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Original Paper

Precision Management of Bread Wheat Growth Using Humic-like Biostimulants from Lignin Waste

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The increasing demand for sustainable agriculture necessitates precision management techniques that optimize plant growth and yield while minimizing environmental impact. A promising direction is the use of humic-like substances derived from industrial waste, such as lignin-containing pulp and paper mill waste. This study involved the development of a specialized reactor for the oxidative-hydrolytic transformation of lignin-containing waste ("KNAUF Petrobord") into humic-like growth regulators (designated KLGK). The physiological activity of the resulting preparations was assessed via biotests on bread wheat seeds (*Triticum aestivum* L. cv. 'Darya' and 'Zlata'). Field experiments on bread wheat were conducted, applying the preparations as foliar feeding. Crop status was monitored using operational systems combining ground truthing and remote sensing (Sentinel-2 satellite data, NDVI index). Laboratory tests identified an optimal activating concentration range for KLGK between 0.0025% and 0.00025%, accelerating seed germination by 20–30%. In field conditions, the application of KLGK on a background of NPK fertilizer resulted in a grain yield of 3.02 t/ha, a 161% increase compared to the fertilizer-only background and a 207% increase over the control. The reference stimulant "Stimulife" yielded 2.55 t/ha. Remote sensing effectively tracked crop development and spatial heterogeneity, confirming the visual impact of the treatments. The methodology of precise regulation of crop growth using real-time monitoring and foliar fertilization based on preparations derived from PPM waste has been successfully tested. The developed technology enables the recycling of any lignin – containing waste into highly effective plant growth regulators, demonstrating significant potential for enhancing agricultural productivity and environmental.

Keywords: Precision Agriculture, Humic Preparations, Lignin Waste, Remote Sensing, Plant Growth Regulators

1 Introduction

Global agriculture is facing an incompatible challenge: on the one hand, the need to increase productivity, and on the other, the increasing environmental impact of industrialization. Precision agriculture (P-Ag) has emerged as a key strategy, traditionally relying on spatial soil agrochemical analysis and variable rate application of fertilizers to manage field heterogeneity (Zhang et al., 2002). However, a more dynamic approach focuses on managing plant development over time using functional diagnostics and targeted Plant Growth Regulators (PGRs) (Calvo et al., 2014; du Jardin, 2015).

Among PGRs, humic substances are of particular interest due to their natural origin and multifaceted effects on plant physiology and soil health (Canellas & Olivares, 2014). The theory of humification, significantly advanced by Russian scientists, e.g., Alexandrova, Kononova (1966), Orlov (1985), Komarov (2004, 2005), posits that these complex molecules play a crucial role in nutrient mobilization and plant stimulation. This classical understanding has been further developed and confirmed in modern research on biostimulants, which provides detailed insights into the physiological mechanisms of humic substances (Canellas & Olivares, 2014).

Internationally, research into humic substances from various sources, including leonardite and lignite, is well-established, showing benefits for seed germination,

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*Corresponding Author:** Arthur I. Novikov, Agrophysical Research Institute, St. Petersburg, Russian Federation, 14, Grazhdansky av., Saint-Peterburg, 195220, Russian Federation, e-mail: arthur.novikov@agrophys.ru ORCID: https://orcid.org/0000-0003-1230-0433 root development, and stress tolerance (Rose et al., 2014). However, the transformation of underutilized, problematic industrial wastes, such as lignin from pulp and paper production, into value-added humic-like products represents a novel and highly promising frontier. This approach aligns with the principles of a circular economy, where industrial by-products are valorized for agricultural applications (Toop et al., 2017). While some international studies exist on the processing of lignocellulosic materials into humic-like substances (e.g., García et al., 2016), the specific oxidative-hydrolytic transformation of pulp and paper mill lignin into precision plant growth regulators, as developed in this study, represents a distinctive approach.

Thus, extensive theoretical research and the practical application of diverse humic preparations and fertilizers, as reflected in global scientific achievements, are reinforced in the present study by the use of modern operational monitoring tools for assessing the state of vegetative plants. This monitoring is conducted using state-of-the-art remote sensing data and employs a geostatistical approach for the digitalization of the obtained data. It is precisely the timely operational adjustment of the bio-production process using highly effective activators of growth processes that can enable the attainment of high-quality crop yields with minimal labor and capital inputs.

The specific objectives of this study were:

1. to synthesize humic-like preparations (KLGK) from lignin-containing waste (KNAUF Petrobord) through an optimized oxidative-hydrolytic process in a custom-designed reactor;
2. to evaluate the physiological activity of KLGK on bread wheat seed germination under laboratory conditions across a range of concentrations;
3. to assess the effects of foliar KLGK application on bread wheat yield and crop structure under field conditions in comparison with a reference biostimulant (Stimulife) and NPK (Nitrogen-Phosphorus-Potassium) background;
4. to demonstrate the feasibility of integrating Sentinel-2 satellite-derived Normalized Difference Vegetation Index (NDVI) data for operational monitoring of crop response to biostimulant treatments throughout the growing season.

