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Critical examination of wood-based pyrolysis liquids as biostimulants for Nordic agriculture: an experimental study

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This study evaluated whether wood-derived pyrolysis liquids can act as biostimulants for boreal crops. In a laboratory pre-experiment, low concentrations of willow-derived pyrolysis liquid promoted root growth of strawberry runners, whereas higher concentrations caused leaf lesions and inhibited rooting, indicating a hormetic response. In field trials in south-west Finland, birch-derived pyrolysis liquid was applied to spring wheat, field pea and spring oat at three dose levels and compared with an untreated control and two commercial biostimulants. Under the tested conditions, pyrolysis liquid did not significantly affect crop ground cover, plant height, grain yield or grain quality, and the commercial products did not outperform the untreated control. Because the tested liquids were not characterised in full batch-specific compositional detail, the observed responses could not be linked to individual compounds. The agronomic benefits of pyrolysis liquids under northern field conditions therefore remain unproven.

Key words: wood distillate, foliar application, hormesis, boreal crops, field trial, crop response

Introduction

As carbon dioxide removal becomes increasingly important in global climate policies, biochar is gaining recognition as one of the solutions for achieving ambitious emissions reduction targets (Hougaard 2024). Research on side streams emerging during woody biochar production is critical for enhancing the economic viability of biochar production (Salo et al. 2024). During pyrolysis, biomass is converted into biochar, along with by-products such as gases and pyrolysis liquids (PLs). In this study, the tested materials were refined aqueous fractions of pyrolysis condensates, hereafter referred to as pyrolysis liquids (PLs). These condensable liquid co-products are increasingly being explored for agricultural applications because they contain bioactive compounds such as phenolics, organic acids, furans, ketones, and aldehydes (Mathew and Zakaria 2015, Cândido et al. 2023, Ouattara et al. 2023, Goularte et al. 2025). By investigating the properties and uses of PLs, researchers can develop new strategies to improve soil health, enhance plant growth and promote environmental sustainability, ultimately contributing to a circular bioeconomy (Luhas et al. 2022). Understanding the chemical composition, efficacy and agronomic potential of these by-products is crucial for optimising their use and maximising the overall benefits of biochar systems (Kalus et al. 2019, Phadtare and Kalbande 2022, Singh Yadav et al. 2023) and thereby strengthening the role of biochar in carbon sequestration efforts.

PLs have been shown to possess herbicidal and fungicidal activity (Korkalo et al. 2022), as well as snail-repelling properties (Hagner et al. 2015), while also exhibiting promising potential as biostimulants (Cândido et al. 2023) in agriculture. Their complex composition, which includes organic acids, phenols, aldehydes, alcohols and various macro- and micronutrients (Sharma et al. 2016, Grewal et al. 2018), may contribute to biostimulant activity, although their composition differs from that of conventional biostimulants such as products containing humic substances and trace minerals (Sharma et al. 2016). Recent studies have highlighted their ability to enhance plant growth, nutrient uptake and stress resistance (Ofoe et al. 2022, Akley et al. 2023, Bennani et al. 2023). For example, combining PLs with other organic inputs has been shown to significantly improve crop productivity. Morcom et al. (2023) reported that a foliar application of PL and municipal solid waste compost enhanced strawberry plant growth, fruit yield and leaf chlorophyll content. Ouertani et al. (2023) observed that PLs derived from black spruce residues improved the growth and yield of crops such as lettuce, basil and pepper, although species-specific responses were noted. Additional evidence of agricultural biostimulant effects has been reported in cowpea, mushroom cultivation and mango production systems, although the tested formulations and application strategies differed among studies (Akley et al. 2023, Abdel-Sattar et al. 2024, Fedeli et al. 2024).

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Further studies have demonstrated that PLs rich in bioactive compounds, such as acetic acid and phenols, can improve germination rates and exhibit herbicidal properties (Fanfarillo et al. 2022, Bennani et al. 2023, Fedeli et al. 2023a). In a related study on a non-biomass pyrolysis by-product, Messias et al. (2015) found that shale water, a liquid by-product from pyrobituminous shale pyrolysis, enhanced nutrient accumulation in lettuce leaves without causing phytotoxic effects. Similar findings have been reported with unconventional feedstocks, for instance, Fedeli et al. (2023b) demonstrated that foliar application of a chestnut-derived PL increased protein, starch and polyphenol content in chickpea seeds. Likewise, Fedeli et al. (2023c) found improvements in soluble sugar and starch content in potatoes treated with wood-derived PLs, while Jindo et al. (2022) explored the combined use of a PL and biochar, reporting enhanced growth and nutrient uptake in Japanese mustard spinach.

The effectiveness of PLs is influenced by factors such as feedstock type, pyrolysis conditions and subsequent refinement processes, which may make them versatile across a wide range of crop species and agricultural practices (Ofoe et al. 2022, Bennani et al. 2023). From a technological perspective, feedstock selection, pyrolysis conditions and post-pyrolysis fractionation shape the physicochemical profile of PLs, including acidity and the relative abundance of acetic acid, phenolic compounds and other low-molecular-weight constituents, which may influence their biostimulant and inhibitory effects (Ofoe et al. 2022, Bennani et al. 2023, Ouattara et al. 2023, Goularte et al. 2025). This versatility, along with their potential to act as biostimulants, underscores the importance of studying different ways to incorporate woody biochar side streams into sustainable agricultural systems. Despite the growing interest in using PLs as biostimulants, research on their effectiveness across different crop species remains rather limited. There is limited knowledge of their impact on key Nordic crops, especially under real-world farming trials. This study seeks to address this knowledge gap by providing an initial field-based evaluation of the agronomic effects of PLs in northern open-air agricultural field plots. The main research question is whether PLs can enhance growth and productivity in spring wheat (*Triticum aestivum* L.), in field pea (*Pisum sativum* var. *arvense* L.) and in spring oat (*Avena sativa* L.) under field conditions. In addition, laboratory tests on strawberries (*Fragaria × ananassa*) assess the hormetic effects of different PL dosages, focusing on their biostimulant activity and potential herbicidal effects.

