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Impacts of Biochar Treatments on Some Soil Properties and Micronutrient Availability

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Abstract

The application of biochar as a soil amendment has been recognized as an environmentally friendly and highly efficient strategy for restoring the fertility of the soil and increasing agricultural productivity. In this study, the impacts of *Senna tora* biochar treatments on soil properties and micronutrient availability in the farmlands of Misau, Bauchi State, Nigeria, were investigated. A complete randomized design replicated three times, which included control soil (no biochar/0 day), 30 days, and 60 days of biochar treatments, was adapted based on the fact that incubation time affects biochar application in soil. After treatments, the biochar was removed and the soil samples from each treatment were analyzed for pH, soil bulk density (BD), cation exchange capacity (CEC), organic carbon (OC) and micronutrient levels using various analytical methods. The results of the analysis show pH, OC and CEC values increased significantly ($p \leq 0.05$) from 6.66 to 7.89, 3.40 to 3.90 g/kg and 5.16 to 7.29 cmol/kg respectively, while BD decreased significantly from 1.56 to 1.48 g/cm^3 after 60 days of biochar treatment. The levels of Mn, Cu and Zn increased from 188.25 to 286.12 mg/kg, 14.38 to 41.88 mg/kg and 68.63 to 140.19 mg/kg respectively, while levels of Fe decreased from 9460.00 to 4782.73 mg/kg after 60 days of biochar treatments. Application of *Senna tora* biochar has generally led to a significant improvement in the fertility of the soil. It is therefore recommended that *Senna tora* biochar be used in the field to demonstrate its practical application.

1. Introduction

Global agricultural productivity has been declining in recent years because of significant soil fertility loss caused by human activities such as mining and smelting activities and geogenic processes like erosion, volcanic eruptions, etc [1]. The decline in agricultural productivity is more noticeable in Sub-Saharan Africa due to enormous pressure on agricultural soils, insufficient investment in agricultural inputs, and a lack of smart, innovative and eco-friendly agricultural technologies [2, 3]. This reduces soil qualities such as organic matter, pH, soil bulk density as well as the availability of important micronutrients for plant uptake [4, 5]

To restore soil fertility and increase agricultural output, sustainable strategies for soil management must be developed to restore the poor and degraded soils. Fertilizers, household solid waste, post-harvest residues, compost, and manures, among other organic and inorganic amendments, were utilized to restore soil fertility and boost crop production [5, 6]. However, the aforementioned materials have significant drawbacks. For example, the use of inorganic fertilizers has been linked to increased global warming and the loss of natural nutrients and minerals in healthy soils [6]. Moreover, it has been reported that the usage of compost and manure causes ammonia and methane emissions, which exacerbate global warming [7]. The interest in the applications of biochar for remediation of degraded and poor-quality soils has been growing rapidly in recent years. This is because it is both environmentally benign and highly successful in improving soil fertility [8]. Biochar is a carbon-rich substance made by pyrolysis of natural biomass [3]. Pyrolysis is a thermochemical method by which the biomass is burned in a limited oxygen environment, resulting in char that is mostly stable carbon [9, 10]. Pyrolysis may be tuned to generate a variety of primary and secondary products, including synthesis gas with varying energy levels, liquid, and char [11]. Biochar is char that is purposely created for agricultural or environmental purposes [12]. Unlike other organic amendments, which have short-term benefits, particularly in tropical areas like Nigeria due to high decomposition rates and the conversion of organic matter into carbon dioxide [13], biochar amendment is likely to remain in effect for several years due to its recalcitrant nature [8, 14]. Biochar's slow degradation and release rates make it last for a longer period, which makes it an ideal candidate for soil fertility improvement when compared to other soil amendments [5].

Biochar is very important in increasing soil fertility because it increases crop yield by providing and absorbing nutrients better than other amendments [7]. It decreases soil bulk density, increases soil pH and cation exchange capacity, provides a medium for nutrient adsorption, improves conditions for soil microorganisms, increases water retention and reduces soil degradation [5]. Biochar may also be utilized as a nitrification inhibitor, which slows the conversion of ammonium to nitrate, thereby keeping the nitrogen in a stable form and making it more readily available for plant uptake and can mainly adsorb ammonium ions via cation exchange [15, 16]. The magnitude of biochar effects on the soil depends on the types of the feedstock used in making the biochar, the soil properties, and the pyrolysis temperatures [17].

