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Posted Date: 11 October 2024

doi: 10.20944/preprints202410.0798.v1

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Article

Title Foliar Fertilization with Organic-Mineral Compounds: A Sustainable Approach to Enhancing Winter Wheat Yields on Low-Fertility Soils

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Abstract: This study aims to evaluate the effectiveness of foliar fertilizers containing mineral nitrogen, organic matter, amino acids, organic acids, and trace elements on winter wheat's grain yield to regulate the crop's mineral nutrition. The research was conducted during the 2022-2023 agricultural years on separate plots, with three repetitions and five variants of foliar fertilizer application: urea, the biostimulant Amino Turbo, the organic-mineral fertilizer Ruter AA, and Geofert, alongside calculated doses of phosphorus-potassium fertilizers. Treatments were applied during the early phases of winter wheat development: the first feeding at the third stage of organogenesis (BBCH 25-29) and the second feeding at the fourth to fifth stages of organogenesis (BBCH 30-31).On average, over three years of research, the most effective results were achieved by applying Ruter AA fertilizer on the leaves, yielding 43.7 kg of grain per hectare. This yield is 3.4 kg/ha higher than that obtained through traditional foliar application of urea. The Geogumat fertilizer, which contains strains of microorganisms, demonstrated similar effectiveness to urea. In contrast, the biostimulant Amino Turbo exhibited significantly lower efficiency than the fertilized variants. In field experiments, the impact of foliar fertilizers on nitrous oxide emissions in winter wheat crops was evaluated. The amino acid biostimulant demonstrated a significant advantage in reducing nitrous oxide emissions. The findings indicate that foliar fertilization of winter wheat can be a sustainable farming practice that enhances crop yields while decreasing N_2O emissions.

Keywords: biostimulants; yield; N_2O emissions

1. Introduction

The primary responsibility of the agricultural sector in any country is to supply its population with food through domestic production. The southeastern region of Kazakhstan is particularly well-suited for crop production development, with winter wheat being a longstanding priority crop. However, a significant challenge hinders the sustainable production of high-quality yields: the low fertility of the region's typical light chernozem soils.

One method that contributes to increased crop productivity on low-fertility soils is using mineral fertilizers, particularly nitrogen fertilizers. These fertilizers supply the essential nitrogen needed for soil nutrition. However, there are risks associated with the systematic application of mineral fertilizers, as they can accumulate significant amounts of ballast elements in the soil. This accumulation can adversely affect soil properties, crop yield, quality, and environment [1,2].

This necessitates the search for various forms and types of nitrogen-containing fertilizers that can serve as alternatives to mineral nitrogen for crops with diverse biological characteristics. This approach aims to enhance economic benefits while minimizing environmental impact through the regulated application of fertilizer doses and reducing greenhouse gas emissions from the soil into the atmosphere. In this context, bioorganic fertilizers and biostimulants are increasingly preferred [3–5].

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They can serve as a promising tool in the current landscape of crop production development. Due to their composition – a compound or mixture of various organic compounds of natural origin – they can enhance plant growth under different environmental stresses [6].

These fertilizers are increasingly utilized in foliar nutrition practices, as they can help achieve maximum yield potential with minimal reliance on synthetic fertilizers. These fertilizers can optimize traditional mineral nutrition schemes [7–9]. Bio-organic fertilizers exhibit lower nitrous oxide emission coefficients compared to mineral fertilizers. Furthermore, this coefficient is influenced by the type of organic fertilizer, C/N ratio, soil properties, and climatic factors such as average annual temperature and rainfall [10,11].

Hamedani (2020) noted that using foliar-applied fertilizers in crop production and synthetic fertilizers can reduce greenhouse gas emissions by 7-24% [12,13].

Additionally, bio-organic fertilizers can facilitate more efficient management of organic waste [14], and their production is more environmentally friendly than synthetic fertilizers [15,16].

Following the Law of the Republic of Kazakhstan on the ratification of the Kyoto Protocol to the United Nations Framework Convention on Climate Change, adopted on March 26, 2009, an important aspect is the assessment of greenhouse gas emissions from soils during the cultivation of strategically prioritized crops that are intensively fertilized. Separate studies have been conducted in various soil-climatic zones of Kazakhstan to address the issue of CO2 and N2O emissions during crop production [17,18].