2 Material and Methods

2.1 Synthesis of Humic-like Preparations

The source material was lignin-containing waste from "KNAUF Petrobord" (Kommunar). The transformation was conducted in a custom-built, 5–10 L reactor resistant to aggressive media, high temperature, and pressure. The oxidative-hydrolytic transformation process was carried out under controlled conditions: temperature (100–180 °C), pressure (5–25 atm), NaOH concentration (2–10%), and aeration (5 L/min^1) according to the previously described method (Komarov, 2005). Samples were taken at intervals (1, 2, 4, 6, 8, 10 hours) to isolate products from different transformation stages. Thus, the optimal regime for obtaining the active product (KLGK) was determined to be 130 °C for 6 hours which corresponded to previously obtained results on the oxidative-hydrolytic transformation of hydrolysis lignin (Komarov, 2004).

2.2 Assessment of Physiological Activity

The physiological activity of the KLGK preparation was evaluated using a seed germination biotest according to station standard of Russian Federation (GOST 12038) and a modified Grodzinsky biotest (Grodzinsky, 1992). Seeds of bread wheat (*Triticum aestivum* L. cv. 'Zlata') were used. This cultivar was selected for the laboratory biotest for the following reasons:

1. the seeds were of high reproduction quality (super-super elite) with 99% baseline germination, which is optimal for standardized biotesting;
2. the small scale of seed consumption (only 100 g per experiment) allowed the use of more expensive elite material (costing 40 RUB/kg) without significantly increasing the research budget.

Experiments were conducted in Petri dishes with KLGK solutions at concentrations of 0.25%, 0.025%, 0.0025%, and 0.00025%, with water as a control. Seed germination was monitored continuously for 7 days.

2.3 Field Experiment and Monitoring

A field experiment was conducted during the 2024 growing season (May–August) on bread wheat (*Triticum aestivum* L. cv. 'Darya') at the Pribytkovsky experimental field, located in the Leningrad region of the Russian Federation (59° 33′ N, 30° 13′ E; elevation 65 m a.s.l.). The total experimental area was 17.2 ha.

The choice of cultivar 'Darya' for the field trial was determined by both agronomic and economic factors. This cultivar is adapted to the conditions of the Leningrad region and is widely used in commercial production. At a seeding rate of 200 kg/ha (total consumption of 2,240 kg for the experimental area), the seed cost was 22,400 RUB at a price of 10 RUB/kg. Using elite seeds of the 'Zlata' cultivar would have increased seed material costs fourfold (to approximately 90,000 Rub), which was economically impractical for a field experiment of this scale. Thus, the choice of cultivars reflects a balance between the need for standardized conditions in laboratory biotesting and the economic realism of field trials.

The experiment was arranged in a randomized complete block design (RCBD) with four replications. The use of four replications was determined based on a priori power analysis ($\alpha = 0.05$, power = 0.80) to detect a minimum yield difference of 15% between treatments, assuming a coefficient of variation of 12% based on previous field trials at the same location.

Each experimental plot measured 36 × 300 m (1.08 ha), resulting in a total of 16 plots (4 treatments × 4 replications). To minimize edge effects and prevent interference between adjacent treatments, 1.5 m buffer zones were established between all plots. These buffer zones were planted with the same wheat cultivar but received no experimental treatments and were excluded from all sampling and yield measurements. The entire experimental area was surrounded by a 5 m border strip planted with wheat to eliminate border effects.

For agrochemical characterization, soil samples were collected from the plow layer (0–30 cm) and analyzed according to the following standard methods: Soil pH (KCl extract) – potentiometrically according to GOST RF 26483–85; Organic matter content – Tyurin method modified by CINAO with photocolorimetric detection (GOST RF 26213–91); Available phosphorus and potassium (Kiryanov method) – according to GOST RF 26207–91; Hydrolytic acidity – Kappen method (GOST RF 26212–91); Sum of exchangeable bases – Kappen-Gilkowitz method (GOST RF 27821–88). The soil at the experimental site was classified as Albic Luvisol (according to IUSS Working Group WRB, 2022) with the following properties in the 0–30 cm layer (mean ±SD, $n = 5$) : $\text{pH}_{\text{KCl}} = 5.6 \pm 0.3$, organic matter content 2.8 ±0.4%, total N 0.16 ±0.02%, available P (P_2O_5) = 65 ±8 mg/kg, available K (K_2O) = 120 ± 15 mg/kg. Soil texture was loam with 28% sand, 42% silt, and 30% clay.