Material and methods

Pyrolysis liquids

A pre-experiment with strawberry plants was conducted using a willow-based (*Salix* sp.) pyrolysis liquid (WPL) produced at 450°C with a holding time of 24 h in the batch retort A according to Fagernäs et al. (2012). For the birch-based pyrolysis liquid (BPL) used in field experiments, birch wood (*Betula* sp.) was pyrolyzed at 450 °C with a holding time of 2 h in the continuous retort C as described by Fagernäs et al. (2012). During the pyrolysis, a composite sample of the total distillate was collected and, after settling for two weeks, the aqueous and tar fractions were decanted. The aqueous fraction was then used in the experiments. Total titratable acidity, expressed as acetic acid equivalents (c[CH_3COOH], %[m V^{-1}]), was 11.6% for the WPL and 14.6% for the BPL, while the respective total organic carbon contents were 16.5% and 25.6%, respectively. The titration curves for the PLs were produced by adding 250 µl aliquots of either 1 M sodium hydroxide (NaOH) or 1 M hydrochloric acid (HCl) to 10 ml samples under continuous magnetic stirring. After each acid/base addition, the pH value of the solution was recorded. Total titratable acidity was estimated from the initial pH to the equivalence point of the NaOH titration, which was determined from the inflection point of the titration curve using a second-derivative method. Total C was determined by an elemental analyser (Thermo Scientific, Flash 2000, Organic Elemental Analyzer) using the flash combustion technique according to Campisi et al. (2016). More information on the PLs used is provided by Hagner et al. (2020a). The WPL used in the present study was the same as that used in their study. Although the BPL used in the present study originated from a different production batch, it was produced by the same manufacturer from the same feedstock using the same pyrolysis process as described by Fagernäs et al. (2012). Because a full compositional analysis was not available for the exact BPL batch used in the present study, Table 1 presents previously reported major organic compounds of a birch-derived PL of comparable origin (Hagner et al. 2021). Total carbon content of BPL 22–26 % was previously reported by Hagner et al. (2020b) and Hagner (2020a), producing estimated water content of 60–75 wt%. This information is provided to contextualise the likely composition of the tested BPL, but it does not represent a batch-specific analysis.

Table 1. Previously reported major organic compounds in a birch-derived pyrolysis liquid of comparable origin. Modified from Hagner et al. (2021)

Compound class	Compound	Content in pyrolysis liquid (g l^{-1})
Carboxylic acids	Acetic acid	98.8
	Propionic acid	4.01
	Formic acid	0.16
	Lactic acid	n.d.
Phenolic compounds	Phenol	0.37
	Catechol	2.67
Alcohols	Methanol	3.74
	Ethanol	n.d.
Furans and aldehydes	Furfural	0.85
	Hydroxymethylfurfural	n.d.
	Acetaldehyde	n.d.
Ketones and esters	1Hydroxy2propanone	25.0
	1Hydroxy2butanone	4.25
	Methyl acetate	n.d.

n.d. = not detected

Laboratory experiment with strawberry (*Fragaria* × *ananassa*)

Rootless strawberry runners with four leaves, each consisting of three leaflets, were separated from the parent plant and placed immediately in tap water. The next day, a dilution series was prepared by diluting WPL with tap water to final concentrations of 10 ml l^{-1}, 5 ml l^{-1}, 1 ml l^{-1}, 0.5 ml l^{-1}, and 0.25 ml l^{-1}. The experiment was conducted in 0.6 l plastic pots (ø 15.5 cm), each filled with 500 ml of the respective WPL dilution. No other growth substrate was used, and the runners were cultivated directly in the solution. Four runners were placed in each pot, with four replicate pots per treatment. The percentage of leaves with lesions and root length were measured on days 5 and 14. If an individual plant had multiple roots, their lengths were summed to obtain one estimate per plant. The average percentage of leaves with lesions and root length (mm) per pot were used in the statistical analyses.

Field experiments with wheat (*Triticum aestivum* L.), pea (*Pisum sativum* var. *arvense* L.), and oat (*Avena sativa* L.)

Overview of the trials and locations

The biostimulant effects of the BPL were studied in 2024 in three field trials: in spring wheat (*Triticum aestivum* L.), in field pea (*Pisum sativum* var. *arvense* L.) and in spring oat (*Avena sativa* L.) on the Finnish fields of the Natural Resources Institute Finland (LUKE) in Jokioinen (oat and pea) and Ypäjä (wheat). The oat (Fig. 1) and pea trials in Jokioinen were on the same field, about 100 m from each other. The wheat trial in Ypäjä, Finland was 6.7 km from the oat and pea trials. The crop varieties, trial locations, soil types and previous crops in two previous years are presented in Table 2.

Fig. 1. Oat trial on 27 June 2024, 7 days after the second biostimulant application (B)

Table 2. Crop varieties, trial locations, soil types, and previous crops for the previous two years

Crop, variety	Trial location	Soil type, OM[1] content	Previous crops
Spring wheat, Hilkka	60.80149 °N, 23.32637 °E	Sandy loam, OM 14 %	Spring wheat (2022), Spring oat (2023)
Field pea, Matilda	60.79887 °N, 23.44993 °E	Clay loam, OM 4 %	Grassland for silage (2022), Winter wheat (2023)
Spring oat, Inka	60.79832 °N, 23.44980 °E	Clay loam, OM 4 %	Grassland for silage (2022), Winter wheat (2023)

[1]Organic Matter

Local weather conditions

The weather conditions were recorded at the Jokioinen observatory, an official weather station of the Finnish Meteorological Institute. The location of the weather station is 60.8142091 °N, 23.49916 °E. The distance to the pea trial was 3.1 km, to the oat trial 3.2 km, and to the wheat trial 9.5 km. The growing season of 2024 started (daily mean temperatures exceeded 5 °C) rather late, on 27 April, and the weather remained rather cool until mid-May, when the weather suddenly turned very warm (Fig. 2 and Fig. 3). In May, there were exceptionally eight days with maximum temperatures above 25 °C, and the mean temperature of May was 4 K higher than the long-term average from 1991 to 2020. The first and the last week of June were exceptionally warm, too. July and August were slightly warmer than the long-term average, and September was exceptionally warm, even with two days exceeding 25 °C. The effective temperature sum of the growing season until the end of September was 1625 °C, and there were 22 days with maximum temperatures above 25 °C. These numbers are among the highest ever measured in Jokioinen. Between 23 May and 15 September, there were no frosty nights, which is very rare. May and the beginning of June were very dry, which in combination with the high temperatures disturbed the emergence of the crops. Especially pea emerged unevenly, but most seeds finally germinated after two rainy days on 26–27 May 2024. In June, July, and August, the precipitation sums were close to the long-term averages.

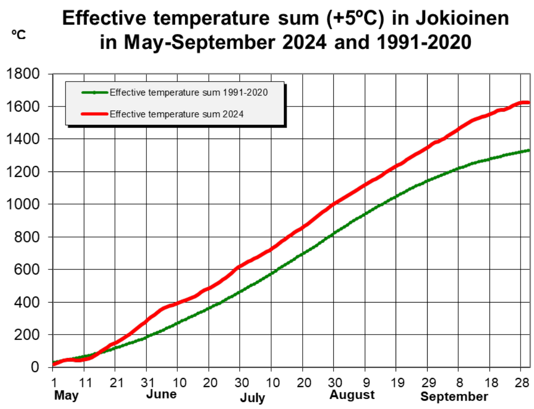


Fig. 2. Effective temperature sum at Jokioinen observatory in May–September 2024 and the 1991–2020 average

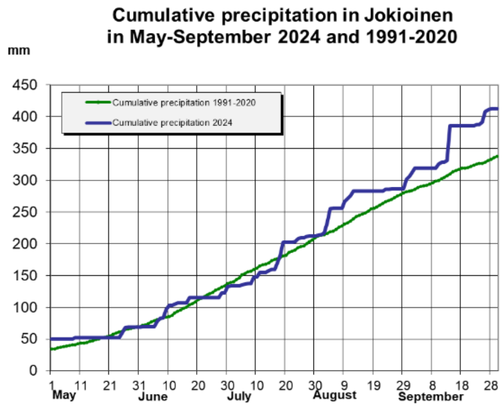


Fig. 3. Cumulative precipitation at Jokioinen observatory in May–September 2024 and the 1991–2020 average

