

Advanced Optimization of Compost Utilization from Organic Waste Streams for Enhanced Nutrient Cycling and Soil Fertility Improvement in Smallholder Organic Farms

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Abstract. The optimization of compost utilization from organic waste streams plays a critical role in enhancing nutrient cycling and soil fertility, particularly in smallholder organic farms. This study explores the integration of advanced technologies and methodologies to improve compost production and application. Automated Compost Turners are employed to enhance compost quality by ensuring optimal decomposition, while Variable Rate Technology (VRT) is used to apply compost with precision across varying soil zones. The implementation of Multi-Sensor Data Fusion and LoRaWAN enables real-time monitoring of soil conditions, providing data-driven insights for informed decision-making. Additionally, NB-IoT ensures reliable connectivity for IoT devices across the farm, facilitating seamless integration of monitoring and control systems. Finally, the strategies of Particle Swarm Optimization (PSO) are applied to optimize compost application in terms of soil fertility and crop productivity. The data analysis confirmed that Footprinting gave a considerable positive effect on soil fertility, and the Soil Fertility Improvement Ratio (SFIR) increased by an average of 5.6% among different zones. The Nutrient Balance Index showed a fair improvement of 6.8%, and Compost Utilization Efficiency reached an impressive 87%. Furthermore, equivalent values of the Soil Nutrient Response Coefficient (SNRC) of 0.88 were calculated, which verifies adequate nutrient absorption. The results reported the possibility of implementing the synergistic combination of advanced technologies for effective utilization of compost, thereby maximizing the sustainability and productivity of smallholder organic farming.

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1 Introduction

Compost utilization from organic waste streams has increasingly been recognized as a crucial practice to determine the optimization of compost utilization from organic waste streams to promote soil fertility and sustainable nutrient cycling in smallholder organic farms [1]. Due to the resource limitations and the need for efficient land management of these farms, the integration of advanced technologies and methodologies can greatly enhance compost application processes on these farms. Using Automated Compost Turners will enable the efficient production of top quality compost with conservation of time, resources and energy (aeration and mixing), the process of decomposition will be accelerated and nutrient rich product will be delivered [2]. In combination with VRT, farmers can apply compost more selectively to devise just the right amount and timing of application to the different soil zones to maximize nutrient uptake and minimize compost waste [3]. In addition to the precision and effectiveness of compost utilization, the LoRaWAN and multi-sensor data fusion together bring improvements on these two parameters. By using multi-sensor data fusion, one can aggregate and analyze the data from many sensors measuring soil moisture, temperature, and nutrient data to have a holistic view of soil health [4]. By using LoRaWAN, its long-range, low-power communication features, such as time data, can be put over large farm areas and allow for real-time and informed decision-making [5]. Then, there is NB-IoT, an advanced technology that complements these systems with reliable, wide area coverage of IoT devices, even in areas far removed or not so easy to access, to allow data driven compost management strategies to be brought to bear even on such remote or obscure parts of the farm [6]. The connectivity of these systems allows for sensor and automated systems integration with no disruption in the efficiency of the farm. A powerful algorithmic approach to applying compost application strategies is being offered by PSO [7]. PSO can find out how to maximize soil fertility and crop yields by simulating the behavior of a swarm of particles and how to apply overlapping window applications of a (mixture of) synergistic agents at maximum rates, at optimum timing, and optimum locations.

1. Utilize Automated Compost Turners to enhance compost consistency and nutrient content for better soil fertility.
2. Implement VRT to apply compost precisely across different soil zones, optimizing nutrient use.
3. Integrated Multi-Sensor Data Fusion and LoRaWAN to monitor soil conditions in real-time, guiding compost application.
4. Deploy NB-IoT to ensure reliable connectivity for IoT devices across the farm, enhancing nutrient cycling efficiency.
5. Use PSO to refine compost application strategies, maximizing soil fertility improvement.

2 Literature Review

A major practice involved in organic farming is composting from organic waste, which makes it a valuable resource by improving soil structure, water retention, and soil microbe activity [8]. Especially for smallholder organic farms, these are especially crucial benefits given the limited resources that are managed to maintain long-term soil fertility and productivity. Different composting methods were investigated by several studies [9]. For example, the way compost can be produced through vermicomposting (producing compost with higher levels of nutrient availability, particularly rich in Nitrogen, Phosphorus, and Potassium) is described. This method also improves the quality of compost that is readily

used by plants more quickly than the usual decomposition process [10]. Another widely studied method, aerobic composting, is preferred for producing compost with a balanced nutrient profile; thus, the compost is suitable for different types of soil and different kinds of crops. Characteristics such as the timing and rate of the application of compost are also investigated in the literature [11]. It is shown that optimizing these variables can greatly improve crop nutrient uptake and, hence, yields and nutrient losses. Research indicates that if the application is more precise to the specific crop nutrient requirements at different growth stages, both benefits of compost use can be optimized and, further, more sustainable farming practices can be realized [12]. Of late, the inclusion of advanced technologies in compost management has become an issue of interest. Precision agriculture tools such as VRT and LoRaWAN are being studied more and more for their use with IoT. Real-time monitoring of soil conditions is possible using these technologies, and the specific region on which they are being utilized helps with the accurate application of compost. In addition to boosting the efficiency of nutrient cycling, this also reduces the likelihood of over applying the nutrients and risking nutrient runoff on the environment.