To change systems of agriculture into a more eco-friendly, sustainable and economically viable, it is absolutely necessary to adapt to our previous practices of using organic amendments in improving the soil fertility, particularly the application of scientifically validated biochar. This study is aimed at assessing the impacts of biochar treatments on some soil properties and micronutrient availability in the farmlands of Misau, Bauchi State, Nigeria.

2. Materials and Methods

2.1 Description of the Study Area

Misau (Fig. 1), situated on the latitude of 11^{0}18’49.32"N and longitude 10^{0}27’59.90"E is an ancient town and the local government headquarters of Bauchi State, Northeastern Nigeria [18]. Misau has an average altitude of 600 m above sea level and a yearly rainfall of approximately 70 mm [19]. The area has a projected population of about 263, 487 people and a total land mass of 1,226 km^{2}, which represents 2.4% of Bauchi state [20]. The main occupation of the residents of Misau local government area is agriculture, with cultivable land of up to 75–85% [18, 19].

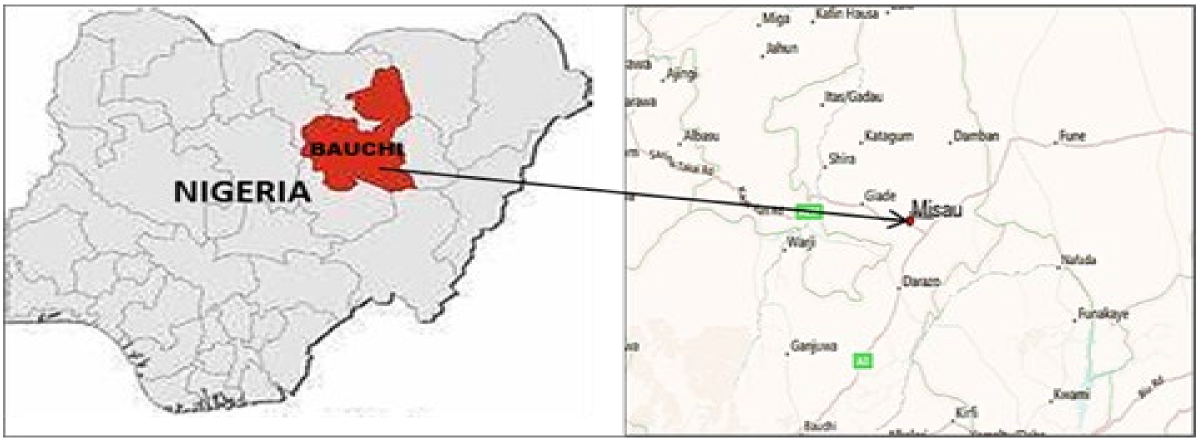

Fig. 1 *Geographical map of the study area*

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2.2 Soil Sampling and Collection

Soil samples were collected randomly from ten (10) different sampling locations in some selected farmlands around the Misau local government area at a depth of 0 to 30 cm using a soil auger. The collected samples were combined to form a composite sample. The sample was air-dried, ground, passed through a 2.00 mm mesh and labeled appropriately.

2.3 Sampling of *Senna tora* Plant and Production of Biochar

The *Senna tora* plant was selected as a feedstock biomass for biochar production. It is a wild plant that is extensively available in the study area. The plants were collected randomly from different locations in Bauchi and combined to form a composite sample. The samples were washed to remove soil particles, air-dried, cut into different pieces, and placed in a polyethylene bag. The plant was pyrolyzed in a furnace at 400 ^{0}C. A temperature of 400 °C is used because it is an average of the pyrolysis temperature range used in the literature [8, 10]. The charred residues were stored in labeled and sealed airtight plastic containers prior to soil treatments.

