation quality. The time taken to reach the maximum carbonisation temperature was recorded when the sawdust was completely converted into charcoal. The carbonised sawdust was immediately removed from the kiln chamber and spread on the floor to cool. Once cooled, the charcoal was carefully placed in plastic bags and labelled [33].

2.3. Pelletisation process

A JS5RK/DL pellet machine equipped with a flat ring die was employed for pelletisation (Fig. 2). According to the manufacturer's specifications, this machine can produce pellets at a rate of up to 20 kg/h. The binders used for pellet formation were molasses, cow dung, and fruit waste. The moisture content of *E. saligna* sawdust was 6.8%, while the moisture contents of molasses, cow dung, and fruit waste were 21.5%, 78%, and 6.4%, respectively. A blend of avocado and banana peels was used as the waste fruit (WF) in this study. During the pelletisation process, carbonised sawdust was mixed with binders in a three-to-one ratio [16]. The blended mixture was then fed into a pellet mill and compressed to achieve densification. Finally, the pellets were air-dried and sealed for further analysis [34].

2.4. Characterisation of the produced pellets

Moisture content determination: The moisture content (MC) on a dry basis was assessed following the established protocol outlined in [35]. A pulverised pellet sample weighing 1 g was subjected to oven drying at 105°C for two hours until its mass reached a constant value. The MC of the sample was then calculated using the following formula:

$$MC(\%) = \frac{W1 - W2}{W1} \times 100 \quad (1)$$

where, $W1$ represents the initial sample weight, $W2$ is the weight after drying, and MC is the moisture content.

Fig. 2. Photographs of the pelletisation process and produced pellets. Source: Authors' research results.

Volatile matter determination: Volatile matter (VM) was determined as in [36]. One gram of pulverised pellets was heated at 925°C for seven minutes, subsequently cooled in a desiccator, and weighed until a consistent mass was achieved. The VM was calculated using the following equation:

$$VM(\%) = \frac{W1 - W2}{W1} \times 100 \quad (2)$$

where *VM* stands for volatile matter, *W1* is the original sample weight, and *W2* is the weight after cooling.

Ash content determination: The ash content (ASH) was assessed following ASTM D3174-12 (2018) standard. To determine the ash weight, 1 g of moisture-free pulverised sample was heated to 550°C for four hours and weighed after cooling in a desiccator. The ash content was determined using the following equation:

$$Ash(\%) = \frac{w2}{w1} \times 100 \quad (3)$$

where *W2* is the weight of cooled ash and *W*1 is the initial weight of the dry sample.

Determination of fixed carbon: The fixed carbon (FC) content was computed by subtracting the sum of VM, ASH, and MC contents from 100% as in the following equation:

$$FC(\%) = 100 - [Ash + MC + VM] \quad (4)$$

2.5. Ultimate analysis of densified biomass pellets

Calorific value determination: The calorific value (CV) of the produced pellets was determined using a Parr oxygen bomb calorimeter, following the procedure outlined in the [38] standard. The bomb calorimeter was calibrated with a standard sample of benzoic acid, which has a known calorific value of 26.4 MJ/kg. A 2 g sample of pulverised pellets was placed in the crucible, and the bomb calorimeter was operated according to the standard procedure.

Sulphur content determination: The sulphur content was determined in accordance with the [39] standard. A 1 g sample of pulverised pellets was mixed with 3 g of Eschka mixture in a porcelain crucible. The crucible was then gradually heated to 800°C over a period of 60 minutes in a cold muffle furnace. The sulphur content was calculated using the formula provided in equation (5) below:

$$Total\ sulphur = A - B \times \frac{13.738}{C} \quad (5)$$

where *A* is the mass of barium sulphate from the sample, *B* is the mass of barium sulphate from the blank, and *C* is the mass of the sample.

Elemental composition analysis: The elemental analysis (C, H, O, N) was carried out using ASTM analytical methods as described by [40, 41].

2.6. Dimensions and density of pellets

The dimensions of pellets were determined (radius and length) using the standard method as described by [42] while bulk density was determined using the standard method given by [43].

2.7. Mechanical properties of pellets

Mechanical durability was determined using the standard method described by [44]. The tensile strength of pellet was determined using a Universal Testing Machine (UTM). The compression test along the diameter of the pellet was conducted using the method described by [45]. The tensile strength was determined using the following equation according to [46].

$$\sigma f = \frac{P_f}{\pi R_{pt}} \quad (6)$$

where σf is the tensile strength, P_f is the failure load, R_p is the radius of the pellet, and t is the thickness of pellet.

