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# Enhancing Nutrient Content in Compost from Agricultural Waste using *Rhizobium* Microorganisms

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## ABSTRACT

*In Laos, where chemical fertilizers are costly and organic matter is underutilized, agricultural waste compost often lacks the nutrients needed for effective soil enrichment. Teak wood sawdust, a byproduct of expanding smallholder teak plantations, is abundant yet remains largely untapped as a compost component. This study evaluated the effectiveness of agricultural waste, specifically sawdust (S) and manure (M), fermented with Rhizobium microorganisms (RM) to enhance compost quality. The objective was to compare the chemical composition of compost arranged in a completely randomized design with 5 treatments and 4 replicates. Treatments evaluated were: $T_1$) S and M (50:50); $T_2$) S and M (50:50) + RM soybean; $T_3$) S and M (50:50) + RM mung bean; $T_4$) S and M (50:50) + RM sunn hemp; $T_5$) S and M (50:50) + RM liquid culture of mung bean. Sawdust and manure were mixed and fermented with 2% Rhizobium, placed in plastic bags, and kept indoors for 45 days. Chemical analyses included DM (dry matter), pH, $N_2$, $P_2O_5$, $K_2O$, OM (organic matter), and ash. Results indicated significant differences ($P<0.05$) in chemical compositions: pH was highest in $T_3$ (7.18), OM in $T_4$ (33.08%), $N_2$ in $T_2$ (0.17%), $P_2O_5$ in $T_3$ (0.36%), $K_2O$ in $T_2$ (0.94%), DM in $T_4$ (59.81%), and ash in $T_1$ (2.45%). Among treatments, RM combined with soybeans emerged as a promising solution to enhance compost nutrient content. These findings support the potential for RM-enriched compost to improve soil fertility sustainably, offering an accessible soil amendment for farmers in resource-limited settings.*

**Keywords:** *Rhizobium*, Teak wood sawdust, chemical composition, compost

## INTRODUCTION

Laos PDR is a developing country that focuses on infrastructure development and improving livelihoods based on the potential of country, particularly in agricultural production. This effort aims to generate income for its population of over 7 million, with more than 79% engaged in agriculture, primarily farming and animal husbandry. Therefore, the Laos government has formulated plans to develop the nation into a prosperous and resilient society by accelerating the agricultural sector, leveraging the natural potential in farming and animal husbandry.

As the population continues to grow, meeting the increasing demands for food and resources becomes crucial. Farming and animal husbandry play significant roles in addressing these needs (Akinrinde, 2006; Lehmann, 2007). However, the changing climate presents challenges, as irregular rainfall patterns lead to natural disasters such as droughts, disease outbreaks, and pest infestations. These issues stem from environmental degradation primarily caused by human activities focused on economic growth and the pressures of a rising population.

Environmental problems manifest as both direct and indirect damage, such as air pollution and soil degradation. Deforestation, industrial emissions, and waste discharge into rivers have serious repercussions on soil quality. Fertile soil is vital for agricultural productivity, and its degradation can severely impact crop yields, particularly for vegetables grown for both commercial and household consumption. While the use of manure or compost can enhance soil safety and quality, the increasing cost of chemical fertilizers poses a challenge for farmers. Although organic fertilizers, such as compost and manure are gaining popularity, they often fail to meet the quality demands of farmers.

Sawdust, a byproduct of wood processing, particularly from Teak wood in the Luang Prabang District, is commonly viewed as waste. While some sawdust is used for charcoal production or mushroom cultivation, a substantial amount remains unutilized, contributing to air pollution when burned. However, sawdust can be beneficial as a component in composting. Although sawdust lacks essential nutrients for plant growth, when mixed with compost, it enhances aeration and improves the quality of the final product (Laoh *et al*., 2016).

Farmers often underutilize chemical fertilizers and agricultural residues, leading to low yields (Mugwira *et al*., 2002; Musvoto *et al*., 2000). To support plant growth, sufficient nutrients, especially nitrogen ($N_2$), are essential (Swift, 1987). Fortunately, livestock manure, particularly cattle manure, is readily available and contains approximately 1.1% nitrogen (Seansouk, 2000). Keovilaysak and Silivong (2023) reported that using cattle manure improves soil fertility and increases the productivity of crops, particularly sweet grass.