2.4 Experimental Design

This study adopted a randomized set-up comprising of three (3) treatments as follows:

i. Control (no biochar/ 0 days)
ii. First treatment (100.00 g of *Senna tora* biochar for 30 days)
iii. Second treatment (100.00 g of *Senna tora* biochar for 60 days)

The experiments were carried out in pots with a total of nine pots replicated thrice. 1.00 kg of the collected soil sample was weighed and placed into each of the nine plastic pots. The first (30 days) and second (60 days) treatments were irrigated daily with 50.00 cm^3 of water to maintain a slight moisture in the soils. After each treatment, the biochar residue was removed and the soil samples from each replicate treatment were collected and combined to form a composite sample. The composite sample was dried in air at room temperature, ground, sieved through a 2 mm sieve and properly labeled for physico-chemical parameters analyses.

2.5 Physico-chemical Parameters Analyses

Physicochemical parameters like soil texture, soil bulk density, pH, organic carbon and soil micronutrients were determined using various analytical techniques. The soil texture and bulk density were determined using hydrometer [21]. The organic carbon of the control and treated soils was determined using the Walkley and Black method adopted by Hassan et al. [15]. The soil micronutrients were analyzed following the method [21].

2.6 Quality Control and Statistical Analysis

Analytical-grade chemicals were used in all the solution preparations, and all glass and plastic wares were meticulously washed with So Klin® detergent solution, followed by 20% nitric acid (HNO_3), and rinsed thoroughly with tap water and finally with distilled water. All data were treated as the mean and standard deviation. A single-factor Analysis of Variance (ANOVA) was used to establish the significant differences between study treatments. A Tukey Pairwise test ($p \leq 0.05$) was used to locate the significant difference in each treatment [10]. Microsoft Excel 2010 was used in drawing the tables and graphs.

3. Results and Discussion

3.1 Soil Texture and Textural Class Before Treatment

Table 1 shows the soil texture analysis and textural class of the soil collected from Misau farms before biochar treatments. As shown in Table 1, the soil texture was sandy loam with the highest percentage of sand (60.68%), followed by silt (20.00%), while clay had the lowest percentage (19.32%). The highest percentage of sand in the soil may indicate that the soil may not retain much nutrient. This is because sandy soils have poor structure, low surface area, low organic matter, and low cation exchange capacity. This results in low water holding capacity and low nutrient contents and retention [12, 14].

Table 1 *Particle size analysis and textural class of the soil sample from Misau*

Soil Texture	Value
Clay	19.32 %
Silt	20.00 %
Sand	60.68 %
Textural class	Sandy Loam

3.2 Physical and Chemical Parameters of the Soil After Biochar Treatment

The physical and chemical parameters of the soil after biochar treatment are presented in Table 2.

3.2.1 Variation of Soil pH

The experimental values of soil pH after treatments with the biochar obtained from *Senna tora* plant varied significantly ($p \leq 0.05$) from 6.66 (control) to 8.00 (first treatment). The value of 7.89 in the second treatment fell between the lowest and highest pH values (Table 2). Treating the soil with the biochar of *Senna tora* has changed the pH of the soil from a slightly acidic to a slightly alkaline condition with increments of 20.12% and 18.47% for the 30 and 60-day incubation periods, respectively. This result agrees with the findings of Lehmann [12], Liu et al. [22] and Rogers et al. [1], who reported an increase in soil pH with biochar addition. Atkinson et al. [23] reported an increase in soil pH from 3.90 to 5.10 when biochar was added to an acidic soil at 2.50% and 5.00% concentrations. Laird et al. [24] reported a similar trend when they investigated the effects of biochar treatments on the soil quality and spinach growth. Rodríguez-Vila et al. [3] obtained similar results when they investigated the impacts of biochar on micronutrient availability in tropical soils with two conflicting pH values of 4.5 and 6.9, respectively. The liming effects of biochar in acidic soils have been widely documented in the literature [5, 25]. The increase in pH with biochar addition in the soil could be due to the presence of functional groups with negatives charges like –COOH and -OH groups that decrease the activity of H^+ by binding with it in the soil solution [26, 27]. The results of this study also revealed that the pH of the soil decreased after 30 days of treatment. This suggests that the optimal liming condition of the soil should be around a 30-day incubation period when biochar from *Senna tora* is used as a soil amendment. The decrease in soil pH might be due to the production of acids by biochar during its oxidation [28]. Soil pH regulates by biochar applications and plays a substantial role in controlling the rate of biochar usage [5].