The critical question remains: how does foliar fertilization with non-synthetic fertilizers affect crop yields and the magnitude of nitrous oxide emissions into the atmosphere? Therefore, we initiated research on this topic in 2022 on a farm, employing various methods of fertilization for crops. Our study hypothesized that combining organo-mineral fertilizers and biostimulants with foliar fertilization could positively influence winter wheat yields in a three-field crop rotation system on low-fertility light serozem soils while minimizing nitrous oxide emissions. The results of these studies will serve as a foundation for recommendations regarding their application in farm conditions

2. Materials and Methods

2.1. Site Description and Experimental Design

Field experiments were conducted at the "Kainar Koksu" farm in the Koksu district of the Zhetysu region (44°08′83″ N, 78°11′64″ E) (Figure 1).

Figure 1. Study area.

The climate of the study area is classified as continental. Data from the Taldykorgan meteorological station (45°01′39″ N, 78°26′15″ E) indicate that January is the coldest month, with temperatures ranging from -9°C to -7°C, while July is the hottest, with temperatures between 22°C and 24°C. Winter temperatures can drop as low as -35°C in some areas. During the 2022-2023, annual

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precipitation ranged from 400.1 mm to 468.3 mm. The average annual temperature was 9.4°C, with the growing season averaging 16.3°C. Irrigation was applied, and water availability was not a limiting factor in the experiments.

The experiments were carried out on arable plots under a three-crop rotation of winter wheat, sugar beet, and soybean. The field trials were conducted during the 2022-2023 growing season using a randomized block design with replications, following Dospehov's methodology. This method emphasizes crop interactions with soil-climatic and agrotechnical factors, ensuring experimental typicality, adherence to principles, designated areas, accurate harvest accounting, and experiment credibility.

Each trial plot covered 96 m² (8m × 12m) with protective borders of at least 1m between plots to prevent fertilizer contamination.

The experimental treatments included:

- **Control:** No fertilizers
- **P120 + P.K.**: Calculated dose
- **P120 + N30:** Urea applied at III and IV-V stages of organogenesis (BBCH 25-29 and BBCH 30-31)
- **P120 + Amino Turbo:** Biostimulant applied at III and IV-V stages
- **P120 + Ruter AA:** Applied at III and IV-V stages
- **P120 + Geohumat:** Applied at III and IV-V stages

Before the trials, the soil was tested for mobile nutrient availability to determine the phosphorus and potassium fertilizer rates using the balance method. Phosphorus fertilizer was applied at a rate of 100 kg P/ha two weeks before sowing, with an additional 20 kg P/ha applied in the rows at sowing. Monoammonium phosphate (**$NH_4H_2PO_4$**.) was used, containing 10-12% N and 52% P_2O_5.

This design incorporated mineral and organic-mineral fertilizers and biostimulants for foliar treatment during critical growth stages. Fertilizer and biostimulant application rates followed manufacturer recommendations.

2.2. Object of the Study

The winter wheat variety **Bezostaya 100** was used in this study. Developed at the National Grain Centre named after P.P. Lukyanenko in Russia, this variety is classified as medium-early, with a growth period ranging from 221 to 296 days and an average yield of 5.0 to 6.0 tonnes per hectare. Bezostaya 100 is known for its susceptibility to shattering but offers resistance to drought, heat, and other environmental stresses.