Field preparations and sowing

Basic tillage in all trials was carried out using a disc cultivator, in the oat and pea field in autumn 2023 and in the wheat field in spring 2024. Seedbed preparation was carried out using an S-tine harrow in all trials, in the oat and wheat trials one day before drilling and in the pea trial on the day of drilling. All crops were drilled using seed drills with a 12.5 cm row spacing, equipped with fertiliser units that placed the fertiliser in the soil between the crop rows. Spring wheat, variety Hilkka, was drilled at a seed rate of 240 kg ha^{-1} to a depth of 3 cm on 14 May 2024. Field pea, variety Matilda, was drilled at a seed rate of 312 kg ha^{-1} to a depth of 5 cm on 15 May 2024, and spring oat, variety Inka, was drilled at a seed rate of 192 kg ha^{-1} to a depth of 3 cm on 16 May 2024. All trials were fertilised with N-P-K fertilisers at drilling. Spring wheat was fertilised with 400 kg ha^{-1} of YaraMila Y2 fertiliser, containing 27% N, 2.6% P and 3% K. Oat was fertilised with 280 kg ha^{-1} of the same fertiliser, and pea was fertilised with 111 kg ha^{-1} of Befert 27-3-5 fertiliser, containing 27% N, 3% P and 5% K. Weeds were controlled with herbicides. In wheat and oat, Ariane S (MCPA 200 g l^{-1} + fluroxypyr 40 g l^{-1} + clopyralid 20 g l^{-1}, Corteva Agriscience) was used, in wheat on 14 June 2024 at 2.0 l ha^{-1} and in oat on 12 June 2024 at 2.5 l ha^{-1}. Weeds in pea were controlled with Fenix (aclonifen 600 g l^{-1}, Bayer CropScience) on 29 May 2024 at 1.0 l ha^{-1}.

Trial design and treatments

In all three trials (see Table 3), a similar trial protocol based on a randomised complete block design, with six treatments and four replicates (plot size 3 m × 8 m), was used. The treatments included an untreated control and two reference spray treatments with commercial biostimulant products applied at their recommended doses and application timings. Three BPL treatments were included at different doses. The biostimulant products and the BPL were sprayed at two application timings (A and B), with all treatments applied at the same timings. The spray volume was 200 l ha^{-1} and the spray pressure was 2.0 bar in all applications. The tested doses of the BPL were based on the laboratory experiment with strawberry and recent publications (e.g. Fedeli et al. (2022), with a “typical dose” of 1.0 l ha^{-1} per application (corresponding to a 1:200 PL:tap water dilution), and a half dose (0.5 l ha^{-1}, 1:400) and a double dose (2.0 l ha^{-1}, 1:100) of the normal dose. Because full batch-specific compositional data were not available, dose selection was based on volumetric dilution ranges reported in the literature and on the strawberry pre-experiment rather than on quantified concentrations of individual compounds. The spray applications were made with a portable plot sprayer powered with pressurised air and equipped with flat-fan spray nozzles (Hardi 4110-12).

Table 3. Biostimulant treatments applied in the three field trials (spring wheat, spring oat and field pea; n = 4). Application codes A and B are described in Table 4.

Treatment name	Treatment description	Application code	Rate	Rate unit
Untreated	Untreated reference	–	–	–
PPS Biostimulant	Commercial reference product 1	A	80	ml ha^{-1}
		B	80	ml ha^{-1}
YaraVita BioNUE	Commercial reference product 2	A	1	l ha^{-1}
		B	1	l ha^{-1}
BPL 0.5	Half dose	A	0.5	l ha^{-1}
		B	0.5	l ha^{-1}
BPL 1.0	Normal dose	A	1	l ha^{-1}
		B	1	l ha^{-1}
BPL 2.0	Double dose	A	2	l ha^{-1}
		B	2	l ha^{-1}

Reference biostimulants and application timings

The first commercial reference product is PPS Biostimulant (PPS), manufactured by BASF and made from oilseed rape pollen, containing a mixture of amino acids. The second commercial reference product is YaraVita BioNUE (BioNUE), manufactured by Yara and made from leonardite, containing humic and fulvic acids and small amounts of Mg (10 g l^{-1}) and Zn (10 g l^{-1}). Both products claim to improve stress tolerance (e.g. to water or nutrient deficiency) and thus the growth of crops.

The spray application timings were determined according to the label recommendations of the reference commercial biostimulant products for cereal crops. The recommendations for cereals were to spray at the BBCH stages (Meier 2001) from 21 to 29 (tillering stage) and from 30 to 33 (stem elongation stage). For pea there were no recommendations; therefore, the pea trial was sprayed on the same dates as the oat trial on the same field. The first spray applications (application code A) in June were made in slightly unstable weather conditions. In spring wheat on 7 June, the first rain occurred about four hours after spraying (Table 4). In oat and pea on 11 June, there was light drizzle of 0.5 mm shortly after the applications, starting 35 minutes after the spraying of pea and only 15 minutes after the spraying of oat. During and after the second spray applications (application code B) on 19 and 20 June, the weather conditions were dry. The actual growth stages, heights, and ground cover of the crops and the weather conditions at the application times in each crop are presented in Table 4.

Table 4. Spray application dates, weather conditions, and crop stages at the time of application

Crop	Spring oat		Field pea		Spring wheat	
Application code	A	B	A	B	A	B
Application date	11 June 2024	20 June 2024	11 June 2024	20 June 2024	7 June 2024	19 June 2024
Application time	13:35–13:50	8:35–8:50	13:15–13:30	8:10–8:25	8:30–8:50	8:15–8:35
Air temperature	14.6 °C	12.2 °C	16.4 °C	13.3 °C	15.8 °C	16.3 °C
Relative humidity of air	64.7 %	65.2 %	56.2 %	67.8 %	64.9 %	75 %
Wind velocity	2 m s^{-1}	3 m s^{-1}	1 m s^{-1}	4 m s^{-1}	1 m s^{-1}	2 m s^{-1}
Soil temperature	15.8 °C	16.5 °C	15.8 °C	16 °C	15.4 °C	16.3 °C
BBCH[1] growth stage of the crop	13–22	31–32	32–35	35–39	14–22	30–32
Average height of the crop	20 cm	30 cm	14 cm	25 cm	15 cm	25 cm
Ground cover of the crop	50 %	70 %	23 %	50 %	35 %	75 %
Time to first rain	15 min	8 days	35 min	8 days	4 hours	9 days
Amount of first rain	0.5 mm	6.7 mm	0.5 mm	6.7 mm	10 mm	6.7 mm

[1]Biologische Bundesanstalt, Bundessortenamt and CHemical industry

Crop assessments and harvest

During the growing season, the effects of the treatments on the crops were assessed with visual assessments and measurements of the crop stand. These included assessments of treatment phytotoxicity and crop cover and measurements of crop height. The phytotoxicity and crop cover assessments were made visually from the whole plot by a person with long experience of such visual assessments. At the end of the experiments, the seed yields were harvested with a plot combine (Sampo Rosenlew 2010). Pea was harvested on 26 August, oat on 27 August, and spring wheat on 9 September 2024. The harvested plot size in each trial was 13.6 m² (2.0 m × 6.8 m). The grain yield and the harvest moisture of spring wheat and oat were recorded with the built-in weight and moisture sensors of the plot combine. At harvest, the plot combine took representative yield samples (approximately 1 kg per plot) of spring wheat and oat for grain quality analyses. The plot yields of pea were, however, harvested in full, and the pea grain yield was weighed after drying and cleaning.

