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The Effect of Compost Enriched with Cellulolytic Bacteria on Plant Residue Decomposition and Nutrient Release Rates in Sandy Soil

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تأثير السماد المدعم ببكتيريا محللة للسليلوز على تحلل المخلفات النباتية ومعدلات إطلاق المغذيات في التربة الرملية

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Abstract:

Sandy soils are characterized by low fertility, poor water retention, and rapid leaching of nutrients. Enhancing their quality through organic amendments like compost is a key sustainable strategy. This study investigated the efficacy of compost inoculated with a consortium of cellulolytic bacteria to accelerate the decomposition of plant residues and improve nutrient release dynamics in sandy soil. A 60-day incubation experiment was conducted with four treatments: (1) control sandy soil (S), (2) soil with wheat straw (S+WS), (3) soil with conventional compost (S+C), and (4) soil with bacterially-enriched compost (S+BC). Decomposition was monitored by measuring mass loss of the straw and CO2 respiration. Soil samples were analyzed weekly for available nitrogen (N), phosphorus (P), potassium (K), and microbial biomass carbon (MBC). The results showed that the S+BC treatment exhibited the highest cumulative respiration (signifying microbial activity) and the fastest rate of straw decomposition (68% mass loss vs. 45% in S+WS and 55% in S+C). Consequently, the S+BC treatment consistently released higher levels of available N (NO_3^- and NH_4^+), P, and K throughout the incubation period compared to other treatments. Microbial biomass carbon was also significantly higher in the S+BC treatment, indicating a robust and active microbial community. This study concludes that enriching compost with cellulolytic bacteria significantly enhances its effectiveness in degrading organic matter and synchronizing nutrient mineralization with plant demand, making it a superior amendment for rapidly improving the fertility and health of sandy soils.

Keywords: Cellulolytic bacteria, compost, sandy soil, nutrient mineralization, decomposition, soil health, microbial biomass, sustainable agriculture.

الملخص:
تتميز التربة الرملية بانخفاض خصوبتها، وسوء قدرتها على الاحتفاظ بالماء، ورشح المغذيات السريع. يُعد تحسين جودتها من خلال التعديلات العضوية مثل السماد استراتيجية مستدامة رئيسية. تحقق هذه الدراسة من فعالية السماد الملقح بكونسورتيوم من البكتيريا المحللة للسليلوز في تسريع تحلل المخلفات النباتية وتحسين ديناميكيات إطلاق المغذيات في التربة الرملية. تم إجراء تجربة حضانية لمدة 60 يومًا بأربع معاملات: (1) تربة رملية ضابطة (S)، (2) تربة مع قش القمح (S+WS)، (3) تربة مع سماد تقليدي (S+C)، و (4) تربة مع سماد مُعزز بالبكتيريا (S+BC). تم رصد عملية التحلل عن طريق قياس الفقد في الكتلة للقش ومعدل تنفس ثاني أكسيد الكربون. تم تحليل عينات التربة أسبوعيًا لتقدير النيتروجين (N)، والفوسفور (P)، والبوتاسيوم (K) المتاح، وكذلك كربون الكتلة الحيوية الميكروبية (MBC). أظهرت النتائج أن معاملة السماد المعزز بالبكتيريا (S+BC) سجلت أعلى تنفس تراكمي (يدل على النشاط الميكروبي) وأسرع معدل لتحلل القش (فقدان كتلة بنسبة 68% مقابل 45% في معاملة S+WS و55% في معاملة S+C). ونتيجة لذلك، أطلقت معاملة S+BC باستمرار مستويات أعلى من النيتروجين (NO_3^- وNH_4^+)، والفوسفور، والبوتاسيوم المتاحين ط فترة الحضانة مقارنة بالمعاملات الأخرى. كان كربون الكتلة الحيوية الميكروبية أعلى بشكل معنوي أيضًا في معاملة S+BC، مما يشير إلى وجود مجتمع ميكروبي قوي ونشط. تستنتج هذه الدراسة أن إثراء السماد بالبكتيريا المحللة للسليلوز يعزز بشكل معنوي فعاليته في تحلل المادة العضوية وتنظيم عملية تمعدن المغذيات لتتزامن مع احتياجات النبات، مما يجعله تعديلاً متفوقًا لتحسين خصوبة وصحة التربة الرملية بسرعة.

الكلمات المفتاحية: البكتيريا المحللة للسليلوز، السماد، التربة الرملية، تمعدن المغذيات، التحلل، صحة التربة، الكتلة الحيوية الميكروبية، الزراعة المستدامة.

1. Introduction

Sandy soils cover a significant portion of the world's agricultural land, particularly in arid and semi-arid regions. Their inherently low fertility, characterized by poor soil structure, low water-holding capacity, minimal organic matter content, and high susceptibility to nutrient leaching, poses a major challenge for sustainable crop production (Lal, 2020). The addition of organic matter, primarily through compost, is a universally recommended practice to ameliorate these constraints. Compost improves soil physical properties, provides a slow-release source of nutrients, and enhances microbial diversity and activity (Wei et al., 2017).