In the experiments, the following fertilizers were used:

- **Urea (granular)**: Nitrogen content of 46%
- **Amino Turbo (powder, AS CROP Sp. z o.o., Poland)**: Organic Carbon (C) 39.0%, Organic Nitrogen (N) 12.8%, Free Amino Acids 80.0%, Total Amino Acids 85.0%
- **Ruter AA (liquid, TradeCorp, Spain)**: Sorg - 180 g/L, Free L-α Amino Acids - 84 g/L, Total Nitrogen (N) - 66 g/L, Phosphorus Pentoxide (P_2O_5) - 60 g/L, Potassium Oxide (K_2O) - 42 g/L, Chelated with EDDHA: Iron (Fe) - 0.4 g/L, Manganese (Mn) - 0.6 g/L, Zinc (Zn) - 0.8 g/L, Molybdenum (Mo) - 1.2 g/L
- **Geohumate (powder, GeoFert, Georgia)**: Organic Carbon (C org) - 12.0%, Organic Nitrogen (N org) - 1.2%, Phosphorus Pentoxide (P_2O_5) - 0.55%, Potassium Oxide (K_2O) - 6.5%, Calcium (Ca) - 0.56%, Sulfur (S) - 2.1%, Magnesium Oxide (MgO) - 0.32%, Iron (Fe) - 0.50%, Manganese (Mn) - 0.083%, Molybdenum (Mo) - 0.3%, Zinc (Zn) - 0.4%, Silicon (Si) - 5.06%, Aluminum (Al) - 3.3%, Humic Acid - 34.0%, Fulvic Acid - 25.0%, Bacillus strains: *Bacillus megaterium, Bacillus mucilaginosus, Bacillus subtilis*

All the above-trademarked fertilizers are registered and available to farmers in Kazakhstan.

2.3. Methods

Soil samples were collected from each plot using the envelope method at two depths: 0-20 cm and 20-40 cm. The samples were prepared by drying and grinding in a soil mill and passing them through sieves with 1 mm and 0.25 mm mesh sizes.

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- **Nitrogen**: Extracted with sulfuric acid to measure nitrogen from easily mineralizable organic compounds.
- **Mobile phosphorus and potassium**: Measured by extracting these mobile compounds from carbonate soils using a 1% ammonium carbonate solution at pH 9.0.
- **pH of the water extract**: Measured ionometrically.
- **Granulometric composition**: Assessed using the N. Kachinsky pipette method.

The experiments were conducted on light serozem soils, classified as medium loam and loess loam, typical for the region. The soil had a slightly alkaline pH of 8.54 (Table 1), low humus content (0.57% to 1.11%), and low levels of easily hydrolyzable nitrogen (22.4 to 33.6 mg/kg). Phosphorus content was low to average (10.0 to 18.0 mg/kg), and exchangeable potassium ranged from low to average (200 to 260 mg/kg).

Table 1. Soil characteristics at different depths in the experimental plots.

Soil Depths [cm]	Humus content [%]	pH	Plant available N ([mg/kg]	P_2O_5 [mg/kg[	K_2O [mg/kg]	Content of soil fractions <0,01 mm [%]
0-20	0,79	8,54	27,4	14,0	236,0	33,12
20-40	0,73	8,49	26,3	7,2	168,0	41,78

Nitrous oxide (N_2O) emissions were measured using the closed chamber method (Figure 2a,b). Gas samples were collected during the main crop development phases, before and after foliar treatments, and during the vegetation period and post-harvest.

a

b.

Figure 2. Gas Sampling Using the Closed Chamber Method: (a) Overview of the Chamber; (b) Installation of the Chamber at the Field Site.

The closed chambers were constructed from inverted cylindrical plastic vessels with a diameter of 20 cm and a height of 11 cm. Four chambers were placed on each plot and inserted into the soil to a depth of about 2 cm, and the soil outside the chamber was compacted to ensure it was airtight. The three-way stopcock on each chamber was closed after placement to prevent pressure buildup. After 60-75 minutes, gas samples were collected using a syringe.

Gas samples were drawn into 60 ml syringes, with 50 ml passed through a 10 ml vial pre-filled with air. The remaining 10 ml was injected into the vial to create overpressure. The samples were then transferred into 3 ml vials and analyzed for N_2O using a Thermo Scientific TSQ 8000 EVO triple

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quadrupole gas chromatograph/mass spectrometer (GC-MS) with a Supel-Q PLOT capillary column (30m x 0.32 mm). Helium was used as the carrier gas at a 1 mL/min flow rate. Calibration was performed using certified reference gas mixtures. The retention time for N_2O was 1.45 minutes, and the total sample processing time was 5 minutes per sample.

