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Effects of leachate-based liquid organic fertilizer on soil fertility and chili growth in biochar-amended marginal soil

Pengaruh pupuk organik cair berbasis lindi terhadap kesuburan tanah dan pertumbuhan cabai pada tanah marginal yang diberi biochar

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ABSTRACT
Soil fertility degradation and limited access to sustainable inputs pose major constraints in marginal agricultural lands. Organic waste leachate, although rich in nutrients, often contains phytotoxic compounds that limit its direct application as fertilizer. This study evaluated the effect of leachate-based liquid organic fertilizer (LOF) on soil fertility and the growth response of chili pepper (*Capsicum frutescens*) in marginal soils amended with biochar. Four treatments were tested: no LOF, 20% LOF, 40% LOF, and 60% LOF. Soil analysis showed that LOF application improved pH, organic carbon, and macronutrient content (N,P,K), with the highest pH in the 20% LOF treatment and the highest C-organic in the 60% LOF treatment. However, the best plant growth was observed in the control treatment, possibly indicating inhibitory effects of phytotoxic compounds such as phenols and organic acids present in the LOF. Although 20% LOF resulted in the highest fruit weight, differences among treatments were not statistically significant. These results suggest that while leachate-based LOF enhances soil quality, its high concentration may hinder plant growth. The findings support the potential use of leachate as a low-cost nutrient source for sustainable agriculture, provided that proper detoxification and formulation strategies are applied.

ABSTRAK
Degradasi kesuburan tanah dan keterbatasan akses terhadap input pertanian berkelanjutan merupakan kendala utama di lahan marginal. Lindi limbah organik mengandung nutrien yang tinggi, namun juga mengandung senyawa fitotoksik yang dapat menghambat pertumbuhan tanaman. Penelitian ini mengevaluasi pengaruh pupuk organik cair (POC) berbasis lindi terhadap kesuburan tanah dan respons pertumbuhan tanaman cabai rawit (*Capsicum frutescens*) di tanah marginal yang diberi biochar. Empat perlakuan diuji, yaitu tanpa POC, POC 20%, POC 40%, dan POC 60%. Hasil analisis tanah menunjukkan bahwa aplikasi POC meningkatkan pH, karbon organik, dan kandungan hara makro (N,P,K), dengan pH tertinggi pada perlakuan 20% dan kadar C-organik tertinggi pada perlakuan 60%. Namun, pertumbuhan tanaman terbaik justru diperoleh pada perlakuan kontrol tanpa POC, yang kemungkinan mengindikasikan adanya pengaruh penghambatan dari senyawa fitotoksik seperti fenol dan asam organik dalam POC. Meskipun perlakuan 20% menghasilkan bobot buah tertinggi, perbedaannya tidak signifikan secara statistik. Hasil ini menunjukkan bahwa meskipun POC berbasis lindi dapat meningkatkan kualitas tanah, konsentrasi tinggi justru dapat menghambat pertumbuhan tanaman. Temuan ini mendukung potensi pemanfaatan lindi sebagai sumber nutrien berbiaya rendah untuk pertanian berkelanjutan, asalkan diiringi dengan strategi detoksifikasi dan formulasi yang tepat.

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INTRODUCTION

Marginal soils, particularly in coastal regions, are typically characterized by low fertility, poor organic matter content, and high porosity (Su et al., 2022; Vasu et al., 2021). In Indonesia, coastal lands extend from Sabang to Merauke, and areas such as Majene Regency in West Sulawesi are dominated by Alfisols and Ultisols with red-yellow Mediterranean and podzolic characteristics (Purnama et al., 2023; Santoso et al., 2022). These soils are also prone to salinity due to their proximity to the coastline, further constraining their suitability for crop production (Mitran et al., 2021; Song et al., 2023).

In addition to poor soil conditions, ineffective waste management is another major issue in Majene (Ahmad, 2022). Organic waste, such as litter and fruit peels, when improperly handled, may cause environmental hazards or disease outbreaks (Arista, 2024). To address both soil fertility and waste issues, the utilization of organic waste as soil amendment and fertilizer presents a promising solution. Solid organic waste can be transformed into biochar, a carbon-rich material produced via pyrolysis, which improves physical, chemical, and biological soil properties (Su et al., 2021; Luo et al., 2024; Qiu et al., 2023). Biochar has been shown to enhance nutrient retention and support soil health in horticultural systems (Khan et al., 2024).