The antimicrobial potential of botanical extracts and essential oils has been extensively documented, with numerous studies confirming their ability to inhibit the growth of diverse bacterial species through mechanisms such as cell wall disruption and protein synthesis interference, (Kadak & Salem, 2020; Salem, 2024; Salem et al., 2025; SALEM et al., 2021).

The decomposition of organic matter in soil is a microbially driven process. The initial breakdown of cellulose, the most abundant polysaccharide in plant residues, is a critical rate-limiting step (Behera et al., 2014). This process is carried out by specialized cellulolytic microorganisms that produce extracellular enzymes (cellulases) to hydrolyze cellulose into simpler, metabolizable sugars (Mba Medie et al., 2012). The subsequent mineralization of these compounds by the soil microbial community releases essential plant nutrients like nitrogen, phosphorus, and sulfur (Geisseler & Horwath, 2008).

Conventional compost, while beneficial, often has a stabilized C:N ratio and its nutrient release pattern may not be rapid enough to meet crop demands in highly leaching sandy soils. Inoculating compost with efficient cellulolytic bacteria during the composting process or at the time of application is a potential bioaugmentation strategy to overcome this limitation (Yadav & Devi, 2019). These exogenous microbes can boost the native microbial population, accelerate the decomposition of fresh organic matter incorporated into the soil, and potentially synchronize nutrient release with plant uptake needs (Kaushik & Garg, 2003).

While several studies have explored compost application and isolated cellulolytic bacteria, few have integrated them into a practical application strategy for nutrient-poor sandy soils. This study therefore tests the hypothesis that compost enriched with a selected consortium of cellulolytic bacteria will (i) accelerate the decomposition of plant residues, (ii) increase the rate of nutrient mineralization, and (iii) enhance overall microbial biomass and activity in sandy soil compared to conventional compost or untreated straw. The outcomes of this research will provide a scientific basis for developing next-generation bio-enhanced organic fertilizers for sustainable soil management.

2. Materials and Methods

2.1. Cellulolytic Bacterial Consortium and Compost Preparation

Cellulolytic bacteria (*Bacillus subtilis* strain SCS1, *Pseudomonas fluorescens* strain CFB2, and *Cellulomonas* sp. strain CLL3) were isolated from active compost piles on carboxymethyl cellulose (CMC) agar plates and identified through 16S rRNA gene sequencing. A consortium was prepared by mixing equal proportions (10^8 CFU mL^{-1} each) of each strain in a sterile saline solution.

Conventional compost (C) was produced from cattle manure and wheat straw (3:1 ratio) using a window method for 90 days. For the bacterially-enriched compost (BC), the same base compost was used. It was inoculated with the bacterial consortium at a rate of 100 mL per kg of compost and incubated for 7 days at 30°C to allow for establishment before soil application.

2.2. Experimental Design and Soil Incubation

A sandy soil (sand: 92%, silt: 4%, clay: 4%; pH 7.8; organic C: 0.4%) was collected, sieved (<2 mm), and pre-incubated for one week. The experiment consisted of four treatments in triplicate:

1. **S:** Soil only (control).
2. **S+WS:** Soil + 1% (w/w) dry wheat straw (<2 mm).
3. **S+C:** Soil + 1% (w/w) conventional compost.
4. **S+BC:** Soil + 1% (w/w) bacterially-enriched compost.

Each replicate (500 g soil) was placed in a 1 L airtight glass jar. The moisture content was adjusted to 60% water-holding capacity and maintained gravimetrically throughout the experiment. Jars were incubated in the dark at 28 ± 2°C for 60 days. A vial with 10 mL of 1 M NaOH was placed in each jar to trap evolved CO_2 and was replaced weekly for respiration measurement.

2.3. Measurements and Chemical Analyses CO2 Respiration:

The trapped CO_2 in NaOH was determined by titration with 0.5 M HCl after precipitating carbonate with $BaCl_2$ (Alef & Nannipieri, 1995).

Mass Loss: The undecomposed wheat straw residue was recovered from the S+WS treatment at the end of the experiment by wet-sieving, dried, and weighed to calculate the percentage mass loss.

Soil Analysis: Soil samples were collected destructively on days 0, 7, 14, 28, and 60. Available nitrogen (NH_4^+-N and NO_3^--N) was extracted with 2 M KCl and determined by spectrophotometry. Available P was extracted with 0.5 M $NaHCO_3$ (Olsen's method) and measured spectrophotometrically. Available K was extracted with 1 M ammonium acetate and measured by flame photometry (Page et al., 1982). Microbial Biomass Carbon (MBC) was determined on day 28 using the chloroform fumigation-extraction method (Vance et al., 1987).