Winter wheat sowing and other agronomic practices followed standard regional guidelines. Yields were measured using a continuous method from each sample plot.

2.4. Statistical Analysis

The statistical analysis of the research results was conducted using a one-way analysis of variance (ANOVA) to evaluate data from the field experiments involving annual crops. The experiments were analyzed using the System for Combined Block Design (SCBD) framework. ANOVA was performed using the Excel software (ANOVA function).

The average values were compared using the Least Significant Difference (L.S.D.) test, with a significance level set at $\mathbf{p < 0.05}$. Differences at this level were considered statistically significant. The primary assumption in the analysis was that the effect of each level of the study factor remained consistent across all levels of the blocking factor.

3. Results

During the experiment, we evaluated the effect of foliar fertilization with organo-mineral fertilizers and biostimulants on nitrous oxide (N_2O) emissions from serozem soils in the experimental plots. Under winter wheat crops in the sprouting phase, following the autumn application of phosphorus fertilizers, the initial concentration of N_2O averaged 440.3 μg/m³, ranging from 246.03 to 467.9 μg/m³.

The analysis of N_2O emissions following the first foliar treatment showed that emissions in the experimental variants of winter wheat ranged from 406 μg/m³ in the control group to between 400.8 and 434.5 μg/m³ (Figure 3).

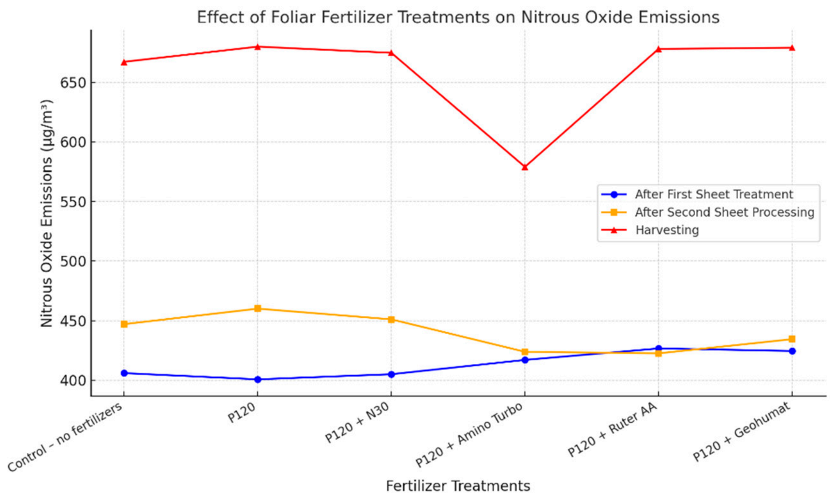

Figure 3. Effect of Foliar Treatments on N_2O Emmissions.

In the variant without foliar treatments, N_2O emissions were minimal with the application of P_{120} (120 kg P_2O_5), but emissions increased with the application of Geogumate. After the second treatment, N_2O emissions increased by 1.5 times in almost all fertilizer variants. However, when using the amino acid biostimulant Amino Turbo, nitrogen emissions decreased by 100 μg/m³.

By harvest time, nitrogen emissions decreased to levels similar to the beginning of the growing season, averaging 438.2 μg/m³, slightly higher than the initial readings. Among the treatments, Amino Turbo showed the most significant reduction in N_2O emissions, measuring 473.3 μg/m³.

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doi:10.20944/preprints202410.0798.v1

The research conducted between 2022 and 2024 demonstrated that double foliar treatments with organo-mineral fertilizers and biostimulants, in combination with pre-sowing phosphorus fertilizer, significantly impacted winter wheat yield. The least favourable year for yields was 2022, with an average of 33 quintals per hectare (c/ha). In the following years, yields averaged around 40 c/ha.

The study showed that all foliar fertilizers significantly increased yields compared to the control variant, ranging from 6.1 to 13.7 c/ha. Ruter AA, a liquid organic-mineral fertilizer enriched with chelates and plant-derived amino acids, achieved the highest efficiency. Over three years, the average yield was 43.7 c/ha, 13.7 c/ha (45.4%) higher than the control variant. Additionally, phosphorus fertilizer increased yield by 5.8 c/ha (see Table 2).