Meanwhile, the liquid fraction of waste decomposition—leachate—is often rich in nutrients such as ammoniacal nitrogen, phosphorus, and organic carbon (Nguyen et al., 2017; Turki and Bouzid, 2017; Kurniawan et al., 2023). Despite its phytotoxic potential due to the presence of complex organics and phenolic compounds, leachate can serve as a nutrient source when properly processed. Studies have shown that leachate-based liquid organic fertilizers (LOFs) can improve plant performance when used at appropriate concentrations (Hasnelly et al., 2021). However, concerns remain about the toxicity of unprocessed leachate and the variability in its nutrient composition (Martin-Utrillas et al., 2015; Santiago Badillo et al., 2021).

Biochar and LOFs have each demonstrated benefits in restoring soil fertility, particularly in degraded lands. The integration of both is expected to produce synergistic effects, as biochar may mitigate the potential toxicity of leachate while enhancing nutrient availability (Tang et al., 2023; Zhao et al., 2023). In addition, biochar contributes to climate change mitigation through carbon sequestration and greenhouse gas reduction (Yadav et al., 2023). Despite the promising potential of both amendments, limited studies have explored their combined application, especially using leachate as the LOF source. This study aims to evaluate the effect of leachate-based LOF combined with biochar on soil fertility and the growth of chili pepper (*Capsicum frutescens*) in coastal marginal soils. Chili was selected due to its high nutritional value and increasing consumer demand (Miranda-Molina et al., 2019; Pola et al., 2020). The findings are expected to contribute to the sustainable use of waste-derived inputs and the enhancement of marginal land productivity in tropical agriculture.

MATERIALS & METHODS

Study site and materials

The experiment was conducted in a controlled greenhouse environment at the Faculty of Agriculture and Forestry, University of West Sulawesi, Indonesia. The study utilized *Capsicum frutescens* (Dewata 43 F1) seeds sourced from PT. East West Seed Cap Panah Merah, Indonesia. Biochar used in the experiment was derived from rice husks collected at a local rice mill in Tinambung District, while organic waste in the form of fruit peels was obtained from local vendors at the Banggae District Market. Alfisol soil, characterized by its low fertility, was collected from idle marginal land around Majene City and used as the planting medium.

Leachate-based liquid organic fertilizer (LOF) preparation

The production of LOF followed a modified version of the method by Mangera and Ekowati (2022), utilizing a stacked bucket system. The process began with the decomposition of 5 kg of green vegetable waste mixed with a decomposer solution (EM-4, PT. Songgolangit Persada, Indonesia) diluted in 2 L of water. This mixture was incubated in a stacked fermentation bucket for 14 days to produce leachate. The leachate was then blended with a brown sugar solution (500 g) and rice washing water in a 1:1:1 ratio (v/v/v). The resulting mixture underwent anaerobic fermentation for 7 days. The LOF was considered ready for application once it exhibited an alcohol-like aroma, indicating the end of active fermentation.

Experimental design

This experiment was arranged using a randomized block design (RBD) to ensure statistical reliability and minimize environmental variability within the greenhouse setting. Four treatment groups were established based on different concentrations of LOF. The control group (BL0) received no LOF, while the other treatments received increasing concentrations of LOF: 20% (BL1), 40% (BL2), and 60% (BL3). Each treatment solution was prepared by diluting the LOF with distilled water in specific ratios: 20 mL LOF + 80 mL water for BL1, 40 mL LOF + 60 mL water for BL2, and 60 mL LOF + 40 mL water for BL3. To account for experimental variability, each treatment was replicated four times, resulting in a total of 16 experimental units. This design allowed for the assessment of treatment effects on plant performance and soil characteristics under uniform conditions.

Planting media preparation and seedling transplantation

Chili seedlings were first germinated in trays filled with a 1:1:1 mixture of rice husks, chicken manure, and soil (w/w/w). The trays were watered with a hand sprayer, and four seeds were placed into each hole. After 14 days, seedlings with at least two true leaves were transplanted into polybags (30 × 40 cm) containing a planting mixture of Alfisol, rice husks, and chicken manure in a 2:1:2 ratio (w/w/w). Prior to transplanting, the media was moistened with water to facilitate seedling adaptation. Biochar was applied to the planting medium at a rate of 9 g per kg of soil, following the method described by Bahrun et al. (2018). LOF was applied around the base of the plant four times throughout the growth period until the final harvest.