A single foliar application was performed during the critical growth stage – the transition from vegetative growth to grain formation (stem elongation phase). The following four treatments were applied:

- Absolute control (C): Foliar application of water only (200 L/ha).
- Fertilizer background (B): Foliar application of polymer-based fertilizers "Vitanoll-N" (containing N – 25%, SO_3 – 10% + micronutrients: Mg, Zn, Mn, Cu, B) at a rate of 1 L/ha and "Vitanoll-RK" (containing K_2O – 20%, P_2O_5 – 16% + micronutrients: S, Mg, Mn, B) at a rate of 1 L/ha. Manufacturer: Agromarket-24 LLC, Russia (https://vitanoll.ru). Both fertilizers were dissolved in water (200 L/ha).
- Background + KLGK (B + KLGK): Foliar application of NPK fertilizers (as above) supplemented with 100 mL/ ha of KLGK preparation dissolved in water (200 L/ha).
- Background + Stimulife (B + Stim): Foliar application of NPK fertilizers (as above) supplemented with 300 mL/ha of the reference biostimulant 'Stimulife' dissolved in water (200 L/ha). Stimulife is a commercially available plant growth regulator containing humic and fulvic acids (certified under EU Regulation 2019/1009) and was used as a positive control for comparison.

Treatments were applied using a mounted boom sprayer with an 18 m working width, aggregated with a wheeled tractor (Belarus-82.1, power class 1.4–2.0). Applications were carried out between 08:00 and 10:00 local time under calm wind conditions (< 3 m/s^1) to minimize spray drift. The sprayer tank and boom were thoroughly rinsed with clean water between treatments to prevent cross-contamination.

The preceding crop was bare fallow. Wheat was sown on 10 May 2024 at a seeding rate of 200 kg/ha (approximately 450 ±20 viable seeds per square meter) using a mechanical drill «Amazone» with 15 cm row spacing. No irrigation was applied; crop water requirements were met by natural precipitation. Weeds were controlled by mechanical harrowing at the three-leaf stage, and no herbicides were applied. No fungicides or insecticides were used, as pest and disease pressure remained below economic thresholds throughout the season.

Yield was determined by continuous combine harvesting using a Claas D130 combine harvester equipped with an ACT (Automatic Control Terminal) system, recording yield values and corresponding GPS coordinates in real time across the experimental field. In addition, for statistical analysis, yield was measured from four 1 m^2 sampling quadrats for each treatment.

Foliar fertilization was carried out during the period from tillering to stem elongation. Crop monitoring was performed using Sentinel-2 satellite imagery. The Normalized Difference Vegetation Index (NDVI) was calculated and analyzed using the LandViewer service to assess plant status and field heterogeneity throughout the growing season. The application of Sentinel-2 data for vegetation monitoring is a well-established approach in precision agriculture, providing high-resolution spatial and temporal data for crop assessment (Segarra et al., 2020).

To assess the dynamics of crop development and the spatial heterogeneity of the experimental field in response to the applied treatments, remote sensing data from the European Space Agency's Sentinel-2 satellite constellation were utilized. Monitoring was conducted throughout the 2024 growing season, from May to September.

Sentinel-2 Level-2A products (bottom-of-atmosphere corrected reflectance images) with cloud cover over the experimental field of less than 10% were obtained via the Copernicus Open Access Hub. A total of 12 cloud-free scenes covering key phenological stages of bread wheat (emergence, tillering, stem elongation, heading, and ripening) were selected. For vegetation index calculation, bands with 10 m resolution (Band 4 – Red, 665 nm; Band 8 – Near-Infrared, 842 nm) were used.

The Normalized Difference Vegetation Index (*NDVI*) was calculated according to the standard formula:

$$NDVI = (NIR - RED)\big/(NIR + RED)$$

where: *NIR* and *RED* – the reflectance values in the near-infrared and red bands, respectively

All satellite data processing was performed using the LandViewer web-based service (EOS Data Analytics, Inc.). The workflow was as follows. The boundaries of the Pribytkovsky experimental field were delineated as a vector polygon; for each selected acquisition date, NDVI was calculated on a per-pixel basis across the entire field; for each acquisition date, descriptive statistics of the NDVI distribution across all field pixels were calculated, including the median, minimum, maximum, and first and third quartiles (or confidence intervals). This allowed for a quantitative assessment of both the average vegetation level and the degree of spatial heterogeneity of the crops at each time point. Based on the obtained data, a graph of NDVI dynamics over the season was constructed (see Figure 3), which displays the median (central tendency) for each date, along with spread ranges (min-max or interquartile range) characterizing the variability of the index within the field. The resulting time series was analyzed to identify the period of maximum vegetative activity (late June to late July), when the highest NDVI values were observed.

The presented NDVI dynamics, including indicators of spatial variability, were subsequently compared with yield data to assess the effectiveness of the studied preparations under conditions of field heterogeneity.

2.4 Data Analysis

Yield and yield structure data (total biomass, grain weight, plant height, number of stems) were collected from sample plots and by continuous combine harvesting. The yield data were then evaluated using a geostatistical approach (Zakharyan & Komarov, 2019).

Given that the studied field areas exhibit significant heterogeneity in vegetation indices, and consequently in potential productivity, a geostatistical method was adopted as the basis for assessment. Conventional visualization methods do not allow for an objective evaluation of the treatment effects on crop yield. To objectively assess the effect of the preparations on plant productivity, it is necessary to employ geostatistical methods based on variogram analysis, clustering of heterogeneity zones, and delineation of these objects.