Quality analysis of harvested grains

For each crop, grain yield per hectare, hectolitre weight, 1000-seed weight, and grain protein content were recorded. Before quality analyses, the grain samples of approximately 1 kg per plot were cleaned of weed seeds and other impurities using a flat-sieve-type seed cleaner, Jaakko. For pea, the whole-plot yields were cleaned using the same seed cleaner, and representative samples of approximately 1 kg per plot were taken with a sample divider for quality analyses. The 1000-seed weight of all crops was determined by counting four 100-grain subsamples per plot with a Durant Nurmgal seed counter, weighing them, and using the two middle subsamples to calculate the 1000-seed weight. The hectolitre weight and the protein content of spring wheat and oat were analysed using a NIT (Near Infrared Transmission) analyser, Infratec 1241. The hectolitre weight of pea was analysed using a Granomat 2.0 grain analyser, and the protein content of pea was analysed from ground pea samples by analysing the nitrogen content with the Kjeldahl method and multiplying it by 6.25 to obtain the protein content (ISO 20483:2013). The NIT analyser and the Granomat analyser also provided the grain moisture contents, which were needed to adjust the results to the standard moisture content. The results from the NIT analyser and the Granomat analyser were based on two grain subsamples per plot. The protein content of each crop is presented as a percentage of grain dry matter. Grain yield, the hectolitre weight and the 1000-seed weight results were adjusted to the standard moisture content of 14% before statistical analyses.

Statistical and data analyses

For statistical analyses of the pre-experiment, mean values of leaf lesion (%) and root length (mm) per pot were used. For each response variable, the homogeneity of variances and normality of model residuals were tested using Levene's test and the Shapiro-Wilk test, respectively. The effects of the WPL concentration on leaf lesion and root length were first tested using repeated-measures ANOVA. As a significant interaction occurred between time and treatment, the treatment effects were analysed separately for each time point. These statistical analyses were carried out using the SPSS statistical package (IBM Corp. 2016).

All assessment data from the field trials were analysed with ARM software, Rev. 2024.0 (GDM Solutions, Inc.). The data of each field trial were analysed separately. For each response variable on each assessment date, the homogeneity of variances and normality of model residuals were tested using Levene's test and the Shapiro-Wilk test, respectively. ANOVA and the Student-Newman-Keuls test were used for multiple comparisons of treatment means.

An AI-based language assistance tool was used only for proofreading and language polishing. No AI tool was used to generate, analyse or interpret research data. All outputs were reviewed and approved by the authors.

Results

Biostimulant and phytotoxic activity of the pyrolysis liquid on strawberry

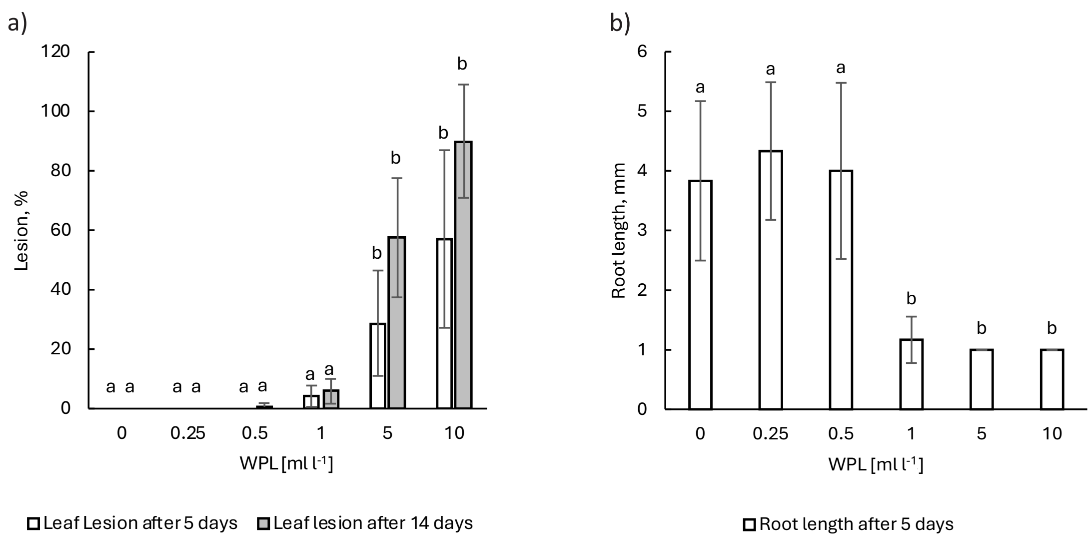
Leaf lesion

On day five (Fig. 4a), leaf lesions were observed in strawberry plants treated with higher concentrations of the WPL (≥1 ml l^{-1}). At lower concentrations (0.25 and 0.5 ml l^{-1}), no lesions occurred, as in the control (0 ml l^{-1}). Notably, a significant increase in leaf lesions occurred at 5 ml l^{-1} and 10 ml l^{-1}, with lesion percentages reaching 28.8% (±17.7) and 57.1% (±29.9), respectively compared with the control ($p < 0.05$). There were no statistically significant differences between the treatments of 0, 0.25, 0.5, and 1 ml l^{-1} ($p > 0.05$). However, lesion formation at 5 and 10 ml l^{-1} was significantly higher compared with the control and lower concentrations.

A similar trend persisted after 14 days (Fig. 4a). Leaf lesions remained absent or minimal at lower concentrations (0–0.5 ml l^{-1}), while lesions escalated drastically at higher concentrations, being 57.5% (±20.1) at 5 ml l^{-1} and 90.0% (±19.1) at 10 ml l^{-1}. The control, 0.25 ml l^{-1}, 0.5 ml l^{-1}, and 1 ml l^{-1} treatments remained statistically similar, whereas 5 ml l^{-1} and 10 ml l^{-1} were significantly different, indicating phytotoxicity ($p < 0.05$).

Root growth

On day five (Fig. 4b), the control group exhibited an average root length of 3.8 mm (±1.3), while the 0.25 and 0.5 ml l^{-1} treatments reached averages of 4.3 mm (±1.2) and 4.0 mm (±1.5), respectively. These differences were not statistically significant ($p > 0.05$). In contrast, at concentrations of 1 ml l^{-1} and above, root growth was significantly inhibited. Root lengths were reduced to 1.2 mm (±0.4) at 1 ml l^{-1}, and completely inhibited at 5 and 10 ml l^{-1}.