Utilizing compost made from a mix of plant materials and animal manure has gained traction, as it reduces vegetable cultivation costs and is environmentally friendly. The incorporation of compost positively affects soil microorganisms (Lorchamyer *et al*., 2017). Research demonstrates that the application of compost significantly enhances cabbage growth (Jang and Thammavong, 2013). However, issues with compost quality, particularly nutrient content, remain a primary concern. Many researchers have explored the use of effective microorganisms (EM) to expedite fermentation and enhance the nutritional value of compost (Manivanh *et al*., 2018).

*Rhizobium* microorganisms, known for their nitrogen-fixing properties, present a promising avenue for improving compost quality. They can enhance nitrogen content by drawing it from the air, potentially increasing the nutritional value of fertilizers. Studies indicate that *Rhizobium* can improve soil fertility and increase yields by 25-30% (Schoot and Uiterkamp, 1990). Previous research highlights the positive effects of these microorganisms on vegetables and pasture growth (Burns and Hardy, 1975; Paul and Towards, 1998; Peoples *et al*., 1995; Sprent and Sprent, 1990). Incorporating *Rhizobium* or *BradyRhizobium* with leguminous plants in vegetable and pasture cultivation has shown promising results, providing a low-cost and effective strategy for improving soil quality (Mandimba, 1995; Viera *et al*., 1995). Given the diversity of *Rhizobium* species, their varying properties, and the environmental conditions they thrive in, further research comparing the chemical composition of compost utilizing different *Rhizobium* microorganisms is warranted.

In Laos PDR, where agriculture sustains a large portion of the population, farmers increasingly face challenges from climate change and soil degradation along with the rising costs of chemical fertilizers. Teak wood sawdust, a nutrient-poor byproduct from expanding smallholder Teak plantations remains largely underutilized despite its potential in composting applications. While it contributes to compost structure by enhancing aeration, its limited nutrient content restricts its value as a soil amendment. Studies suggest that *Rhizobium* microorganisms were known as nitrogen-fixing abilities could improve nutrient availability in compost. However, the impact of *Rhizobium* when combined with Teak wood sawdust and cattle manure remains underexplored. This study addresses evaluating the effects of different *Rhizobium* strains on nutrient enrichment in Teak wood sawdust compost. Specifically, it seeks to identify the most effective *Rhizobium* treatment for enhancing nitrogen and other key nutrients providing farmers with a locally sourced and sustainable alternative to chemical fertilizers.

## MATERIALS AND METHODS

The experiment was conducted from April to July 2024 at the demonstration farm and laboratory of the Faculty of Agriculture and Forest Resource, Souphanouvong University, Luang Prabang Province, Lao PDR. The materials used included Teak wood sawdust (4.9 kg, 50% w/w) and cattle manure (4.9 kg, 50% w/w). A total of 0.2 kg of 4 types of *Rhizobium* microorganisms were applied as shown in **Table 1**: soybean *Rhizobium*, mung bean *Rhizobium*, sunn hemp *Rhizobium*, and mung bean *Rhizobium* in liquid form. All *Rhizobium* strains were obtained from the Department of Agriculture, Agricultural Production Factors Research and Development Division, Thailand. Teak wood sawdust was sourced from local wood processing factories, while cattle manure was collected from the livestock farm at Souphanouvong University, Luang Prabang Province.