For statistical assessments in the agricultural sector, the theoretical parameters of the distribution of random variables (processes, fields) are typically replaced by empirical estimates calculated from finite samples, i.e., determined on the basis of limited experimental material. In geostatistics, to obtain empirical estimates of variograms, the second-order stationarity formula is commonly used. This approach assumes that the mean value and covariance structure of the random field are constant throughout the space, which simplifies the analysis and allows the use of specific mathematical methods in precision agriculture systems, taking into account the variability of soil and climatic phenomena.

The empirical variogram is calculated using the following formula:

$$\gamma^*\left(\vec{h}\right) = \frac{1}{2n\left(\vec{h}\right)} \sum_{i=1}^{n} \left[f'(r_i + h) - f'(r_i) \right]^2$$

where: the asterisk (*) distinguishes the empirical estimate from the corresponding theoretical value; $n\left(\vec{h}\right)$ – the number of pairs of points separated by the distance vector $\vec{h}$ over which the averaging is performed

Data were analyzed to calculate percentage increases relative to control and background treatments.

Statistical analysis of treatment effects was performed using one-way and two-way analysis of variance (ANOVA). For each dependent variable (germination rate, NDVI values, grain yield, plant height, stem density, ear mass), data were organized by treatment groups (Control, Background, Background + KLGK, Background + Stimulife). Normality of distribution within each group was checked using the Shapiro-Wilk test ($p > 0.05$), and homogeneity of variances was verified using Levene's test ($p > 0.05$). Model specification: For laboratory germination data and yield components, a one-way ANOVA model was applied with treatment as the fixed factor. For NDVI time-series data, a two-way repeated measures ANOVA was used with treatment as the between-subjects factor and time (acquisition date) as the within-subjects factor. The total variance was partitioned into between-group variance (explained by treatment) and within-group variance (unexplained, residual). The calculated *F*-value was compared to the critical *F*-value from the *F*-distribution table at $\alpha = 0.05$ with appropriate degrees of freedom (dfbetween, dfwithin). A *p*-value < 0.05 was considered statistically significant. When a significant main effect was detected ($p < 0.05$), post-hoc multiple comparisons were performed using Tukey's Honestly Significant Difference (HSD) test (Novikov et al., 2019; Novikova et al., 2023) to identify which specific treatment pairs differed significantly. The Tukey HSD test controls for Type I error across all pairwise comparisons. All statistical analyses were performed using Statsoft Statistica software. Results are presented as means ±standard deviation (SD) unless otherwise specified. Percentage increases were calculated relative to both the absolute control and fertilizer background treatments.

3 Results and Discussion

3.1 Laboratory Biotest

The seed germination test revealed a strong, germination-activating effect of the KLGK preparation, which depends on the concentration. Statistical analysis (one-way ANOVA followed by Tukey's HSD post-hoc test, $p < 0.05$) showed that all KLGK concentrations significantly increased germination rate compared to the control at 24 hours after sowing ($F(4, 25) = 18.7$, $p < 0.001$). The optimal physiological activity was observed in the concentration range of 0.0025% to 0.00025%, which accelerated seed germination by 28.3% and 31.2%, respectively, compared to the control within the first 22–24 hours (Figure 1 and 2). The dose-response relationship was well-described by both linear and polynomial functions with high reliability ($R^2 > 0.95$).

3.2 Remote Sensing Monitoring

Satellite monitoring (NDVI) successfully captured the dynamics of crop growth and the spatial heterogeneity of the experimental field (Figure 3). Descriptive analysis of the temporal NDVI profiles revealed distinct phenological patterns across all treatments, with a clear peak in vegetative activity identified between late June and late July. For quantitative assessment, mean NDVI values were calculated for each treatment plot during the peak vegetation period (July 15–25). The Background + KLGK treatment exhibited the highest mean NDVI value (0.87 ±0.04), compared to Background+Stimulife (0.81 ±0.05), Background only (0.79 ±0.06), and Control (0.74 ±0.07). A two-way repeated measures ANOVA (treatment × time) revealed a significant main effect of treatment on NDVI values during the peak period ($F(3, 36) = 12.4$, $p < 0.001$). Post-hoc comparisons (Tukey's HSD) confirmed that NDVI in the KLGK treatment was significantly higher than in Control ($p < 0.001$), Background ($p < 0.01$), and Stimulife ($p < 0.05$) treatments.