Table 2 *Some physico-chemical properties of soil treated with Senna tora biochar after 30 and 60 days*

Parameters	Treatments		
	Control	30 Days	60 Days
pH	$6.66^b \pm 0.06$	$8.00^a \pm 0.50$	$7.89^a \pm 0.22$
Bulk Density (BD), g/cm^3	$1.56^a \pm 0.04$	$1.51^a \pm 0.02$	$1.48^a \pm 0.04$
Organic Carbon (OC), g/kg	$3.40^a \pm 0.40$	$3.40^a \pm 0.40$	$3.90^a \pm 0.26$
Cation Exchange Capacity (CEC), cmol/kg	$5.16^c \pm 0.09$	$6.20^b \pm 0.15$	$7.29^a \pm 0.17$

Values are mean ± standard error of the mean (SEM) (n = 3), values on the same row with the similar superscript letter are significantly the same, while values on the same row with different superscript letters are significantly different as obtained from the Tukey Pairwise test.

3.2.2 Variation of Soil Bulk Density (BD)

The observed values of bulk density (BD) of the soil ranged from 1.48 (second treatment) to 1.56 g/cm^3 (control). The value of 1.51 g/cm^3 in the first treatment fell between the lowest and highest values (Table 2). A significant difference was observed between the BD of the control soil sample ($p \leq 0.05$) and the observed values in the first and second treatments respectively. Application of biochar has been reported to increase the soil's total porosity, which leads to the decrease in soil's BD [10, 22, 29]. Zhang et al. [30] confirms a decrease in soil BD and increase in the soil porosity when they studied the effects of biochar on the growth of maize (*Zea mays*) from soils of Central China. Similarly, Githinji [31] reported a reduction in soil BD when they studied the effects of biochar treatments on the physical and hydraulic properties of sandy loan soil. In another study, Herath et al. [29] confirmed a decrease in soil BD when they investigated the impact of biochar treatments on the physical properties of two distinct soils. The decrease in soil BD has positive effects on other soil physicochemical and microbial properties [5]. Due to its significant importance, soil BD is one of the most extensively investigated soil properties with regard to biochar application [10]. Soil's BD is a good indicator of the suitability for root growth and soil permeability and is vitally important for soil quality. Generally, a soil with a low BD of less than 1.5 g/cm^3 is desirable for optimum movement of air, water, and nutrients through the soil [26].

3.2.3 Variation of Organic Carbon (OC)

The experimental values of the organic carbon (OC) in the soil investigated varied from 3.40 g/kg (control and first treatment) to 3.90 g/kg (second treatment). Biochar applications have been found to improve the OC of the soil due to the high levels of carbon content in biochar [30]. Shenbagavalli & Mahimairaja [32] reported 33.00 %–35.00 % higher soil carbon content after the applications with different biochar levels. A comparable increasing trend was also reported by Islami et al. [33], with 255.50 g/kg and 404.20 g/kg increases for farmyard biochar and cassava stem biochar, respectively. The OC content of the control and treated soils was not significantly affected ($p \leq 0.05$) after 30 and 60 days of treatment, respectively. High contents of OC in the soil enhance the retention and absorption of soil micronutrients in soil for plant uptake [12]. Soil OC provides several advantages for soil health, fertility, and productivity. It binds soil particles into stable aggregates, improving soil structure, aeration, water retention capacity, and reducing erosion [23]. It also serves as a food supply for soil organisms, increasing biodiversity and biological activity. It also aids in the regulation of nutrient delivery and microbial activities such as nitrogen fixation and breakdown [26].

3.2.4 Variation in Cation Exchange Capacity (CEC)

The values of cation exchange capacity (CEC) as presented in Table 2 varied from 5.16 cmol/kg (control sample) to 7.29 cmol/kg (second treatment). An experimental value of 6.20 cmol/kg in the first treatment fell between the lowest and highest CEC values. The CEC values significantly ($p \leq 0.05$) increase with increase in biochar treatments, with an increment of 20.16 and 41.28% after 30 and 60 days of incubation, respectively, compared to the control. This result followed a similar trend observed by Premalatha et al. [5], Atkinson et al. [23] and Van Zwieten et al. [34]. This increase in soil CEC could be due to the formation of basic cations with the reduction of acidic cations [10]. Moreover, the presence of -OH and -COOH functional groups, a large surface area and variable charges of biochar improve the CEC of the soil [2]. CEC is an inherent soil property and plays a paramount role in influencing the capacity of the soil to hold on to essential nutrients and provide a strong buffer against soil acidity by holding on to essential nutrients in the soil [23].