2.8. Data analysis

The collected data, including fixed carbon, moisture content, volatile matter, ash content, sulphur content, and calorific value of the pellets, were subjected to statistical analysis using SAS software (Version 9). The experiment was conducted following a completely randomised design (CRD) with two factors: the binding agent and the particle size of the sawdust. Each treatment included three levels and three replications. The Least Significant Difference (LSD) test at a significance level of $p<0.001$ was employed to compare the means.

3. Results and discussion

The findings of this study revealed that *E. saligna* sawdust pellets produced with organic binders (cow dung, molasses, and fruit waste) exhibited high calorific values, making them suitable for clean cooking and heating applications. The use of fruit waste as a binder produced pellets with superior fuel characteristics, underscoring the potential of agricultural waste as a sustainable binding agent. The maximum carbonisation temperature was 500°C, and it took approximately 1.2 hours to reach this temperature. The total residence time for carbonisation was 1.5 hours, with additional time required for cooling.

3.1. Proximate analysis results

The type of binder used showed a significant effect on the proximate and ultimate test parameters at the probability level of P<0.001. The interaction effect between binding agent and particle size had no significant influence on the percentage of fixed carbon, ash content, calorific value, or sulphur content, as presented in Table 1.

3.1.1. The main effects of particle sizes of sawdust and binding agents on fuel qualities of pellets

Fixed carbon (FC): Fixed carbon (FC) is essential for assessing the viability of bio-carbon in metallurgical applications, as it represents the residual carbon remaining after pyrolysis at 900°C for ten minutes [47]. The binding agent significantly influenced FC, with the highest concentration observed in pellets bound with cow dung (44.02%), followed by waste fruit (38.92%) and molasses (27.31%). The enhanced carbon retention in cow dung-bound pellets is likely due to its high lignin and cellulose content; cow dung contains approximately 13.9% lignin [48].

Particle size had a modest yet significant effect, with 0.6 mm and 1.18 mm particles yielding FC values of 38.7% and 34.49%, respectively. This finding concurs with [49] and [50], who reported FC increases from 23.86% to 30.28% and from 50.76% to 53.86%, respectively, using cow dung and molasses as binders. The substantial FC observed in cow dung-bound pellets suggests their suitability for high-energy applications, although practical considerations such as binder availability and environmental impact must also be evaluated.

Ash content (AC): Ash content, representing the inorganic residue remaining after combustion, indicates the overall mineral composition of biomass waste and plays a crucial role in determining fuel quality and combustion efficiency [51]. High ash content can cause dust emissions, contributing to air pollution, and reduces the combustion efficiency of biofuels [52]. It also lowers the calorific value, as it affects the burning rate and limits heat transfer within the fuel [53].

The highest ash content was recorded in molasses-bound pellets (8.18%), likely due to the elevated mineral content of molasses [54]. In contrast, fruit waste-bound pellets exhibited the lowest ash content (3.82%), indicating superior fuel quality and a lower mineral concentration in fruit waste [54]. Particle size also influenced ash content: pellets produced from particles sized 1.18 mm and 0.6 mm had ash contents of 6.9% and 5.84%, respectively. These results suggest that finer particles may retain more ash due to their greater surface area during combustion. The low ash content of fruit waste-bound pellets aligns with [50], who reported comparable results using carbonised *Pinus patula* sawdust, reinforcing their potential as a cleaner fuel alternative.

Calorific value (CV): CV quantifies the total energy released during complete combustion [55, 56]. The highest CV was obtained in cow dung-bound pellets (20.84 MJ/kg), attributed to their high combustible matter (carbon) content and low moisture content.

Table 1. Analysis of variance (ANOVA).

Source of variation	Degree of freedom	Moisture content (%)	Volatile matter (%)	Fixed carbon (%)	Ash content (%)	Calorific value (cal/g)	Sulphur content (%)
BA	2	170***	347***	6.29***	43.16***	815411***	0.028*
PS	2	1.53**	77**	66*	4.34*	122423NS	0.0018NS
BA*PS	4	0.48*	29*	30NS	1.87NS	809NS	0.003NS
CV (%)		3.95	7.13	13.08	19.51	8.26	47.45
R-square		0.99	0.84	0.81	0.82	0.67	0.44

BA - binding agents; PS - particle sizes; CV (%) - coefficient of variations; R^2 - coefficient of determination. NS - not significant.