Thus, the quantitative NDVI analysis supports the descriptive observation of enhanced vegetative development in KLGK-treated plots, providing

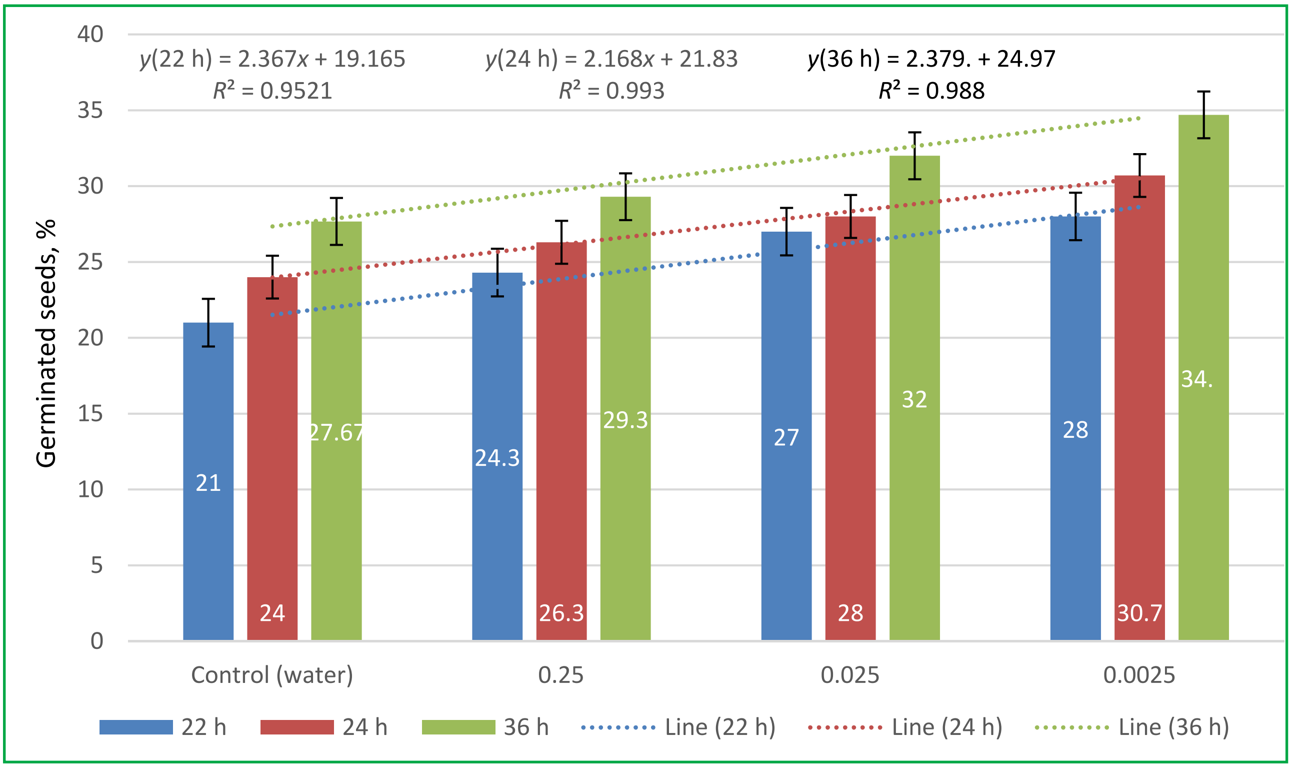

Figure 1 Dynamics of seed germination at different concentrations (*X*-axis) of the preparation, linear function