3.2.5 Variation of Micronutrient (Fe, Mn, Cu and Zn)

The variations of *Senna tora* biochar treatments on the concentrations of micronutrients in the agricultural soil of Misau, Bauchi State, Nigeria, are depicted in Figure 2. The experimental values of iron ranged from 3188.63 (first treatment) to 9460.00 mg/kg (control). The value of 4782.73 mg/kg in the second treatment fell between the two ranges. The level of iron decreased significantly ($p \leq 0.05$) by 6271.37 and 4677.27 mg/kg after 30 and 60 days of biochar treatments, respectively, compared to the control. The decrease in the levels of iron after the biochar treatment might be due to the reaction between the positively charged Fe and negatively charged functional groups like –COOH, -OH and others present in the biochar, which results in a decrease in iron availability [35]. Iron is a vital element for plant growth; its deficiency causes stunted growth and reduced productivity [36].

The levels of manganese in the soil range from 188.25 mg/kg (control) to 286.12 mg/kg (second treatment), with 201.15 mg/kg (first treatment) falling in between the two extreme values. The experimental value of manganese in the second treatment significantly influenced the levels of manganese in the control and first treatment ($p \leq 0.05$) when compared with others. The levels of manganese increased significantly ($p \leq 0.05$) with the increase in biochar incubation time. This may demonstrate that the biochar of the *Sena Tora* Plant used for this study contained high levels of manganese. Manganese is a constituent of enzymes responsible for the transformation of certain nitrogen and protein synthesis [23].