Pellets bound with molasses and fruit waste showed lower, though statistically similar, CVs of 17.13 MJ/kg and 18.45 MJ/kg, respectively, due to their lower fixed carbon content and higher moisture levels, which reduce the heating value. Interestingly, particle size did not significantly affect CV, with values ranging from 18.43 MJ/kg (1.18 mm) to 19.36 MJ/kg (2.36 mm). This suggests that the chemical composition of the binder plays a more decisive role in determining energy content than particle size. These findings are consistent with [57], who reported calorific values ranging from 17.63 MJ/kg to 20.81 MJ/kg.

Sulphur content (SC): Sulphur content is a key environmental consideration, as elevated levels contribute to SO_2 emissions and acid rain. The highest sulphur content was observed in molasses-bound pellets (0.23%), likely due to sulphurous compounds present in molasses. Cow dung-bound pellets exhibited slightly lower sulphur content (0.20%), while fruit waste-bound pellets had the lowest (0.12%). Particle size had no significant effect on sulphur content, with all values falling within the acceptable range established by the German standard for high-quality pellets [58], which specifies a sulphur content of ≤0.5%. These findings confirm that all tested pellets are environmentally compliant for combustion (Table 2).

Table 2. Main effects of binding agents and particle sizes.

Treatments	Fixed carbon (%)	Ash content (%)	Calorific value (MJ/kg)	Sulphur content (%)
ML	27.31a	8.18a	17.13b	0.23a
CD	44.02a	6.33b	20.84a	0.20ab
FW	38.92b	3.82c	18.45b	0.12b
LSD 0.05	4.6562	1.1924	1.55	0.0883
0.6 mm	38.7a	5.84ab	18.63a	0.17a
1.18 mm	34.49ab	6.9a	18.43a	0.19a
2.36 mm	33.66b	5.6b	19.36a	0.19a

a, b, c letters show significant difference in means along the column. There is no significant difference in means with the same letters along the column. BA - Binding agents; ML - Molasses; CD - Cow dung; FW - Fruit waste; LSD - Least significant difference.

3.1.2. Interaction effects of sawdust particle size and types of binding agents

Moisture content: Moisture content profoundly affects pellet ignition and calorific value, as energy is required to evaporate water during combustion [59]. The moisture content of pellets increases as binder concentration increases [6]. The lowest moisture content was recorded in fruit waste-bound pellets across all particle sizes, with values of 8.5% (0.6 mm), 8.44% (1.18 mm), and 8.12% (2.36 mm). This is because the moisture content of the fruit waste was reduced to less than 8% by drying, and the dried fruit waste subsequently absorbed some moisture from the pellets.

In contrast, molasses-bound pellets exhibited the highest moisture content due to the inherently high moisture level of molasses. Furthermore, the moisture in molasses-bound pellets cannot be easily removed during drying because of the hygroscopic (water-absorbing) nature of molasses [60]. The results obtained are consistent with [61], who reported a moisture content range of 5-10% for good-quality pellets, and with [62], who noted that low moisture content enhances ignition and calorific value.

Volatile matter: Volatile matter (VM) influences ignition and combustion stability; higher VM facilitates easier ignition and produces more stable flames [63]. The lowest VM was detected in cow dung-bound pellets (40.27%) due to the relatively low content of volatile organic compounds in cow dung. In contrast, molasses- and fruit waste-bound pellets exhibited higher VM values (48.9% and 52.31%, respectively) owing to the higher concentrations of volatile compounds in both materials. For example, sugarcane molasses contains approximately 28 volatile compounds [64], while fruit waste can have an average volatile matter content as high as 86% [51].

These findings are in agreement with [33], who reported a highest VM value of 39.39% for fruit waste and a lowest value of 22.12% for cow dung. The elevated VM in fruit waste-bound pellets promotes easier ignition, aligning with the results of [65] and [66].

However, the lower VM in cow dung-bound pellets may hinder ignition and increase the likelihood of smoke and toxic emissions during incomplete combustion, as noted by [67]. These results highlight the trade-offs between fuel stability and environmental performance, suggesting that fruit waste may be the preferred binder for cleaner combustion (Table 3).

Table 3. Interaction effects of particle sizes and binding agents on moisture and volatile matter content.

Binding agents	Particle sizes (mm)	Moisture content (%)	Volatile matter (%)
Molasses	0.6	16.84a	45.71b
	1.18	16.53a	50.3a
	2.36	15.62b	50.67a
Cow dung	0.6	9.1d	34.89cd
	1.18	10.09c	39.18c
	2.36	8.93e	46.73a
Fruit waste	0.6	8.5f	51.32a
	1.18	8.44g	53.75a
	2.36	8.12h	51.86a

a, b, c, d, e, f, g, h letters show significant difference in means along the column. There is no significant difference in means with the same letters along the column.