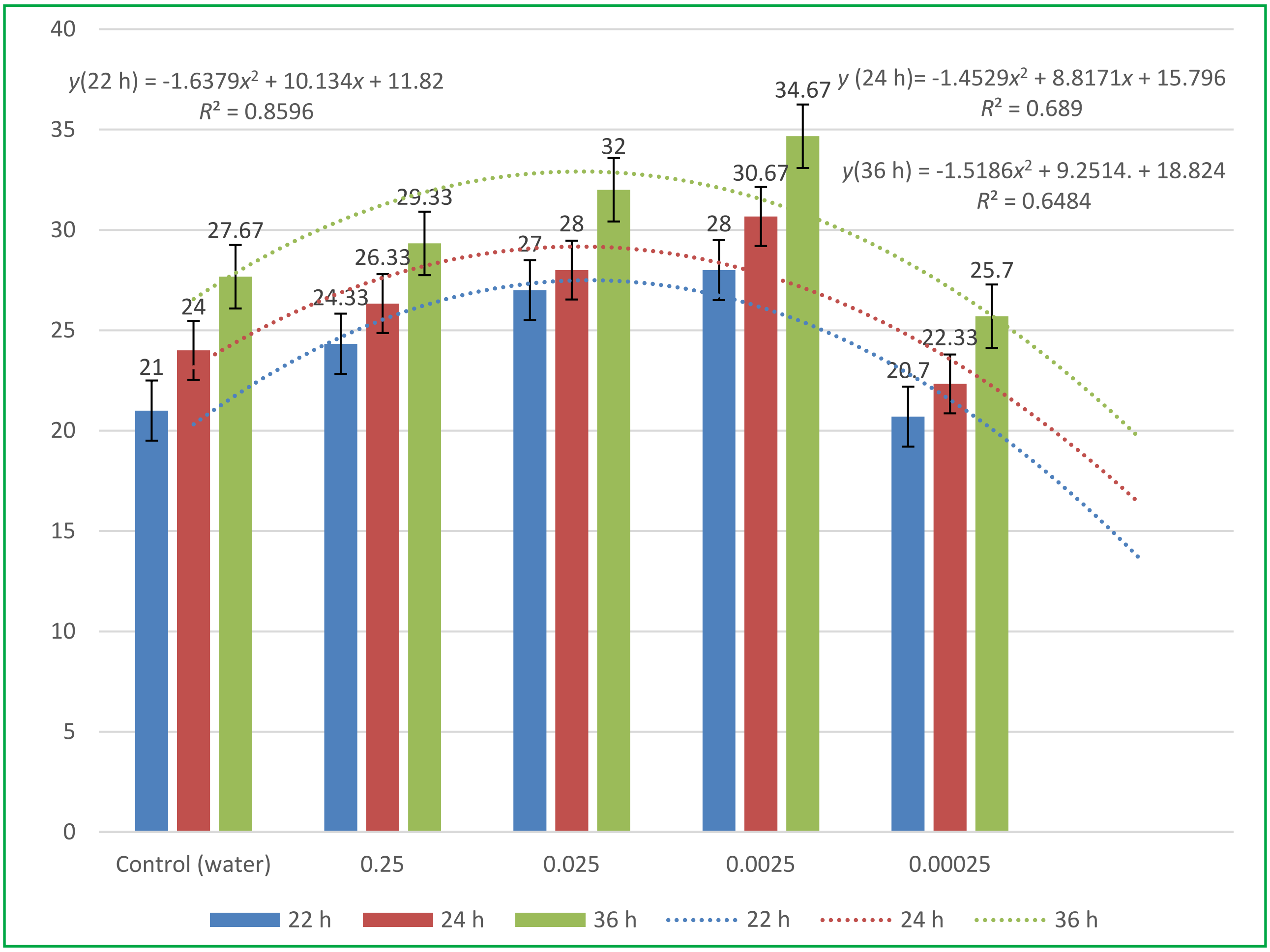

Figure 2 Dynamics of seed germination at maximum dilution (*X*-axis) of the preparation, polynomial function

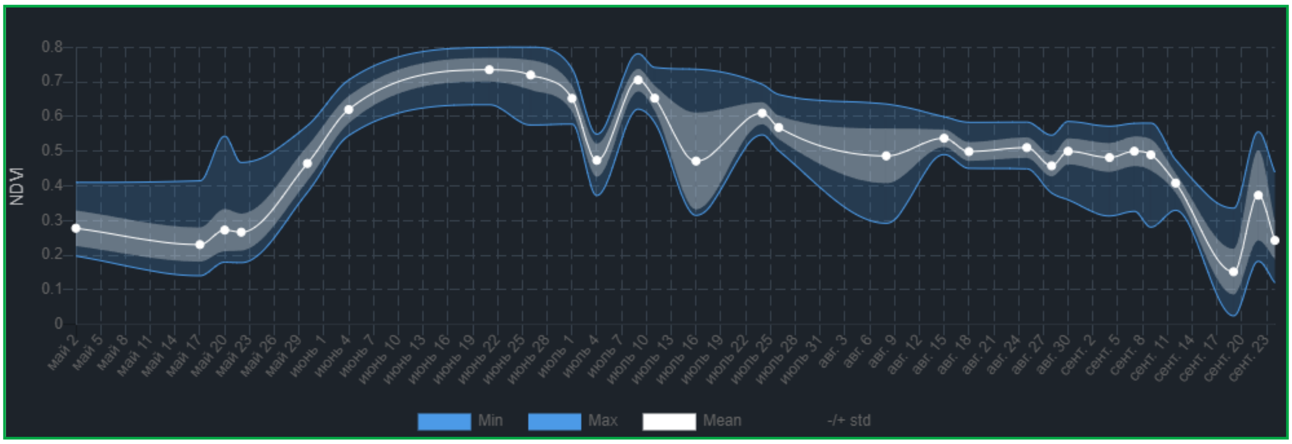

Figure 3 Dynamics of the NDVI vegetation index during bread wheat growth and development (May 1 – September 25, 2024)

statistical evidence for treatment effects on crop canopy development. The observed NDVI dynamics are consistent with typical crop growth patterns captured by high-resolution satellite imagery in precision agriculture studies (Segarra et al., 2020).

By monitoring the growth and development of plants using ground-based and related remote sensing data, the periods of active plant vegetation were identified. Thus, the period from late June to late July was determined as the peak of vegetative activity, which is optimal for assessing the effects of the studied drugs. Analysis of NDVI values during this period showed that the plot treated with KLGK exhibited the highest vegetation index (0.8–0.9), compared to the control (0.7–0.8) and the reference Stimulife plot (0.7–0.8).

3.3 Field Experiment Yield and Structure

The results of the field experiment demonstrated the high efficiency of the tested preparations. The highest grain yield was obtained with the KLGK treatment.