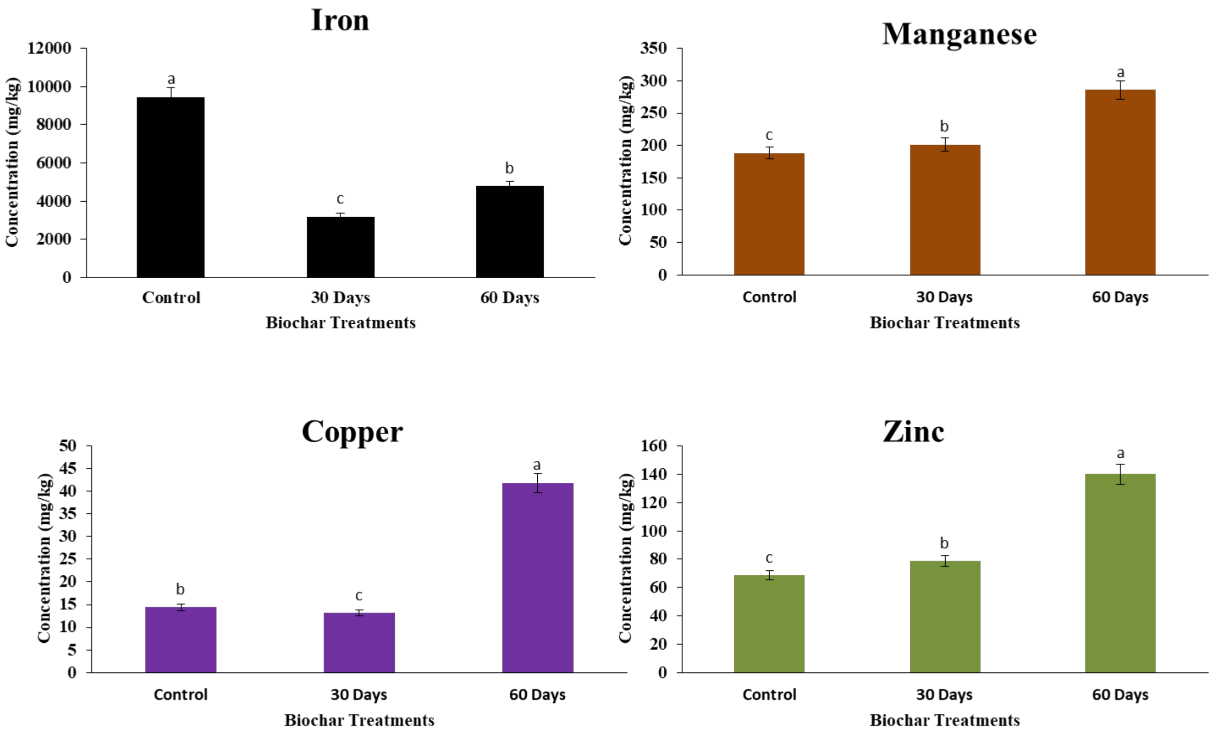

Fig. 2 *Effects of Senna tora biochar treatments on the levels of micronutrient in the farm soil of Misau*

The experimental concentration of copper in the soil (control and treatment) ranged from 13.13 mg/kg (first treatment) to 41.88 mg/kg (second treatment). The value of 14.38 mg/kg (control) fell between the lowest and highest concentrations. The experimental value of copper in the second treatment significantly ($p \leq 0.05$) influenced the levels of copper in the control and first treatment when compared with others. The level of copper in the soil was found to decrease by 1.25 mg/kg after 30 days of biochar application when compared with control soil. This might be due to the reaction between the positively charged Cu^{2+} ion and negatively charged functional groups like -COOH, -OH, and others present in the biochar, which results in a decrease in copper availability [35]. The level of copper in the soil, however, increased by 27.50 mg/kg after 60 days of biochar treatments. The increase in the levels of copper after 60 days of biochar treatments could be due to the release of more copper ions as a result of the slow degradation of biochar [5, 22].

The observed value of zinc in the soil ranged from 68.63 (control) to 140.19 mg/kg (second treatment). The value of 78.71 mg/kg (first treatment) fell between the lowest and highest concentrations. The experimental concentration of zinc in the second treatment significantly ($p \leq 0.05$) influenced the levels of zinc in the control and first treatment when compared with others. The levels of zinc were increased with the increasing incubation time of biochar. This may suggest that the biochar of the Senna tora plant used for this study contained high levels of zinc, and zinc could be easily released from biochar due to the weak bond between them [14, 27]. Zinc is an important nutrient needed for producing chlorophyll, aiding in plant growth, and improving root development, flowering, and fruit production. About 6.0 mg/kg of zinc is needed in the soil for optimal growth of the plants [1].

Generally, the impacts of biochar on the properties and micronutrients availability vary depending on the types of biochar and their chemical compositions, soil pH, biochar treatment dosage, soil's nutrient status as well as the interaction of microorganisms with biochar in the soil [36, 37]. For instance, biochar can hold on and retain positively charged ions through various processes such as adsorption, complexation, and precipitation, which causes a decline in the leaching of nutrients. This is due to the greater surface area and surface negative charge of biochar [35, 38]. Biochar is considered a slow-release fertilizer and contributes large amounts of micronutrients to the soil [39; 40]. Based on these findings, it is therefore recommended that different commonly available feedstock materials be used at different temperatures (400–700 °C) in order to select the best biochar that can be used practically in the field. Furthermore, because of the slow-release nature of biochar, it is suggested that longer incubation periods (greater than 60 days) be employed in future study.

4. Conclusion

In this study, the effects of biochar treatments on some soil properties and micronutrient availability in the farmland of Misau, Bauchi State, Nigeria were investigated. The findings of the study revealed that the values of

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pH, OC and CEC increased significantly ($p \leq 0.05$) from 6.66 to 7.89, 3.40 to 3.90 g/kg and 5.16 to 7.29 cmol/kg respectively, while the values of BD decreased significantly from 1.56 to 1.48 g/cm^3 after 60 days of biochar treatment. After 60 days of biochar treatment, Mn, Cu, and Zn levels increased from 188.25 to 286.12 mg/kg, 14.38 to 41.88 mg/kg, and 68.63 to 140.19 mg/kg, respectively, but Fe levels decreased from 9460.00 to 4782.73 mg/kg. The applications of biochar obtained from *Senna tora* significantly increased the fertility of the soil by improving its chemical and physical properties as well as some levels of micronutrients. The improvement was more noticeable after 60 days of biochar treatments.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

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