**Table 1**: treatments were used in this experiment

| Treatment | Teak wood sawdust (%) | Cattle manure (%) | *Rhizobium* source |
|---|---|---|---|
| $T_1$ | 50 | 50 | Without *Rhizobium* |
| $T_2$ | 50 | 50 | Soybean *Rhizobium* |
| $T_3$ | 50 | 50 | Mung bean *Rhizobium* |
| $T_4$ | 50 | 50 | Sunn hemp *Rhizobium* |
| $T_5$ | 50 | 50 | Mung bean *Rhizobium* was applied as a liquid culture |

### Procedure and data collection

The preparation process was demonstrated in **Figure 1**. The manure was crushed and mixed with sawdust according to the experimental design, then inoculated with 2% soluble *Rhizobium* and moistened to approximately 40-50% moisture content. The mixture was packed in 10 kg white plastic bags, sealed tightly to promote aerobic fermentation, and stored in the shade for 1.5 months. After fermentation, compost samples were randomized into 4 replicates for each treatment for compositional analysis.

a. *Rhizobium* microorganismes product

b. Preparation of Teak wood sawdust and cattle manure

c. Mixing and testing of moisture

d. The fermented compost in plastic bag

**Figure 1 (a – d)**: Procedures of compost fermentation using Teak wood sawdust, cattle manure mixed with *Rhizobium*

**Chemical analysis**

Composition analyses (DM, $N_2$, $P_2O_5$, $K_2O$, and ash) were conducted following AOAC (1990) methods. The pH was measured using a digital pH meter. For each sample, 5 g of compost was mixed with 25 ml of distilled water and allowed to incubate overnight to reach equilibrium and allow sedimentation. After incubation, the mixture was stirred briefly, and the pH was measured by immersing the pH meter electrode into the supernatant.

**Statistical analysis**

Data were analyzed using analysis of variance (ANOVA), and treatment means were compared using Duncan's Multiple Range Test (DMRT; P<0.05) for detect the significant grouping among the treatment. All data were analyzed using Minitab software 2000 (version 16).

## RESULTS AND DISCUSSION

The pH comparison was shown in **Table 2**. $T_3$ had the highest pH (7.19) indicating a more alkaline environment, this condition maybe simply explains due to activity of microbe in fermentation produced alkaline environment (Zheng *et al*., 2013), while $T_2$ had the lowest pH (6.21), suggesting greater acidity maybe cause from organic acid was produce during fermentation (Schlembach *et al*., 2020; Mahgoub *et al*., 2022). The OM content was significant difference across treatments with $T_4$ showing the highest OM content at 33.08%, suggesting its effectiveness in retaining organic matter. $T_2$ also had a relatively high OM content (33.01%). The control ($T_1$) had the lowest OM content at 32.41%. this highlight displayed *Rhizobium* strains showed minimal impact on OM variation (Guo *et al*., 2018).

The OM content was highest in the sunn hemp *Rhizobium* treatment ($T_4$: 33.08%), indicating a strong capacity of this *Rhizobium* strain to enhance OM retention in compost. This increase suggests that *Rhizobium* strains can significantly boost OM in compost by enhancing nutrient retention, soil structure, and microbial activity. When *Rhizobium* is combined with compost or other beneficial microorganisms, it not only increases soil organic carbon but also helps stabilize organic matter, creating a more fertile and resilient soil environment (Ben-Laouane *et al*., 2021). Previous report showed that *Rhizobium* can also accelerate decomposition and nutrient cycling, promoting better organic matter stability and supporting sustainable agricultural practices (Ju *et al*., 2019; Baral *et al*., 2012). The OM content varied significantly across treatments, with $T_4$ displaying the highest OM content at 33.08%, indicating a strong capacity of this strain to enhance organic matter retention. $T_2$ also had relatively high OM content (33.01%), while the control ($T_1$) showed the lowest OM content at 32.41%. Although these results suggested minimal impact of *Rhizobium* strains on OM variation (Guo *et al*., 2018), the higher OM levels in $T_4$ indicate that certain strains may enhance nutrient retention, soil structure, and microbial activity. When combined with compost, *Rhizobium* not only boosted soil organic carbon but also stabilized organic matter creating a more fertile soil environment (Ben-Laouane *et al*., 2021). Studies further reported that decomposition and nutrient cycling were accelerated by Rhizobium, promoting OM stability and supporting sustainable agricultural practices (Ju *et al*., 2019; Baral *et al*., 2012).