Crop maintenance, observed parameters, and laboratory analyses

Standard horticultural practices were followed to maintain plant health and uniform growth. Watering was conducted regularly to maintain optimal moisture levels, and weeds were manually removed throughout the cropping period. No additional chemical fertilizers or pesticides were applied during the study. Plant growth and yield parameters—including plant height, stem diameter, number of fruits, and fresh fruit weight—were recorded throughout the experimental period, based on the procedure adapted from Arta et al. (2024). Soil chemical properties were assessed before and after treatment application, covering organic carbon, total nitrogen, available phosphorus, and total potassium, following the methodology of Sulaeman et al. (2005).

A total of 48 plants (4 treatments × 4 replicates × 3 plants per replicate) were observed for agronomic parameters. For laboratory analyses of soil chemical properties, one composite soil sample was collected per treatment by combining soils from all four replicates, resulting in four representative samples. This approach was chosen to evaluate treatment-level effects on soil fertility indicators.

Statistical analysis

The data obtained were first tested for normality and homogeneity of variance. If assumptions were met, analysis of variance (ANOVA) was performed at a 5% significance level ($p < 0.05$). When significant differences were found, means were compared using Duncan's Multiple Range Test (DMRT) to determine the effects of the treatments.

RESULTS & DISCUSSIONS

Climatic conditions during the study period

The study was conducted in Majene Regency, West Sulawesi, where the climate characteristics during the experimental months (May to August 2023) were relatively stable. Based on NASA's POWER data (www.nasa.gov), Table 1 presents monthly averages of key climatic parameters, including air temperature, relative humidity, rainfall, photosynthetically active radiation (PAR), and wind speed. Table 1 shows that the minimum temperature ranged narrowly from 25.33 °C to

26.30 °C, while the maximum temperature fluctuated slightly between 29.13 °C and 30.40 °C. This limited variation indicates a relatively stable temperature regime, which is beneficial for chili pepper (*Capsicum frutescens* L.) growth. Relative humidity remained high throughout the period, increasing slightly from 78.56% in May to above 80% in the following months. High humidity levels can promote vegetative growth but may also influence disease pressure in crops.

Table 1. Average monthly climate data in Majene Regency 2023

Month	Temperature (C)		Relative humidity (%)	Rainfall (mm)	Clear PAR (W/m^2)	Wind speed (m/s)
	Min	Max				
May	26.30	30.40	78.56	7.91	123.73	2.28
June	25.33	29.46	80.25	8.08	118.03	2.86
July	25.80	29.13	81.12	5.36	120.23	3.64
August	25.58	29.31	80.12	5.58	128.59	3.91

Source: NASA (https://power.larc.nasa.gov/data-access-viewer/)

Rainfall during the study period was relatively low, particularly in July and August, which aligns with the dry season pattern in this region. Notably, PAR values increased progressively, reaching a peak of 128.59 W/m^2 in August. This suggests an increase in solar radiation intensity, possibly due to clearer skies or extended daylight hours, both of which can enhance photosynthetic activity. Wind speed also exhibited a consistent upward trend, rising from 2.28 m/s in May to 3.91 m/s in August. Elevated wind speed may influence transpiration rates and microclimatic conditions around the plant canopy, affecting nutrient uptake and stress responses. Collectively, these climatic conditions indicate that the site offered a relatively consistent tropical environment suitable for chili cultivation. The importance of such climatic stability has been underscored by Nurcahyo et al. (2024), who reported that solar radiation, air temperature, and relative humidity significantly influence chili pepper yield, accounting for approximately 55.84% of its production variability.

Changes in soil chemical properties following biochar and LOF application

The application of biochar and LOF derived from vegetable waste leachate significantly affected several soil chemical parameters, as shown in Table 2. The treatments altered soil pH, organic carbon (C-organic), total nitrogen (N-total), available phosphorus (P-available), and total potassium (K-total), indicating improved nutrient availability. The soil pH increased from 6.12 in the control (without LOF) to 6.46 under the 20% LOF treatment, indicating a shift toward neutrality. This pH improvement is likely due to the alkaline nature of some dissolved minerals in the LOF, such as calcium, magnesium, and potassium, which can buffer soil acidity. Sinurat and Karo (2022) noted that LOF derived from vegetable waste contains these cations, contributing to pH elevation in acidic soils.