The KLGK treatment provided a substantial yield increase of 108% over the control and 61% over the NPK background. To confirm statistical significance, a one-way ANOVA was performed on grain yield data across all four treatments, revealing a significant treatment effect ($F(3, 28) = 24.6, p < 0.001$). Post-hoc comparisons using Tukey's HSD test ($\alpha = 0.05$) confirmed that the KLGK treatment (3.02 ±0.21 t/ha) produced significantly higher yield than Control (1.46 ±0.18 t/ha, $p < 0.001$), Background (1.88 ±0.23 t/ha, $p < 0.01$), and Stimulife (2.55 ±0.19 t/ha, $p < 0.05$) treatments.

Yield structure components were similarly analyzed (Table 1). KLGK treatment resulted in the highest number of stems per m^2 (441 ±28), significantly greater than Control (312 ±24, $p < 0.001$) and Background (378 ±31, $p < 0.05$). Plant height was also maximized in KLGK-treated plots (110.2 ±4.3 cm), significantly exceeding Control (94.5 ±5.1 cm, $p < 0.001$) and Background (102.8 ±4.7 cm, $p < 0.05$). Ear mass followed the same pattern, with KLGK (108 ±9 g/m^2) significantly outperforming Control (72 ±8 g/m^2, $p < 0.001$) and Background (89 ±10 g/m^2, $p < 0.05$). These quantitative comparisons, supported by appropriate statistical tests, clearly differentiate treatment effects and provide robust evidence for the superior performance of the KLGK preparation.

The results in this study confirm the high potential of using humic-like preparations obtained from lignin-containing waste for precision plant growth management.t

The statistically validated yield increase (3.02 ±0.21 t/ha with KLGK, representing a 61% increase over fertilizer background, $p < 0.01$) aligns with international studies reporting positive effects of humic substances on crop yield. For instance, Rose et al. (2014) reported yield increases in wheat ranging from 15–40% depending on humic substance source and application method, while our results demonstrate that lignin-derived preparations can achieve yield gains at the upper end of this range under appropriate conditions.

The quantitative analysis of yield components provides additional mechanistic insight: the 16.8% increase in stem density (441 vs. 378 stems/m^2 in Background) and 21.4% increase in ear mass (108 vs. 89 g/m^2 in Background) suggest that KLGK treatment enhanced both tillering capacity and grain filling efficiency. These findings are consistent with the physiological effects observed in our laboratory germination tests, where KLGK accelerated early seedling development by 28–31% ($p < 0.01$). For instance, research on humic acids from leonardite has shown yield increases in wheat and maize by improving nutrient uptake and root development (Rose et al., 2014). Furthermore, studies specifically investigating lignin-derived humic-like substances have demonstrated similar positive effects on wheat yield and soil microbial activity, confirming the potential of this approach (Diatta et al., 2020).

The specific mechanism of action for such oxidized lignin products likely involves their role as biostimulants, enhancing metabolic activity and stress resistance, rather than acting as direct nutrients (Yakhin et al., 2017). This is supported by our laboratory data, where extremely low concentrations (0.00025%) were highly effective in stimulating germination.

Table 1 Yield and biomass of bread wheat in the field experiment (2024)

Treatment	Total biomass (g/m^2)	Root mass (g/m^2)	Grain yield (t/ha)	Yield (% of control)	Yield (% of background)
Control (C)	366 ±31c	72 ±8c	1. 46 ±0.18d	100	–
Background (NPK)	448 ±36b	138 ±12a	1.88 ±0.23c	129	100
Background + KLGK	663 ±42a	126 ±11ab	3.02 ±0.21a	207	161
Background + stimulife	405 ±33b	81 ±9bc	2.55 ±0.19b	175	136

Values represent means ±standard deviation (*n* = 4 replicates per treatment). Different lowercase letters (a, b, c, d) within the same column indicate statistically significant differences between treatments according to Tukey's HSD post-hoc test (α = 0.05). Treatments sharing the same letter are not significantly different

The high efficacy of the studied preparations on plants is explained not by their elemental composition, but by their physiological action. This treatment was designed to leverage the physiological effect of the evaluated preparations, providing an attraction effect–the redistribution of accumulated nutrients from biomass to reproductive organs. The mechanism of physiological action of the studied preparations can be explained by the transformation features of the polymeric lignin matrix, which consists of various phenolic fragments closely related to natural phytohormones. Phytohormones are organic regulators that govern all stages of plant life: growth, cell division and differentiation, flowering, fruit ripening, and stress responses. They act in low concentrations, coordinating plant growth and development processes. The mechanism of phytohormone action is as follows: plant cells perceive the hormone through specific receptors, which, after interacting with the hormone, change their spatial conformation and transmit a signal into the cell. The ultimate targets of phytohormones in the cell are genes, upon which the formation or disappearance of corresponding enzymes occurs. Enzymes, in turn, act as biological catalysts, accelerating processes in the soil and the plant itself, repeatedly increasing their productivity.