Nitrogen content was highest in $T_2$ (0.17%) with soybean *Rhizobium* indicating strong compatibility between this *Rhizobium* strain and the compost material. This increase in nitrogen is likely due to the highly efficient nitrogen-fixing ability of soybean-associated *Rhizobium*, particularly *BradyRhizobium japonicum*. This strain is well-documented for its hydrogenase systems (Meena *et al*., 2018), which recycle hydrogen to enhance nitrogen availability and promote plant growth (Bothe *et al*., 2010; Jaiswal *et al*., 2021). In comparison, *Rhizobium* strains associated with mung bean fix nitrogen at lower rates with effectiveness influenced by phosphorus availability and strain compatibility (Solaiman *et al*., 2003). Sunn hemp *Rhizobium*, while beneficial, generally exhibits even lower nitrogen fixation rates making it less effective than soybean for enhancing nitrogen content (Parvin *et al*., 2022). These findings underscore the advantage of soybean *Rhizobium* in boosting nitrogen levels in compost, supporting improved soil fertility. In case the higher nitrogen content in $T_1$ (without *Rhizobium*) compared to $T_3$ and $T_5$ (with mung bean *Rhizobium*) may be due to increased nitrogen loss in $T_3$ and $T_5$ from enhanced decomposition activity and microbial competition. The lower nitrogen content in the *Rhizobium*-treated compost may be due to nitrogen immobilization for microbial growth, limited nitrogen fixation without a host plant, potential nitrogen losses through volatilization, and increased microbial competition for nitrogen (Jackson and Firestone, 1989). These factors could collectively reduce nitrogen availability, resulting in a lower nitrogen content compared to the control (Unkovich and Pate, 2000). An appraisal of recent field measurements of symbiotic $N_2$ fixation by annual legumes. Additionally, mung bean *Rhizobium* strains may require specific conditions (Lindström and Mousavi, 2019), such as optimal pH or phosphorus levels, to fix nitrogen effectively (Tajini *et al*., 2012; Favero *et al*., 2021). Without these conditions, their nitrogen-fixing efficiency could be limited, leading to lower nitrogen content in $T_3$ and $T_5$.

The $P_2O_5$ and $K_2O$ contents showed significant variation across treatments. For $P_2O_5$, $T_3$ and $T_5$ exhibited the highest content at 0.36%, 0.34% respectively, which aligns with previous findings by Shome *et al*. (2022). who reported *Rhizobium japonicum* enhanced soil nitrogen content, which can indirectly improve phosphorus availability when used in conjunction with phosphate solubilizing bacteria, in contrast $T_2$ showed the lowest $P_2O_5$ content at 0.25%. For $K_2O$ content, $T_2$ showed the highest value at 0.94%, supporting by Sawale *et al*. (2024) reported that soybean *Rhizobium* strains can enhance potassium retention in organic substrates. $T_3$ exhibited the lowest $K_2O$ content at 0.56%. These differential effects align with Teotia *et al*. (2016) mentioned *Rhizobium* and other potassium-solubilizing bacteria played a significant role in enhancing potassium availability during fermentation processes. These microbes convert insoluble potassium forms in the soil into accessible forms, thereby improving plant nutrient uptake and reducing reliance on chemical fertilizers. Dry matter (DM) content was highest in $T_4$ (59.81%), showing that sunn hemp *Rhizobium* promotes a compost composition with lower moisture retention. This property may help prevent anaerobic conditions in the soil, which is beneficial for root health and microbial activity. Ash content was highest in $T_1$ (2.45%), which lacked *Rhizobium*, suggesting that *Rhizobium* addition influences mineral residue content in compost.

**Table 2**: The chemical composition of compost used in the Teak wood sawdust and cattle manure with different *Rhizobium* microorganisms