Table 2. - Effect of foliar fertilizers on winter wheat grain yield (kg/ha).

Variants	Yield capacity, c/ha			
	Year 2022	Year 2023	Year 2024	Mean value
Control – no fertilizers	25,0	33,3	31,9	30,1
P120 +PK calculated dose	32,6	43,1	38,2	38,0
P120 + N30 - III s/o and IV-V s/o	35,4	42,9	42,6	40,3
P120 + Amino turbo - III s/o and IV-V s/o	33,6	39,2	35,6	36,1
P120 + Ruter AA - III s/o and IV-V s/o	38,4	46,9	45,9	43,7
P120 + Geohumat - III s/o and IV-V s/o	32,1	41,8	45,7	39,9
$LSD_{0,05}$, c/ha	4,9	4,3	4,9	
P,%	4,7	3,3	3,6	

Ruter AA was more effective than traditional urea foliar treatments, showing a 3.4 c/ha yield advantage. Over three years, urea consistently outperformed other foliar fertilizers. Geogumate applied at the same level as urea resulted in a yield of 39.9 c/ha.

The most effective method for increasing winter wheat yield while maintaining similar N_2O emissions was applying Ruter AA as a foliar treatment. Although Amino Turbo had a lesser effect than phosphorus fertilizers, it increased yields by up to 6 c/ha compared to the control group. Amino Turbo's amino acid complex also improved the heat resistance of wheat during hot summer periods, positively affecting yields.

Differences in efficiency under field conditions can be attributed to several factors, including the interaction between biostimulants and soil properties, crop-soil microflora, and climate conditions. Foliar fertilizer applications can significantly enhance winter wheat yields, particularly in nutrient-deficient soils or under unfavourable weather conditions.

The statistical analysis of field experiment data confirmed the significance of the results. Fisher's criterion indicated that F_actual > F_table (at $\alpha = 0.05$), with a probability of obtaining such an F-criterion value by chance below 5%. This confirms that the observed results are statistically significant and not random, demonstrating the strength of the relationship between the treatment factors and the outcomes.

4. Discussion

Effective nitrogen management strategies during plant growth can enhance nitrogen use efficiency and minimize environmental pollution.

An essential issue in fertilizer application is the nitrous oxide released into the atmosphere. According to Novoa et al. (2006), this indicator is influenced by crop type, biochemical quality of residues, agricultural management, climate and season, soil properties, and soil moisture [28].

These findings are supported by the studies of Koga, N. (2012) [29], which observed relatively higher levels of N_2O emissions during the growing season of soybean cultivation. This increase was attributed to the release of nitrogen from root exudates rather than biological nitrogen fixation by nodules. The lower nitrous oxide emissions from winter wheat can be explained by the

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decomposition of organic matter from crop residues, which have a high C/N ratio, leading to the immobilization of soil mineral nitrogen.

The rate of nitrous oxide reduction in soils may primarily depend on the concentration of mineral nitrogen compounds, the content of organic matter, the presence of plants, and other factors [30].

All fertilizers increased nitrous oxide emissions in our experiments, and their differences were insignificant. The extent of these emissions depended more on the season; spring measurements recorded the minimum values at 440 μg/m^3. As the crop developed and grew, the effect of fertilizers became more pronounced, resulting in nitrogen emissions of approximately 700 μg/m^3. By the end of the growing season, nitrogen emissions decreased to 550 μg/m^3 just before harvesting.

The primary agronomic indicator of the effectiveness and efficiency of agro-technology applications, including fertilizers, is yield. Currently, new types and formulations of fertilizers that serve as alternatives to mineral fertilizers are particularly relevant [31]. Among these alternatives are fertilizers that combine microelements with organic substances, such as amino acids and humic substances. Fertilizers that incorporate organic nutrient sources offer a significant advantage as a controlled factor in managing the production process, particularly foliar fertilizers. These fertilizers are effective during critical developmental stages that influence future yield, especially under stress conditions such as low temperatures and pesticide application [32].