Table 2. Soil chemical characteristics of chili pepper crops applied with biochar and LOF

Treatment	pH	C-organic (%)	N-total (%)	P-available (ppm)	K-total (cmol kg^{-1})
Without LOF	6.12	1.98	0.12	11.14	0.16
20% LOF	6.46	2.31	0.16	13.17	0.30
40% LOF	6.38	2.16	0.25	15.21	0.25
60% LOF	6.21	2.46	0.24	14.54	0.31

Regarding organic carbon, the highest C-organic content was observed in the 60% LOF treatment (2.46%), while the control had the lowest (1.98%). The increase in organic carbon is likely driven by microbial decomposition of organic matter in the LOF. During this process, soil microbes metabolize complex organic substrates, releasing simpler carbon compounds into the soil matrix. Haryanta et al. (2023) demonstrated similar outcomes, reporting increased total organic carbon and nutrient content following LOF application.

Applying LOF from vegetable waste leachate can also increase the soil's macronutrients N, P, and K levels. Table 2 shows that the highest total N and available P levels were shown in the 40% LOF treatment with N values of 0.25% and P of 15.21 ppm. Meanwhile, the 60% LOF treatment showed the highest K content with a K value of 0.31 cmol kg^{-1}. The lowest N, P, and K levels were shown in the treatment without using LOF with levels of 0.12%, 11.14 ppm, and 0.16 cmol kg^{-1}, respectively. The increased levels of N, P, and K in the soil are due to the application of LOF made from vegetable waste leachate because vegetable waste leachate contains various nutrients that are dissolved during the decomposition process of vegetables. These nutrients include nitrogen, phosphorus, and potassium, which come from organic materials that decompose when LOF is applied to the soil. This is in line with Chirila et al. (2013), who stated that when vegetable waste leachate decomposes, it causes the release of nutrients such as Nitrogen, Phosphorus, and Potassium into the soil, the process occurs during the application of LOF to the soil.

Effects on growth and yield of chili pepper

The combined application of biochar and leachate-based LOF substantially influenced the vegetative and reproductive performance of chili pepper (*Capsicum frutescens*), as reflected in plant height, stem diameter, number of fruits, and fresh fruit weight (Table 3). Analysis of chili pepper plant height showed that the treatment without LOF had the highest height at 24.826 cm. In contrast, the lowest plant height was shown in the 60% LOF treatment, which was 17.920 cm. The statistical analysis results show that the treatment without LOF significantly differs from that of 60% LOF application. Other parameters, such as stem diameter and number of fruits, showed similar results; without LOF application, it had the highest stem diameter and number of fruits with respective values of 0.541 cm and 15.60 fruits. In comparison, the treatment of 40% LOF application showed the lowest stem diameter value of 0.368 cm, and the application of 60% LOF had the lowest number of 12.00 fruits.

Table 3. Growth and yield performance of chili pepper plants under different LOF concentrations combined with biochar

Treatment	Plant height (cm)	Stem diameter (cm)	Fruit number	Fresh fruit weight (g)
Without LOF	24.83 ± 1.12b	0.54 ± 0.00b	15.60 ± 3.90	11.04 ± 2.42
20% LOF	21.87 ± 0.46ab	0.50 ± 0.01ab	12.20 ± 0.92	13.36 ± 3.40
40% LOF	18.00 ± 2.72a	0.37 ± 0.07a	14.06 ± 1.47	11.02 ± 1.42
60% LOF	17.92 ± 4.35a	0.38 ± 0.09a	12.00 ± 3.52	10.27 ± 2.75

Notes. Numbers followed by the same column and variable are not significantly different based on Duncan's test at the 5% level. Different final letters indicate significant results. Mean values that have an F value <0.05 will be subjected to further testing.