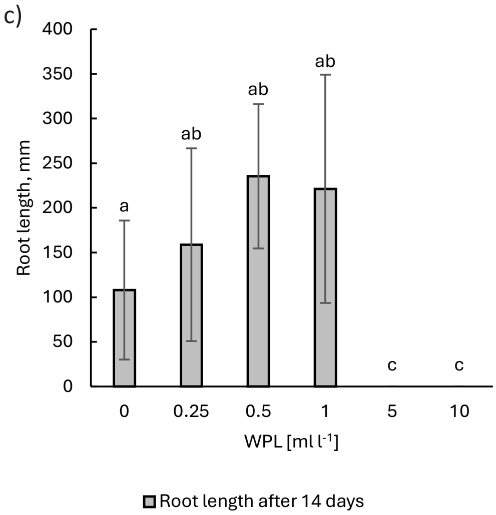


Fig. 4. Effects of WPL concentration on leaf lesions and root length in strawberry over time. Lesion development on strawberry leaves is presented at 5 and 14 days post-treatment (a), while root length is measured at 5 days (b) and 14 days post-treatment (c). Bars represent means ± SD (n = 4). Bars sharing the same letter do not differ significantly among treatments within each time point (Bonferroni test, $p > 0.05$).

The biostimulant effect of lower concentrations became evident on day 14 (Fig. 4c). Strawberry roots growing in WPL concentrations of 0.25 ml l^{-1} and 0.5 ml l^{-1} grew to 158.8 mm (±108.0) and 235.4 mm (±80.8), respectively, both outperforming the control (108.0 mm ±77.8). Statistical significance was not consistent across these groups, as treatments at 0.25, 0.5, and 1 ml l^{-1} were statistically similar. Phytotoxicity was clearly apparent at 5 and 10 ml l-1, where no root growth occurred. Comparison of the effects of birch-based pyrolysis liquid and commercial biostimulants on wheat, oat, and pea.

Effects on crop growth parameters

Effects on ground cover

The effects of birch-based pyrolysis liquid (BPL) and commercial biostimulants on the ground cover (%) of spring wheat, spring oat, and pea crops, compared to the untreated control, were evaluated. Coverage of the crop refers to the proportion of the soil surface occupied by cultivated plants. It is expressed as a percentage, with higher values indicating more extensive plant coverage. Coverage was visually assessed 6–7 days after the second spray application (B) (on 26 June 2024), with the results presented in Figure 5. Across all treatments, there were no statistically significant differences ($p > 0.05$) in ground cover percentage for any of the crops analysed (spring wheat, oat, or pea).

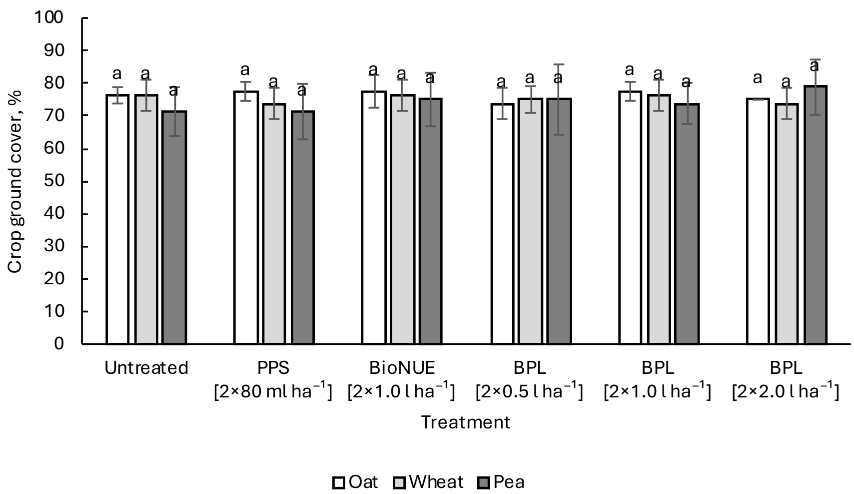


Fig. 5. Ground cover (%) of spring wheat, spring oat, and field pea on 26 June 2024 (6–7 days after the second biostimulant application, B). Bars represent means ± SD (n = 4). Bars sharing the same letter do not differ significantly among treatments within each crop ($p > 0.05$).

For spring wheat, the ground cover ranged from 73.8% to 76.3% across all treatments, with the untreated control, BioNUE (2×1.0 l ha^{-1}), and BPL (2×1.0 l ha^{-1}) yielding the highest average percentages. The spring oat ground cover ranged between 73.8% and 77.5%, with the untreated control and BPL (2×1.0 l ha^{-1}) having the highest averages. For pea, the ground cover ranged from 71.3% to 78.8%, with the highest values recorded for BPL (2×2.0 l ha^{-1}), although, like the other treatments, the differences were not statistically significant ($p > 0.05$). The lack of significant differences between treatments across all crops suggests that neither BPL nor the commercial biostimulants had a substantial effect on ground cover compared to the untreated control.

Effects on crop height

The application of BPL, along with the commercial biostimulant products PPS and BioNUE, did not result in statistically significant differences in the height of oat, wheat, or pea plants compared to the untreated control. For oat, the control exhibited an average height of 93.2 cm, while the BPL 2×0.5 l ha^{-1} treatment resulted in a slightly higher height of 96.3 cm. Other treatments, such as PPS 2×80 ml ha^{-1} (95.6 cm) and BioNUE 2×1.0 l ha^{-1} (94.9 cm), also showed marginal increases, but none were statistically significant ($p > 0.05$).

Wheat heights showed similar results, with the untreated control reaching 65.7 cm. The BioNUE 2×1.0 l ha^{-1} treatment achieved the highest average wheat height at 67.6 cm, while the BPL 2×0.5 l ha^{-1} treatment recorded the lowest height (63.8 cm). Yet again, no significant differences were observed among treatments.

In pea, the untreated control had an average height of 91.7 cm. The BPL 2×1.0 l ha^{-1} treatment produced the tallest plants, averaging 93.6 cm, whereas BioNUE 2×1.0 l ha^{-1} had a slightly lower height of 89.7 cm. All variations in plant height were non-significant across treatments (Fig. 6).

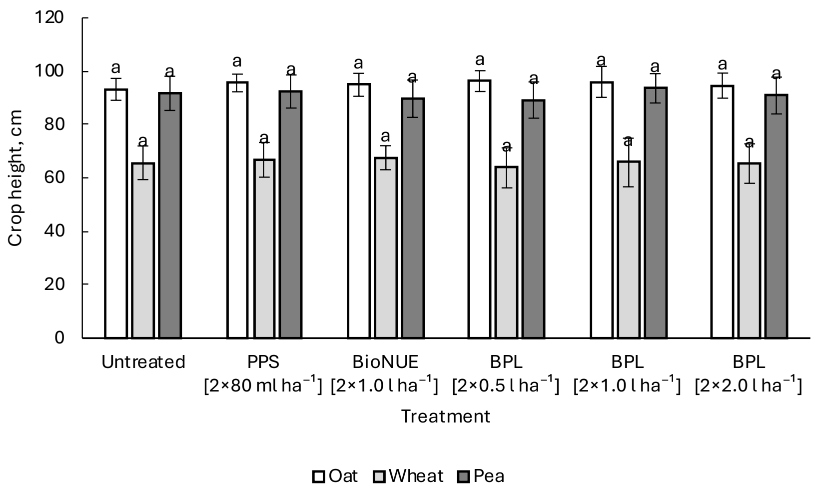


Fig. 6. Crop height (cm) of oat, wheat, and pea on 8 August 2024, 49–50 days after spray application B. Bars represent means ± SD (n = 4). Bars sharing the same letter do not differ significantly among treatments within each crop ($p > 0.05$).