| No | Items | Treatments | | | | | SEM | *P* |
|---|---|---|---|---|---|---|---|---|
| | | $T_1$ | $T_2$ | $T_3$ | $T_4$ | $T_5$ | | |
| 1 | **pH** | 6.53 $^b$ | 6.22 $^e$ | 7.18 $^a$ | 6.48 $^c$ | 6.33 $^d$ | 0.0058 | 0.001 |
| 2 | **OM (%)** | 32.41 $^e$ | 33.02 $^b$ | 32.69 $^d$ | 33.08 $^a$ | 32.82 $^c$ | 0.0049 | 0.001 |
| 3 | **N (%)** | 0.11 $^c$ | 0.17 $^a$ | 0.08 $^d$ | 0.12 $^b$ | 0.08 $^d$ | 0.0033 | 0.001 |
| 4 | **$P_2O_5$ (%)** | 0.26 $^d$ | 0.25 $^e$ | 0.36 $^a$ | 0.31 $^c$ | 0.34 $^b$ | 0.0033 | 0.001 |
| 5 | **$K_2O$ (%)** | 0.67 $^b$ | 0.94 $^a$ | 0.55 $^e$ | 0.63 $^c$ | 0.57 $^d$ | 0.0033 | 0.001 |
| 6 | **DM (%)** | 47.32 $^d$ | 43.77 $^e$ | 54.21 $^b$ | 59.81 $^a$ | 50.67 $^c$ | 0.0063 | 0.001 |
| 7 | **Ash (%)** | 2.45 $^a$ | 1.86 $^e$ | 1.98 $^c$ | 2.24 $^b$ | 1.92 d | 0.0067 | 0.001 |

*Note: Means ± standard error of the mean analyzed by ANOVA. Different letters within each row indicate significant differences at $P<0.05$ based on DMRT. OM: Organic matter; DM: Dry matter; N:Nitrogen ; $P_2O_5$:phosphorus ; $K_2O$:potassium*

## CONCLUSION

In summary, it can be concluded that compost fermented with *Rhizobium* microorganisms showed enhanced nitrogen content with variations observed across different *Rhizobium* species. The compost inoculated with soybean-associated *Rhizobium* demonstrated the highest nitrogen increase, outperforming the control by 35%, indicating that this strain is particularly effective in nitrogen enrichment. Furthermore, variations in phosphorus and potassium content across treatments suggest that specific *Rhizobium* strains may also improve other essential nutrients in compost, contributing to a more balanced nutrient profile for soil applications. These findings highlight the potential of *Rhizobium*-enhanced compost for sustainable agriculture, especially for smallholder farmers in Laos PDR. Using locally sourced materials like Teak wood sawdust and cattle manure, *Rhizobium*-enriched compost can reduce reliance on costly chemical fertilizers, lower production costs, and lessen environmental impact. Additionally, it supports soil health through enhanced microbial activity, nutrient retention, and organic matter stability. Adopting *Rhizobium*-based compost offers an eco-friendly, cost-effective solution for boosting crop yields and advancing sustainable soil management. Further research on its effects across crop types and soils is recommended to validate these benefits for wider agricultural use.

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## REFERENCES

Akinrinde, A. E. 2006. *Soils: Nature, fertility conservation and management*. Agronomy Department, University of Ibadan, Ibadan, Nigeria:1.

AOAC. 1990. *Official methods of analysis.* 15th ed. AOAC, Washington, D.C.

Baral, B., Bhattarai, N., and Shrestha, G. 2012. Microbial effectiveness through vermicomposting technique for the biological stabilization of solid waste. *Journal of Natural History Museum* 26:126-135.

Ben-Laouane, R., Ait-El-Mokhtar, M., Anli, M., Boutasknit, A., Ait Rahou, Y., Raklami, A., Oufdou, K., Wahbi, S. and Meddich, A. 2021. Green compost combined with mycorrhizae and rhizobia: A Strategy for improving alfalfa growth and yield under field conditions. *Gesunde Pflanzen* 73: 193-207.

Bothe, H., Schmitz, O., Yates, M.G., and Newton, W.E. 2010. Nitrogen fixation and hydrogen metabolism in cyanobacteria. *Microbiology and molecular biology reviews* 74(4): 529-551. Burns, R. C., and Hardy, R. W. F. 1975. *Nitrogen fixation in bacteria and higher plants*. New York, N.Y: Springer-Verlag.

Favero, V.O., Carvalho, R.H., Motta, V.M., Leite, A.B.C., Coelho, M.R.R., Xavier, G.R., and Urquiaga, S. 2021. *Bradyrhizobium* as the only rhizobial inhabitant of mung bean (*Vigna radiata*) nodules in tropical soils: A strategy based on microbiome for improving biological nitrogen fixation using bio-products. *Frontiers in Plant Science* 11:602645.