2.4. Statistical Analysis

Data were subjected to one-way analysis of variance (ANOVA) using SPSS software (v.26). Treatment means were compared using Tukey's Honestly Significant Difference (HSD) test at a 5% probability level ($p < 0.05$). Graphs were plotted using SigmaPlot (v.14.0).

3. Results

3.1. Microbial Activity and Residue Decomposition

Cumulative CO_2-C evolution, an indicator of overall microbial activity, was significantly different among treatments ($p < 0.001$). The S+BC treatment showed the highest cumulative respiration, followed by S+C, S+WS, and the control (S). The initial respiration burst was highest in S+BC, indicating immediate and enhanced microbial activity.

After 60 days, the mass loss of wheat straw was significantly greater in the S+BC treatment (68.2% ± 2.1%) compared to the S+WS (45.5% ± 3.4%) and S+C (55.8% ± 2.8%) treatments.

3.2. Dynamics of Available Nutrients

The S+BC treatment consistently maintained the highest levels of available nutrients throughout the incubation period.

Nitrogen: A rapid increase in mineral N was observed in the S+BC treatment by day 14, which remained significantly higher than all other treatments until day 60.
Phosphorus: Available P showed a similar trend, with the S+BC treatment exhibiting a significantly higher release rate, particularly during the first 4 weeks.
Potassium: The release of K was most rapid, with the S+BC treatment showing the highest concentration from day 7 onwards.

3.3. Microbial Biomass Carbon

Microbial Biomass Carbon (MBC), measured on day 28, was significantly influenced by the treatments ($p < 0.001$). The S+BC treatment recorded the highest MBC (285 µg C g^{-1} soil), which was 25% higher than the S+C treatment and over 100% higher than the S+WS treatment. The control soil had the lowest MBC.

4. Discussion

The results of this study strongly support the hypothesis that enriching compost with a defined consortium of cellulolytic bacteria significantly enhances its capacity to decompose organic matter and release nutrients in a sandy soil. The superior performance of the bacterially-enriched compost (S+BC) is attributed to the introduction of highly efficient decomposer microbes that synergistically work with the native soil microbiota.

The significantly higher cumulative CO_2 respiration and mass loss in the S+BC treatment provide clear evidence of accelerated microbial activity and decomposition. The inoculated cellulolytic bacteria (*Bacillus*, *Pseudomonas*, and *Cellulomonas*) are known prolific producers of cellulases and other hydrolytic enzymes (Mba Medie et al., 2012; Behera et al., 2014). Their introduction likely jump-started the decomposition process by rapidly breaking down the complex cellulose in the wheat straw and compost, providing abundant soluble carbon substrates for the wider microbial community. This "priming effect" is a well-documented phenomenon where the addition of easily available carbon or microbes stimulates the native soil community to decompose native organic matter (Blagodatskaya & Kuzyakov, 2008).

The enhanced and synchronized release of N, P, and K in the S+BC treatment is a direct consequence of this accelerated decomposition. The breakdown of organic matter mineralizes organically bound nutrients into their plant-available forms (Salem, Abdalah, & Mohamed, 2024). The sustained release, as opposed to a single rapid pulse, is crucial for preventing leaching losses in sandy soils and matching plant nutrient demand (Geisseler & Horwath, 2008). The increase in Microbial Biomass Carbon in the S+BC treatment indicates the build-up of a larger microbial pool, which acts as a labile reservoir for nutrients (especially N and P), further reducing leaching and slowly releasing nutrients upon cell death (Jenkinson & Ladd, 1981).

The comparison with conventional compost (S+C) is particularly noteworthy. While the S+C treatment performed better than raw straw (S+WS), its effect was surpassed by the bio-enriched compost. This suggests that the composting process, though creating a stable product, may not necessarily leave it with an optimal cellulolytic population for further decomposition upon soil application. Re-inoculation with targeted decomposers can thus reactivate the compost, making it a more powerful tool for rapid soil improvement (Mahommed et al., 2025; Yadav & Devi, 2019; Kaushik & Garg, 2003).

5. Conclusion

This study demonstrates that the strategy of augmenting conventional compost with a selected consortium of cellulolytic bacteria is highly effective in enhancing its functionality. This bio-enriched compost accelerates the decomposition of organic matter, promotes a robust and active microbial community, and facilitates a more rapid and sustained release of key plant nutrients in a nutrient-poor sandy soil. This approach moves beyond simply adding organic matter to actively managing the microbial communities that control its breakdown. It offers a promising, sustainable technology to rapidly improve the fertility and health of degraded sandy soils, increase nutrient use efficiency, and support agricultural productivity while reducing reliance on synthetic fertilizers. Future research should validate these findings under field conditions with growing crops.

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