This proposed mechanism is strongly supported by recent international research on lignin-derived biostimulants. A recent study by Faleiro et al. (2025) demonstrated that lignin nanoparticles encapsulating indole-3-acetic acid (IAA) were rapidly absorbed by seeds (within < 5 hours) and transported via the apoplastic pathway, with the composition of lignin nanoparticles significantly influencing germination rates. Similarly, research on oxygen-alkali-modified bamboo kraft lignin applied to maize seedlings revealed that low-molecular-weight lignin derivatives promoted chlorophyll synthesis and stress resilience, with transcriptomics analysis showing upregulation of 1,333 genes, including key transcription factors (AP2/ERF, WRKY, MYB, and NAC) involved in regulating cell proliferation, tropisms, carbon metabolism, and stress responses (Shi et al., 2026). Gene Ontology analysis further identified plant hormone signal transduction regulated by lignin as a major pathway. A review by Wang et al. (2025) on lignin regulating plant growth and development confirms that the abundant oxygen-containing groups in lignin endow it with natural biological activities, such as promoting plant tissue division, enhancing photosynthesis, and improving stress resistance, with effects on endogenous hormone balance and gene expression. Furthermore, lignin-based phenolic aryl acrylic esters have been shown to exhibit plant growth regulation activity dependent on various structural groups (Chen et al., 2025). These findings align with our observation that KLGK acts through hormonal signaling pathways rather than direct nutritional effects, consistent with the concept of biostimulants as enhancers of metabolic activity and stress resistance rather than direct nutrients (Yakhin et al., 2017).

Our approach to the production of plant growth and development regulators using a controlled oxidation-hydrolytic process in a specially designed reactor is innovative. While international studies have described methods for producing humic-like substances from lignin and lignocellulosic biomass through various chemical modification pathways, such as alkaline aerobic oxidation and oxidative ammonolysis (Sutradhar & Fatehi, 2023; Zhao et al., 2007), the precise technological control and step-wise product isolation described here for creating a precision PGR from a specific pulp and paper waste stream represents a distinct technological advancement.

The successful integration of remote sensing (NDVI) for operational monitoring is consistent with modern P-Ag practices (Zhang et al., 2002). This made it possible to visualize the effectiveness of the physiological action of lignin preparations under heterogeneous field conditions, providing a basis for data-based management decisions. The higher NDVI values in the KLGK plot during peak vegetation correlate well with the final yield data, validating the use of this tool for in-season assessment of treatment success.

It should be noted that different wheat cultivars were used in the laboratory and field experiments (′Zlata′ and ′Darya′, respectively). This choice was dictated not only by scientific but also by practical economic considerations. For laboratory biotesting, seeds with maximum and stable germination capacity (super-super elite) were required, which was provided by the ′Zlata′ cultivar, while the small scale of material consumption (100 g) made the use of elite seeds economically justified. For the field experiment with a seeding rate of 200 kg/ha, the use of elite seeds would have led to a fourfold increase in costs (from 22,400 to 90,000 RUB), which would have made the study economically unfeasible. Therefore, the regionally adapted cultivar ′Darya′ with good agronomic characteristics and affordable price was selected. Although cultivar-specific responses to biostimulants cannot be completely excluded, the consistency of positive effects of KLGK in both experiments – accelerated germination in the laboratory and increased yield in the field – indicates the robustness of the physiological action of the preparation across different genetic backgrounds. Nevertheless, future studies should investigate the response of multiple wheat cultivars to KLGK, including both elite and commercial varieties.

4 Conclusions

This study successfully demonstrates a methodology for precision crop management that integrates a novel humic-like biostimulant KLGK, derived from lignin-containing pulp and paper waste through controlled oxidative-hydrolytic transformation, with operational remote sensing monitoring. The foliar application of KLGK on a background of mineral fertilizers significantly increased spring bread wheat yield by 61% compared to the fertilizer-only background, achieving 3.02 t/ha and outperforming both the untreated control and the reference biostimulant «Stimulife». These results confirm the high efficacy of lignin-derived preparations as plant growth regulators. Beyond the agronomic outcomes, the developed technology offers a dual-purpose solution aligned with circular economy principles: it enables the valorization of large-tonnage, hard-to-recycle industrial waste into valuable agro-biostimulants, while simultaneously addressing waste management challenges in the pulp and paper industry. This approach is consistent with global efforts to valorize lignin-based industrial by-products for sustainable agricultural intensification (Fontecha-Cámara et al., 2024). The controlled oxidative-hydrolytic transformation of lignin matrices thus represents a replicable technological pathway for converting underutilized industrial residues into precision plant growth regulators, contributing to both agricultural productivity and environmental sustainability.

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Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Andrey A. Komarov: Conceptualization, Formal analysis, Methodology, Investigation, Project administration, Writing – original draft, Writing – review & editing. Pavel A. Sukhanov: Formal analysis, Investigation, Validation, Writing – review & editing. Yuri G. Zakharian: Data curation, Formal analysis, Validation, Writing – review & editing. Tatyana P. Novikova: Data curation, Formal analysis, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing. Arthur I. Novikov: Conceptualization, Formal analysis, Validation, Visualization, Writing – original draft, Writing – review & editing.

AI and AI-Assisted Technologies use Declaration

No generative AI tools/AI-assisted technologies were used during the preparation of the manuscript.

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