The results obtained show that the higher the application of LOF, the more it inhibits plant growth in terms of plant height, stem diameter, and number of fruits. This is because the LOF made from leachate contains ingredients that can inhibit plant growth, such as phenols and organic acids. Leachate is a liquid produced from the organic decomposition process containing various beneficial and potentially harmful compounds to plants (Said and Hartaja, 2018). Leachate contains phenol and organic acids that can inhibit plant growth (Li et al., 2021; Stanek et al., 2021). Additionally, according to Šourková et al. (2020), leachate contains phenolic compounds, easily degradable organic matter, and high nitrogen levels, which, if applied excessively or in high concentrations, can make the soil toxic and inhibit plant growth and production. In addition, similar results were shown in the study by Singh et al. (2023), which indicated that leachates generally contain heavy metal accumulation that can inhibit plant growth. The higher the concentration of leachates used, the lower the relative water content, thereby reducing the plant's ability to absorb nutrients and perform photosynthesis. The higher leachate concentrations reduced plant height, root length, and leaf area, indicating impaired water absorption and transport (Kalousek et al., 2020). A similar observation was reported by Anggrayni et al. (2025), who demonstrated that the application of wood vinegar—a torrefied liquid derived from waste biomass—at low concentrations effectively promoted plant growth, whereas higher concentrations exhibited phytotoxic effects and inhibited plant development.

The growth parameter of the fruit weight of chili pepper plants shows that the 20% application treatment of LOF has the highest fruit weight of 13.36 g. In comparison, the lowest fruit weight is shown in the 40% application treatment of LOF, which is 11.02 g. Based on the statistical test results, there is no significant difference between each treatment. Based on the results obtained, there is no significant difference between each treatment of LOF application made from vegetable waste leachate on the fruit weight of chili pepper plants. This is due to the excessive dose and frequency of LOF application. Excessive doses and frequencies of application of leachate-based LOF made from vegetable leachate in this study are suspected to result in excessive salt concentrations in the soil, and this condition inhibits plant growth and crop production. Excessive dosage and frequency of application of potassium-containing fertilizers, such as potassium chloride (KCl), can cause an increase in soil chloride content, resulting in soil acidification and potential inhibition of plant growth (Wang et al., 2023). In addition, high salt concentrations in the soil, whether from chloride fertilizers or other sources, are a significant abiotic stress that can affect plant growth and productivity (Zhao et al., 2021). Excessive accumulation of nutrients in the soil, such as nitrate from fertilizers, can contribute to secondary soil salinization, further compromising plant health and soil quality (Wang et al., 2022).

The findings indicate that improvements in soil chemical properties do not automatically lead to enhanced plant performance when phytotoxic compounds are present. Setyorini et al. (2019) reported that compost application as a soil conditioner can increase organic matter content, thereby maintaining or enhancing soil fertility. However, negative impacts may also occur, particularly when immature compost is used. Under anaerobic decomposition conditions, toxic compounds such as organic acids, ammonia, nitrite, and excessive amounts of iron and manganese may be released, posing risks to plant health. Several limitations should be considered in interpreting the results of this study. Only four concentrations of leachate-based LOF were tested, and no biochar-only control treatment was included. As a result, the independent effects of biochar on soil and plant parameters could not be evaluated. Additionally, the study did not analyse the concentrations of phenolic compounds and organic acids in the LOF, even though these compounds are strongly suspected to contribute to the observed growth inhibition in chili plants. Further chemical profiling of the LOF is recommended to clarify the role of these compounds in plant responses.

CONCLUSIONS

Leachate-derived liquid organic fertilizer (LOF) has demonstrated potential in enhancing soil fertility by increasing the availability of essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K). These improvements are attributed to the nutrient-rich nature of vegetable waste leachate, which releases substantial organic and inorganic compounds during decomposition. As such, LOF presents a promising nutrient source for improving soil quality, particularly in marginal coastal areas where conventional fertilization is often limited. However, the application of high LOF concentrations was found to negatively impact plant growth, as evidenced by reductions in plant height, stem diameter, and fruit number. This adverse effect is likely due to the accumulation of phytotoxic compounds—such as phenols and organic acids—commonly present in leachate, especially when not sufficiently diluted. These findings underscore the importance of optimizing LOF concentration to balance nutrient supply and minimize growth inhibition. Future studies are recommended to evaluate lower LOF concentrations (e.g., 5% to 10%) to determine their efficacy in improving soil fertility while mitigating phytotoxic effects. Such adjustments may enable more sustainable and effective use of leachate-based fertilizers in degraded agroecosystems.

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