Guo, Y., Matsuoka, Y., Nishizawa, T., Ohta, H., and Narisawa, K. 2018. Effects of *Rhizobium* species living with the dark septate endophytic fungus veronaeopsis simplex on organic substrate utilization by the host. *Microbes and environments* 33(1): 102-106.

Jackson, L.E., Schimel, J.P., and Firestone, M.K. 1989. Short-term partitioning of ammonium and nitrate between plants and microbes in an annual grassland. *Soil biology and Biochemistry* 21(3): 409-415.

Jaiswal, S.K., Mohammed, M., Ibny, F.Y., and Dakora, F.D. 2021. *Rhizobia* as a source of plant growth-promoting molecules: potential applications and possible operational mechanisms. *Frontiers in Sustainable Food Systems* 4: 619676.

Jang, L ., and Lorchamyer, C. 2013. *Fertilization patterns on the yield of Guangdong cabbage,* Department of Plant Science, Faculty of Agriculture and Forestry, Souphanouvong University: 24-33.

Ju, W., Liu, L., Fang, L., Cui, Y., Duan, C., and Wu, H. 2019. Impact of co-inoculation with plant-growth-promoting *Rhizobacteria* and *Rhizobium* on the biochemical responses of alfalfa-soil system in copper contaminated soil. *Ecotoxicology and Environmental Safety* 167: 218-226.

Keovilaysak, V., and Silivong, P. 2023. Effect of different level of cattle manure on growth performance and chemical composition of sweet grass. *Souphanouvong University Journal of Multidisciplinary Research and Development* 9(3):113 - 121.

Laoh, S., Lorchamyer, C., Silivong, P., and Preston, T.M. 2016. Effect of biochar and compost on growth of water Spinach (*Ipomoea aquatic*) and soil fertility, *Faculty of Agriculture and Forest Resource, Souphanouvong University, LuangPrabang Province, Lao PDR*: 37-38.

Lehmann, J. 2007. A handful of carbon. *Nature* 447: 143 - 144.

Lindström, K., and Mousavi, S.A. 2020. Effectiveness of nitrogen fixation in *Rhizobia*. *Microbial biotechnology* 13(5): 1314-1335.

Lorchamyer, C., Silivong, P., and Preston, T.M. 2017. Effect of biochar and compost on growth performance of water spinach, *Faculty of Agriculture and Forest Resource, Souphanouvong University, LuangPrabang Province, Lao, PDR:* 3-5.

Mahgoub, S.A., Kedra, E.G., Abdelfattah, H.I., Abdelbasit, H.M., Alamoudi, S.A., Al-Quwaie, D.A., Selim, S., Alsharari, S.S., Saber, W.I., and El-Mekkawy, R.M. 2022. Bioconversion of some agro-residues into organic acids by cellulolytic rock-phosphate-solubilizing *Aspergillus japonicus*. *Fermentation* 8(9): 437.

Mandimba, G.R. 1995. Contribution of nodulated legumes on the growth of *Zeamays* L. under various cropping systems. *Symbiosis* 19: 213-222.

Manivanh, N., Preston, T.R., An, L.V., and Thu Hong, T.T. 2018. Improving nutritive value of cassava root (*Manihot esculenta* Crantz) by fermentation with yeast (*Saccharomyces cerevisiae*), urea and di-ammonium phosphate. *Livestock Research for Rural Development. Volume 30, Article #94.* Retrieved September 17, 2023, from http://www.lrrd.org/lrrd30/5/noup30094.html

Meena, R.S., Vijayakumar, V., Yadav, G.S., and Mitran, T. 2018. Response and interaction of Brady*Rhizobium* japonicum and arbuscular mycorrhizal fungi in the soybean rhizosphere. *Plant Growth Regulation* 84: 207-223.

Mugwira, L.M., Nyamangara, J., and Hikwa, D. 2002. Effect of manure and fertilizer on maize at a research station and in a smallholder area of Zimbabwe. *Communications in Soil Science and Plant Analysis* 33: 379 - 402.