Amino acids are among the most active components of metabolism, participating in various biochemical processes. They play a crucial role in synthesizing proteins and growth substances, influencing the speed and intensity of plant growth processes [33].

Preparations containing humic acids are regarded as natural plant growth regulators. Their beneficial effects stem from alterations in the biochemical processes of plant cells and tissues, including the regulation of photosynthesis, protein and carbohydrate metabolism, and plant respiration and transpiration [34].

In addition, the presence of humic substances in the soil enhances the utilization coefficient of essential nutrients by inhibiting the formation of phosphorus and potassium compounds inaccessible to plants [35].

Our studies confirmed the agronomic benefits of fertilizer application; winter wheat plants responded positively to foliar fertilization with the types of fertilizers we studied.

As is well known, the yield of winter wheat is significantly influenced by weather conditions, particularly during the formation and development of reproductive organs, which occurs from autumn to early spring (the third stage of organogenesis) and during the period of rising temperatures (the fourth stage of organogenesis). Therefore, supplying plants with essential mineral elements and substances that enhance plant immunity and accelerate metabolic processes is crucial for achieving a good yield, especially in the face of potential stress factors. It is important to note that early stress has a more detrimental effect than stress that occurs later in the growth cycle [36].

The positive effects of foliar treatment of winter wheat crops with humic and amino acids, in conjunction with essential mineral fertilizers, are also supported by the data from Lozek, O. (1997) and Bărdaş, M. et al. (2024) [37,38].

Our findings are further supported by studies examining the effectiveness of fertilizers that combine microelements with amino acids or humic substances and nitrogen fertilizers, which are directly influenced by the soil's availability of other nutrients, particularly mobile phosphorus [39].

At the same time, it is essential to note that foliar fertilizers allow crop growers to promptly meet the nutrient needs of plants, bypassing the intermediary role of the soil while minimizing the environmental impact.

Thus, despite having a minimal effect compared to traditional mineral fertilizers, these types of fertilizers can still contribute to increased yields. This is likely due to their biostimulating potential, which is a corrector of mineral nutrition. They may also enhance plant immunity, accelerate metabolic processes, and activate the synthesis of proteins and carbohydrates.

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5. Conclusions

The study demonstrated that organic-mineral fertilizers and amino acid biostimulants had no significant effect on nitrous oxide (N_2O) emissions, primarily influenced by seasonal variations. However, foliar treatments positively impacted winter wheat grain yield, with phosphorus fertilizers further enhancing the effectiveness of these foliar applications.

Our findings suggest that foliar fertilization of crops can serve as a sustainable farming method, offering the potential to increase yields while minimizing N_2O emissions. Treatments like Ruter AA and Amino Turbo were especially effective during critical growth stages, helping plants cope with stress and improving crop performance. While traditional mineral fertilizers remain essential, integrating foliar fertilizers with organic components, such as amino acids and humic substances, provides additional benefits, including enhanced plant metabolism, stress resistance, and improved nutrient uptake.

Moreover, using biostimulants contributes to more sustainable agricultural practices by boosting plant health and productivity while reducing dependency on mineral fertilizers. Combining conventional and biostimulant-based fertilization strategies holds promise for increasing crop yields and supporting more sustainable, environmentally responsible farming practices.

In conclusion, adopting foliar fertilization techniques, particularly when combined with phosphorus and biostimulants, can significantly improve crop yields and reduce environmental impacts, providing a viable pathway to more efficient and sustainable agriculture.

Author Contributions: Conceptualization, R.R. and S.T.; methodology, R.R., S.T. and T.Sh.; validation, R.R., T.Sh. and A.S.; formal analysis, S.T. M.P. and A.S., M.Zh; investigation, R.R., T.Sh., S.T. M.P. and M.Zh.; resources, RR., S.T., M.Zh. and A.S.; data curation, R.R. and M.P.; writing – original draft preparation, R.R.T.Sh. M.S-M; writing—review and editing, R.R. T.Sh. and M.Zh; visualization, R.R. T.Sh. and M.P.; supervision, R.R.; project administration, R.R.; funding acquisition, R.R. and S.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP14870711).

Conflicts of Interest: The authors declare no conflict of interest.

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