3.2. Elemental composition (C, H, O, N) results

The elemental composition of the fuel influences its energy value and the suitability of feedstocks for energy applications [68]. The results indicated that the carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) contents showed significant variation depending on the binding agents used and the sawdust particle size.

Table 4. Elemental analysis results.

Test parameters	Cow dung	Fruit waste	Molasses
Carbon (%)	45.88	48.41	39.06
Hydrogen (%)	5.08	5.47	4.63
Oxygen (%)	33.7	37.68	32.03
Nitrogen (%)	1.4	1.49	1.23

As shown in Table 4, the highest C, H, O, and N contents were observed in fruit waste, with values of 48.41%, 5.47%, 37.68%, and 1.49%, respectively. Molasses exhibited the lowest C, H, O, and N values. These results are consistent with the findings reported by [68].

3.3. Dimension and density of pellets

The pellets produced from *E. saligna* had an average length of 30 mm and a diameter of 8 mm. These values fall within the standard range for pellet dimensions-lengths of 3.15-40 mm and diameters of 6-8 mm [42]. The bulk density of the pellets was 670 kg/m^3, which is consistent with the ASTM standard range for wood biomass pellet bulk density (600-750 kg/m^3). Similarly, this finding aligns with the bulk density of wood pellets (680 kg/m^3) reported by [69].

3.4. Mechanical properties

The durability of *E. saligna* pellets was greater than 97.2%. This result is consistent with the ASTM standard range of 96-97.5% [44]. Higher mechanical durability indicates the ability of pellets to withstand abrasion or shock without breakage during handling, storage, and transportation [70].

The tensile strength of pellets made with cow dung binder was 0.908 MPa. This value falls within the standard range of 0.36-2 MPa and aligns with the findings of [46], who reported values between 0.6 and 0.9 MPa for pellets produced from various wood species. Higher tensile strength indicates a greater resistance to breakage during handling, storage, and transportation. Conversely, pellets with lower tensile strength are more prone to fracture under tension [71, 72].

Tensile strength depends on several factors, including biomass type, moisture content, particle size, and compaction pressure. In this study, tensile strength was measured for pellets produced using a cow dung binder and a 0.6 mm particle size, as optimal fuel qualities were observed at these conditions.

4. Conclusions

This study investigated the production of biomass pellets through the densification of *E. saligna* sawdust to address the challenges associated with the traditional consumption of wood fuels. Pellets represent an alternative biofuel produced from various biomass feedstocks through the densification process. Locally available binding agents-cow dung, waste fruit, and molasses-were employed to bind carbonised *E. saligna* sawdust.

This study underscored the effects of binding agents and particle sizes on the physicochemical properties of *E. saligna* sawdust pellets. Cow dung, fruit waste (a composite of banana and avocado peels), and molasses were mixed with carbonised eucalyptus saligna sawdust at a three-to-one sample-to-binder ratio, with the addition of a small amount of water. The findings of the study revealed cow dung-bound pellets displayed the highest fixed carbon content (44.02%) and highest calorific value (4980 cal/g), indicating their suitability for high-energy applications. However, fruit waste-bound pellets exhibited lower ash content (3.82%) and lower sulphur content (0.12%), reflecting superior environmental performance. While particle size had a moderate impact on properties like ash content and fixed carbon, the charcoal pellets produced met all international standard specifications.

The findings emphasise the potential of *E. saligna* as a resource for pellet production and demonstrate the viability of agricultural and industrial by-products as sustainable binding agents for biomass pellet production, contributing to cleaner energy solutions, reduced environmental footprints, and the creation of job opportunities.

However, this study did not examine the life cycle assessment of the pellet production. Hence, future studies should focus on emissions analysis to evaluate the emissions profile of the pellets during combustion to assess their environmental impact. Additionally, economic analyses should be conducted to determine the cost-benefit and compare production costs of the pellets with those of conventional fuels, in addition to a scalability study to investigate the challenges and opportunities for scaling up the production for industrial applications.

CRediT author statement

Gemechu Y Shage: Writing original draft, Conceptualisation, Data curation, Gathering data, Methodology, Formal analysis; Dagnachew G Demissu: Methodology, Data gathering, Formal analysis; Fikremariam H Desalegn: Writing original draft, Conceptualisation, Formal analysis, Supervision; Tegene T Geta: Conceptualisation, Methodology; Tatek D Bekele: Supervision, Validation; Mahelete T Ayele: Methodology; Tewabech A Yetna: Methodology; Abraham D Gashaw: Formal analysis, Validation; Tarekegn G Admasu: Formal analysis; Gemechu J Morkato: Data gathering.

COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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