Musvota, C., Compbell, B.M., and Kirchmannm, H. 2000. Decomposition and nutrient release from mango and miombo litter in Zimbabwe. *Soil Biology and Biochemistry* 32: 1111 - 1119.

Parvin, S., Condon, J., and Rose, T.J. 2022. Potential nitrogen contributions by tropical legume summer cover crops in mediterranean-type cropping systems. *Nitrogen* 3: 592–599.

Paul, E.A., & Wilson, J.R. 1988. Towards the year 2000: directions for future nitrogen research. In *Advances in Nitrogen Cycling in Agricultural Ecosystems conference* (p. 417–425). Wallingford, UK: CAB International.

Peoples, M.B., Herridge, D.F., and Ladha, J.K. 1995. Biological nitrogen fixation: an efficient source of nitrogen for sustainable agricultural production. *Plant Soil*: 174-328.

Sawale, S.K., Pawar, A.S., and Phirke, N.V. 2024. Evaluation of plant growth promoting traits of Soybean (*Glycine max* L.) root nodulating *Rhizobium* and it's characterization. *Ecology, Environment and Conservation (0971765X)*, *7*.

Schlembach, I., Hosseinpour Tehrani, H., Blank, L. M., Büchs, J., Wierckx, N., Regestein, L., and Rosenbaum, M.A. 2020. Consolidated bioprocessing of cellulose to itaconic acid by a co-culture of *Trichoderma reesei* and *Ustilago maydis*. *Biotechnology for Biofuels* 13: 1-18.

Schoot, H., and Uiterkamp, A.J.M. 1990. *Nitrogen cycling and human intervention*. *In: Gressh off P M, Roth L E, Stacey G, Newton W E, editors. Nitrogen fixation: achievements and objectives.* New York, N.Y: Chapman and Hall: 55 - 66.

Seansouk, P. 2000. Management of animal waste (cow dung) in making compost for planting vegetables, *Faculty of Plant Sciences, University of Agriculture, Thailand*: 45-49.

Solaiman, A.R.M., and Haque, M.M. 2003. Responses of mungbean varieties to *Rhizobium* inoculation in respect of nodulation, nitrogenase activity, dry matter yield, and nitrogen uptake. *Korean Journal of Crop Science* 48(5): 355-360.

Sprent, J.I., and Sprent, P. 1990. *Nitrogen fixing organisms. Pure and applied aspects.* London, United Kingdom: Chapman and Hall.

Swift, M.J. 1987. *Integration of nutrient cycling in the plant soil system; the role of the biological processes. In: Amelioration of soil by tree: A review of current practice Eds.* Prinsley R T and Swift M J. Commonwealth Science Council, London.

Tajini, F., Trabelsi, M., and Drevon, J.J. 2012. Combined inoculation with *Glomus intraradices* and *Rhizobium tropici* CIAT899 increases phosphorus use efficiency for symbiotic nitrogen fixation in common bean (*Phaseolus vulgaris* L.). *Saudi journal of biological sciences* 19(2): 157-163.

Teotia, P., Kumar, V., Kumar, M., Shrivastava, N., and Varma, A. 2016. Rhizosphere microbes: potassium solubilization and crop productivity-present and future aspects. *Potassium solubilizing microorganisms for sustainable agriculture*: 315-325.

Unkovich, M.J., and Pate, J.S. 2000. An appraisal of recent field measurements of symbiotic $N_2$ fixation by annual legumes. *Field Crops Research 65*(2-3): 211-228.

Viera, V.M.S., Souto, C.M., Urquiaga, S., and Boddey, R.M. 1995. Quantification of the contribution of $N_2$ fixation to tropical forage legumes and transfer to associated grass. *Soil Biol Biochem* 27:1193-1200.

Zheng, X., Su, Y., Li, X., Xiao, N., Wang, D., and Chen, Y. 2013. Pyrosequencing reveals the key microorganisms involved in sludge alkaline fermentation for efficient short-chain fatty acids production. *Environmental Science and Technology*, *47*(9):4262-4268.