Effects on grain yield

The yield of oat, wheat and pea (kg ha^{-1}) after different treatments is shown in Figure 7. Oat yields ranged from 6327 kg ha^{-1} (BPL 2×0.5 l ha^{-1}) to 6760 kg ha^{-1} (BPL 2×1.0 l ha^{-1}), with the untreated control yielding 6358 kg ha^{-1}. Although there was a slight increase (6.3 %) with the BPL 2×1.0 l ha^{-1} treatment, no significant differences were detected among the treatments. Similarly, wheat yields varied between 3200 kg ha^{-1} (BPL 2×2.0 l ha^{-1}) and 3502 kg ha^{-1} (BioNUE), with the untreated control yielding 3237 kg ha^{-1}, however, neither of these differences were statistically significant. Pea yields followed the same trend, with the untreated control yielding 3259 kg ha^{-1} and the highest yield recorded with the BPL 2×2.0 l ha^{-1} (3333 kg ha^{-1}), but neither increase was statistically significant ($p > 0.05$).

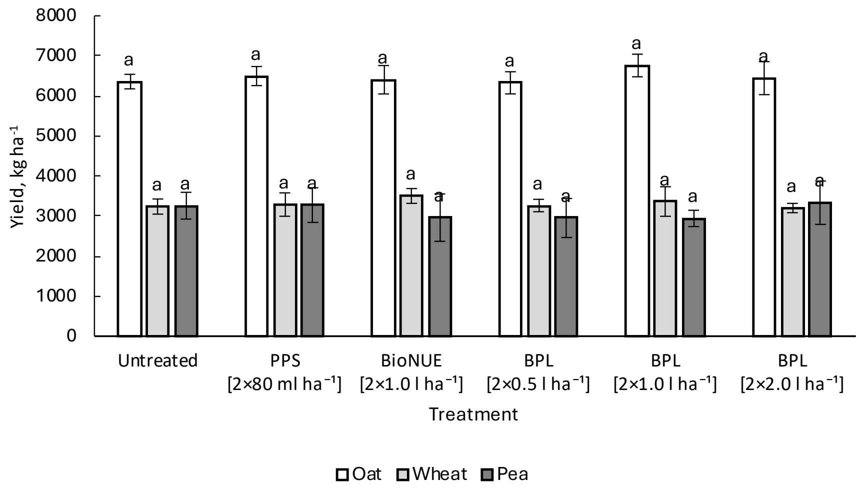


Fig. 7. Grain yield (kg ha^{-1}) of spring wheat, spring oat, and field pea in response to BPL and commercial biostimulant treatments. Bars represent means ± SD (n = 4). Bars sharing the same letter do not differ significantly among treatments within each crop (p > 0.05).

Effects on grain quality parameters

1000-seed weight

1000-seed weight showed no statistically significant differences among treatments in any of the three crops (p > 0.05; Fig. 8). This indicates that none of the biostimulants, including BPL at various concentrations and the commercial products PPS and BioNUE, significantly influenced 1000-seed weight compared to the untreated control. In oat, the 1000-seed weight ranged from 35.74 g (BPL 2×0.5 l ha^{-1}) to 37.14 g in the untreated control. Standard deviations ranged from 1.05 to 2.15 g, suggesting consistent measurements across replicates. In wheat, the untreated control also exhibited one of the highest values (34.52 g), while other treatments produced weights ranging from 33.89 g (BioNUE 2×1.0 l ha^{-1}) to 35.1 g (BPL 2×2.0 l ha^{-1}). All treatments were statistically similar (p > 0.05), with low variability (standard deviations from 1.43 to 2.5 g). For pea, the untreated control yielded a 1000-seed weight of 197.96 g, which was lower than that of the BPL 2×0.5 l ha^{-1} treatment (210.68 g). However, no significant differences occurred among treatments. Standard deviations were higher in pea (4.75–11.73 g) compared to cereals, reflecting greater variability.

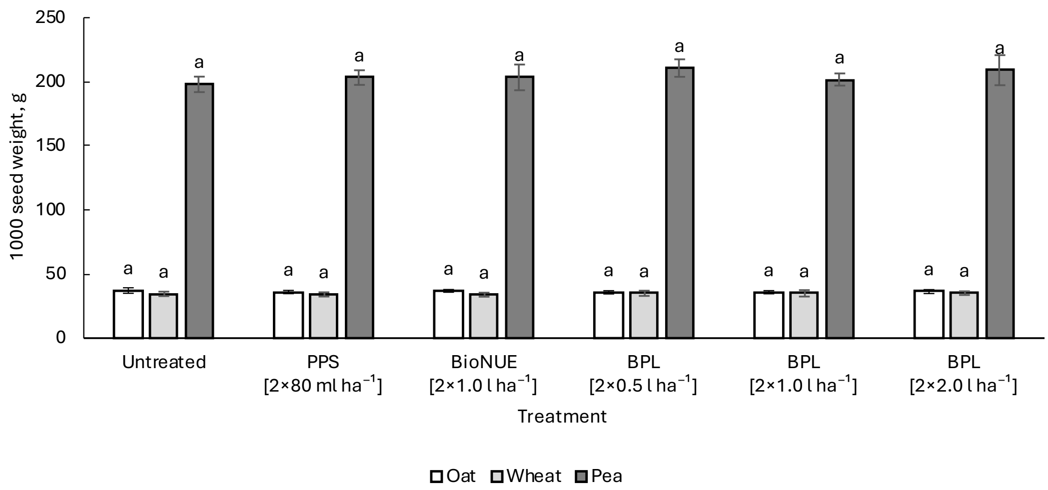


Fig. 8. 1000-seed weight (g) of spring wheat, spring oat, and field pea in response to BPL and commercial biostimulant treatments. Bars represent means ± SD (n = 4). Bars sharing the same letter do not differ significantly among treatments within each crop (p > 0.05).

Hectolitre weight

Hectolitre weight values showed no significant differences ($p > 0.05$) among treatments for any of the crops (Fig. 9). For oat, the hectolitre weight ranged from 57.5 kg (BPL 2×0.5 l ha^{-1}) to 57.9 kg (PPS 2×80 ml ha^{-1} and BPL 2×1.0 l ha^{-1}). The untreated control had a value of 57.7 kg, comparable to all treatments. Standard deviations were minimal (0.3–1.1 kg), indicating consistent results. In wheat, hectolitre weights ranged from 75.5 kg (BPL 2×0.5 l ha^{-1}) to 75.9 kg (untreated control, PPS 2×80 ml ha^{-1}, and BPL 2×2.0 l ha^{-1}). For pea, hectolitre weights were higher than those of oat and wheat, ranging from 81.1 kg (BioNUE 2×1.0 l ha^{-1}) to 82.4 kg (untreated control and PPS 2×80 ml ha^{-1}). Standard deviations were low (0.5–1.2 kg), reflecting a narrow range of variation across treatments.

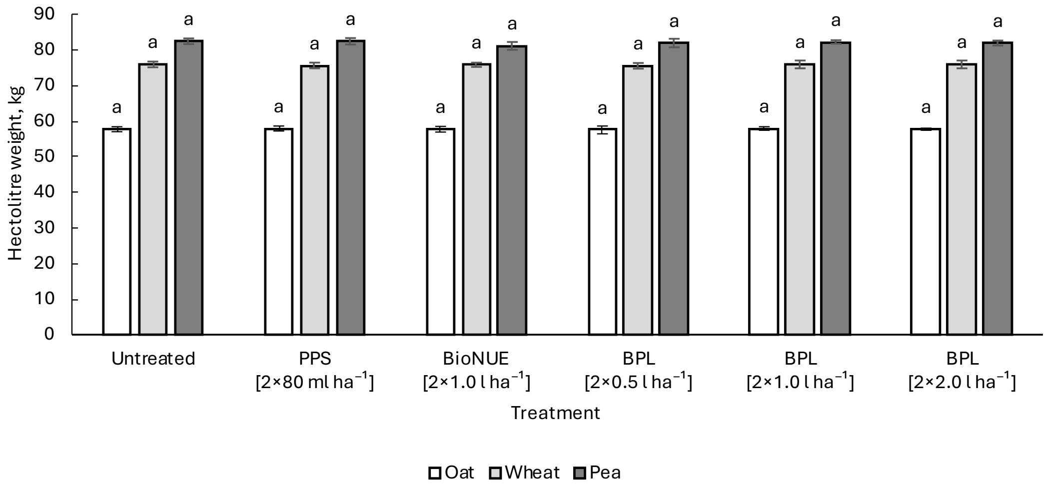


Fig. 9. Hectolitre weight (kg) of spring wheat, spring oat, and field pea in response to BPL and commercial biostimulant treatments. Bars represent means ± SD (n = 4). Bars sharing the same letter do not differ significantly among treatments within each crop ($p > 0.05$).

Protein content

The grain protein content (%, dry matter basis) (NIT analysis for oat and wheat, applied the Kjeldahl method for pea) did not show statistically significant differences for any of the treatments (Fig. 10). For oats, the protein content ranged from 10.59% (BioNUE 2×1.0 l ha^{-1}) to 10.89% (PPS 2×80 ml ha^{-1} and BPL 2×1.0 l ha^{-1}), with the untreated control yielding 10.8%. Standard deviations were consistently low (0.18–0.38%), demonstrating reliable measurements. In wheat, the protein content values ranged from 12.1% (BioNUE 2×1.0 l ha^{-1}) to 12.8% (BPL 2×2.0 l ha^{-1}). The untreated control had a protein content of 12.5%, being comparable to all other treatments. Variability was slightly higher in wheat than in oats (standard deviations of 0.5–1.1%). For peas, the protein content was substantially higher, ranging from 23.27% (BPL 2×0.5 l ha^{-1}) to 23.8% (untreated). The untreated control had the highest protein content, though differences between treatments were not statistically significant.

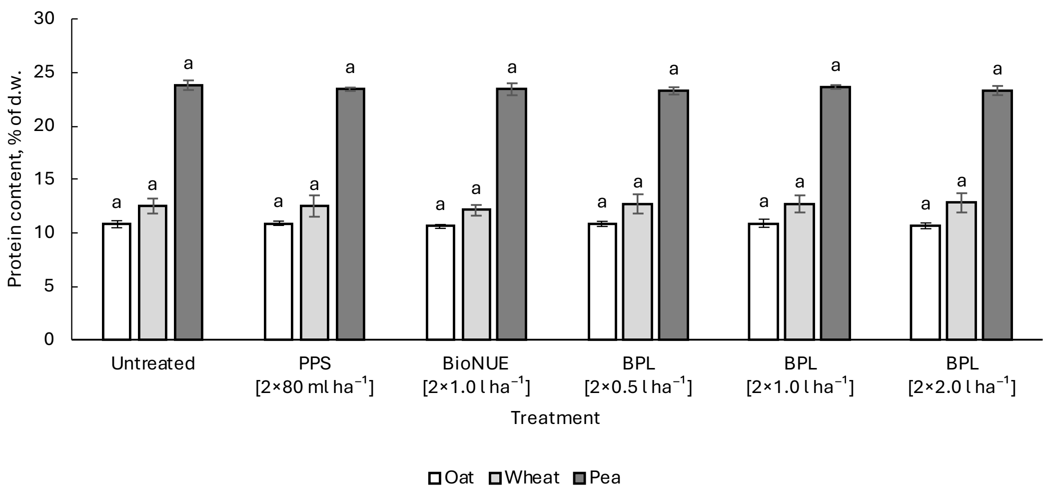


Fig. 10. Protein content (%, dry matter basis) of spring wheat, spring oat, and field pea in response to BPL and commercial biostimulant treatments. Bars represent means ± SD (n = 4). Bars sharing the same letter do not differ significantly among treatments within each crop ($p > 0.05$).

Discussion

Dose-response of strawberry to pyrolysis liquid treatment

The laboratory-scale study demonstrated that the effects of WPL on strawberry growth and health were highly dependent on its concentration. At lower concentrations (0.25 and 0.5 ml l^{-1}), WPL exhibited biostimulant activity, promoting root growth with minimal to no leaf lesions. This effect aligns with studies that have identified low concentrations of organic biostimulants as enhancing root development, likely due to the presence of bioactive compounds commonly reported in PLs that promote plant growth (Uddin et al. 1995, Mungkunkamchao et al. 2013, Malik et al. 2021, Mógor et al. 2021, Yousfi et al. 2021, Morcom et al. 2023).

Conversely, at higher concentrations (≥1 ml l^{-1}), the WPL displayed clear phytotoxic effects. Root growth was significantly inhibited, and leaf lesion formation increased significantly, indicating growth-inhibitory activity, as has been observed in other studies assessing the phytotoxicity of various PLs (Hagner et al. 2010, Hagner et al. 2020a, Hagner et al. 2020b, Korkalo et al. 2022). Particularly at high concentrations, the absence of root growth and the near-total leaf lesion percentage suggest that a toxic threshold had been reached. This may be, for example, due to its low pH destroying cell membranes, which can result in plant tissue desiccation, or to phenolic compounds inhibiting enzymatic activities essential for root elongation (Webber et al. 2018, Morales et al. 2022).

The biphasic response observed in this small-scale study, where low concentrations stimulate growth while higher concentrations cause damage, is consistent with findings on various biostimulants and organic compounds. These substances often exhibit a hormetic dose-response, where beneficial effects occur at low doses and toxic effects emerge at higher doses (Vargas-Hernandez et al. 2017, Di Filippo-Herrera et al. 2021, Hernández-Herrera et al. 2022, Trejo-Téllez et al. 2023). However, in the case of PL, the response is also influenced by its chemical composition (Guo et al. 2022, Jindo et al. 2022). This pattern suggests that while PL has potential as a biostimulant, careful attention to both its concentration and composition is essential to avoid phytotoxicity. In addition, refinement of PL composition may influence its biostimulant potential.

Biostimulant effects of the pyrolysis liquid on wheat, pea and oat crops

The field trials evaluating the impact of BPL on spring wheat (*Triticum aestivum* L.), spring oat (*Avena sativa* L.), and field pea (*Pisum sativum* var. arvense L.) yielded results showing no significant differences in growth, yield, or grain quality compared to the untreated controls. Because detailed batch-specific compositional data were not available for the tested BPL, these field responses cannot be linked to specific compounds or their concentrations. These findings contrast with the positive effects reported in other studies, such as that of Ofoe et al. (2024), who reported that 0.25–2% PL increased photosynthetic capacity, leaf chlorophyll, and fruit number in greenhouse tomato (*Solanum lycopersicum* 'Scotia'). Similarly, Wang et al. (2019) showed that seed pre-soaking with 900-fold diluted wood vinegar significantly enhanced wheat (*Triticum aestivum* L.) seedling growth in laboratory-scale experiments by increasing shoot and root biomass, root system size, and shoot height; under polyethylene glycol-induced drought stress, the treatment also increased abscisic acid content and antioxidant enzyme activity while reducing oxidative damage. A positive effect was also observed in our laboratory-scale strawberry experiment, where low concentrations of the WPL promoted root growth and overall plant health.

Under field conditions, the BPL applications at varying concentrations failed to enhance crop ground cover, height, or yield across the species tested. The low variation observed in the measured parameters within each crop supports the consistency of these results. Notably, commercial biostimulants, PPS Biostimulant and YaraVita BioNUE, did not outperform the untreated controls either. In the oat and pea trials, the small rain shower right after the first biostimulant application may have reduced the efficacy of biostimulants slightly. However, the second biostimulant applications were made in favourable conditions in all crops. Our results differ from findings such as the meta-analysis by Li et al. (2022), which highlighted the benefits of biostimulants under field conditions. Similarly, in wheat field trials in Saudi Arabia, Al Majathoub (2004) found that the biostimulant Vigro (containing amino acids and enzymes), applied as a spray at two early growth timings, improved wheat yield by 8.2% on average over three years. Those trials were conducted in a very dry climate, and improvements in drought tolerance with biostimulants in different crops have been described, for example, by Zulfiqar et al. (2024). In our trials, the crops suffered from drought only briefly at early growth stages before the biostimulant applications. Moreover, nutrient deficiencies were eliminated by fertilising the crops according to soil nutrient analyses and common recommendations for each crop.

As the biostimulant effect of PL under field conditions is still at an experimental stage, only a few publications are available on systematic research on growth, yield and quality of different crops. The biostimulant activity of PL has been linked mainly to low-molecular-weight organic acids and phenolic compounds, while humic-/fulvic-like and amino-acid-like compounds may also contribute to root growth, nutrient uptake and stress responses (Mathew and Zakaria 2015, Jindo et al. 2022, Cândido et al. 2023). PL composition also depends strongly on feedstock and pyrolysis conditions, especially temperature, which may influence its growth-promoting properties (Mathew and Zakaria 2015, Jindo et al. 2022, Cândido et al. 2023). In their recent field study with rapeseed (*Brassica napus*), Zhu et al. (2021) found that a 400-fold dilution significantly increased plant height, total leaf number, green leaf number, leaf area, effective branch number, and pod number per plant.

The lack of significant field responses in our study may be attributed to several factors. Tandzi Ngoune and Mutengwa (2020) note that agricultural practices (including managerial decisions, pests, weeds, diseases, climatic conditions, soil fertility and water quality) can directly impact crop yields. In the current study, the conditions, especially after spraying, may have been too favourable for the biostimulants to provide any visible benefit. In addition, application timing and frequency may also have affected the observed results. In the trials, biostimulants were applied two times per growing season according to the label of commercial products. By contrast, Rogelio (2018) used a biweekly PL application for rice, resulting in a productivity increment of 68%, and Zhang et al. (2020) used monthly applications for blueberry, resulting in an 18.4% increase. It is possible that in our field trials the selected crops did not suffer such abiotic stresses under which the biostimulants could have been beneficial, or that the application timings were not optimal with respect to the stress period. Additionally, laboratory studies, such as the strawberry experiment presented here, often assess short-term physiological responses, whereas field trials span an entire growing season and must account for environmental stressors. In the strawberry pre-experiment, the runners were also continuously exposed to PL in aqueous solution, whereas under field conditions contact with the applied solution was likely shorter and more strongly modified by dilution, weather and crop canopy conditions. These longer timeframes and added complexities may attenuate treatment effects observed in controlled settings. Accordingly, although the WPL improved root growth in strawberry under controlled conditions, neither the BPL nor commercial biostimulants provided measurable advantages in crop height, ground cover, yield, or grain quality in the field.

Conclusion

This study provides new data from an initial field-based assessment of the potential agronomic applications of pyrolysis liquid, a woody biochar co-product, as a biostimulant. To our knowledge, this is the first study to investigate the biostimulant effects of pyrolysis liquid under northern field conditions in several crop species. Under controlled laboratory conditions, pyrolysis liquid demonstrated bioactivity, with low concentrations promoting root growth in strawberry plants without inducing phytotoxic effects. These findings align with prior research suggesting that pyrolysis liquids may exert biostimulant-like effects. However, because the compositions of the liquids used in this study were not characterised in sufficient batch-specific detail, it was not possible to determine which compounds were responsible for the observed responses or to assess how compositional differences may have influenced the results.

By contrast, the efficacy observed in laboratory settings did not translate to the open-field conditions tested here. Field trials on Nordic crops of oat, wheat, and pea revealed no significant improvements in growth, yield, or quality traits following pyrolysis liquid application under the tested conditions. Additionally, commercial biostimulants showed similarly limited impacts on these metrics, emphasising the complexity of replicating controlled experimental results in dynamic agricultural environments. These findings suggest that environmental variability, crop-specific responses, and the broader ecological context play a decisive role in modulating the effectiveness of biostimulants. At the same time, the lack of detailed compositional characterisation and coordinated experimental approaches limits the strength of conclusions that can be drawn regarding the effectiveness, or lack thereof, of the applied pyrolysis liquids.

This research also highlights the importance of coordinated experimental designs and detailed chemical characterisation before the agronomic performance of biochar-derived liquids can be reliably evaluated in field trials. The integration of woody biochar side streams, such as pyrolysis liquid, may still hold promise for advancing sustainable agriculture and enhancing the economic viability of biochar production within a circular bioeconomy framework. Future studies should first focus on substance characterisation, harmonised experimental design, and dose-response relationships, and then assess refined formulations and longer-term impacts across diverse agroecosystems and climatic conditions. Greenhouse pot experiments may be particularly useful for assessing the timing of biostimulant applications under different abiotic stress conditions and for clarifying their interactions.

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