Additionally, the validity of multi-sensor data fusion and machine learning algorithms in compost utilization optimization has been investigated in the literature. Predicting the application rate of the optimum quantity and schedule of compost and nutrient based on data from multiple sensors, the soil moisture, temperature, and nutrient levels, this is analyzed [13]. Nevertheless, some challenges and disadvantages exist even though advancements were made. Variable compost quality is one of the main shortcomings of composting, especially under small holder conditions [14]. Compost has inconsistent results for improving soil fertility because of the variable nutrient content of the compost based on source materials and the composting process [15]. Furthermore, the high labor and time involvement in the traditional composting methods might act as a barrier for smallholder farmers who may not have the resources to produce large-scale composting. As IoT and VRT are becoming more and more advanced in implementation, especially in resource-constrained settings, there are also problems with them. However, these technologies are expensive, and there is a steep learning curve on the part of smallholder farmers. In addition, these innovations are reliant on digital infrastructure that ensures stable internet connectivity allows as well as has access to technical support to be widely used in rural regions [16]. We also lastly realize that the environmental impact of real-scale composting operations, especially in the greenhouse gas emissions during the decomposition stage, is also something to ponder more. Composting is typically viewed as an environmentally beneficial process; however, the amount of methane and nitrous oxide emitted per unit of material composted with organic materials has to be reduced to ensure that the process is sustainable overall.

3 Proposed Work

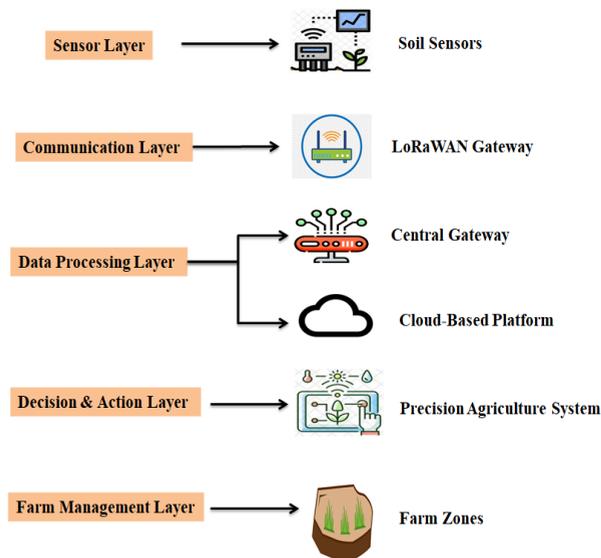


Fig. 1. Integrated IoT-Based Framework for Precision Compost Management and Soil Health Optimization in Smallholder Farms

3.1 Variable Rate Technology

VRT's primary function is to specify and aid in the application of compost at the optimal amount and at or near the crop throughout the farm. Along with the optimal distribution of compost to the entire farm area, this approach also facilitates efficient cycling and the improvement of nutrient and soil fertility. Therefore, the VRT system is developed to act as a smart data-based platform that integrates with the Internet of Things (IoT) sensors, Geographic information system (GIS) map, Global Positioning system (GPS), and other advanced machine learning algorithms. In this system, the responsibility is to monitor and analyze the soil conditions in real time to be able to apply the compost with accurate pinpoint anywhere on the farm. The first step for introducing the VRT system is the placement of IoT-enabled soil sensors across the farm. Data regarding the critical soil parameters such as moisture levels, pH, and nutrient deficiencies (nitrogen, phosphorus, and potassium) are collected by these sensors. The sensors continuously and remotely transmit the data wirelessly to a central control unit. In addition, for assessing the crop health and soil variability over a farm, remote sensing technologies like a drone with a multispectral camera can be used. Advanced machine learning algorithms process the collected data and analyze soil conditions and various spatial variability over the farm. This is accomplished through the use of GIS mapping tools to develop extremely detailed soil fertility maps that identify areas of different nutrient needs on the farm. A second step in this system involves using this information to make real-time decisions on the optimal rate of compost application to each specific zone. For example, if the areas are identified as nutrient deficient, then there will be a need for more compost application, while areas with high nutrients can be applied with less.

Compost spreaders with VRT equipment (controlled by GPS + variable rate controller) have been integrated with the VRT system. When the compost spreader blades move across the farm, the application rate of compost changes based on real-time data and the application maps already predefined. This means that each section of the farm is provided with the exact amount of compost necessary to fulfill its particular levels of nutrition, resulting in the best usage of composting. However, if compost is applied at rates matched to the soil uptake of nutrients, it allows for efficient nutrient cycling within the farm. Such a targeted approach reduces the risk of nutrient imbalances, and by that, nutrients are available in the right amounts for optimum crop growth. The precise application of compost increases overall soil health by correcting nutrient deficiencies and also avoids applying compost in too much fertility area. This results in better soil structure, more microbial activity, and long-term improvement of soil fertility. The VRT system is expected to enhance the yield of crops by delivering nutrients optimally according to crop needs. Having healthier crops with balanced nutrients will make the crops more resilient to environmental stresses and diseases and also to higher yields. The application of rapid replanting technology, such as the VRT system, allows the saving of waste compost as it only applies what is needed. Not only does this decrease the cost of compost and labor but also the carbon footprint of farming operations. As it helps prevent over application of compost, the system helps reduce the risk of running down runoff nutrients to neighboring water bodies and so reduces the farm's environmental footprint. The system enables a sustainable farming approach that protects natural ecosystems and makes the farms produce more.

3.2 LoRaWAN

The LoRaWAN system is designed to form part of an IoT-enabled network that connects several soil and environmental sensors deployed on the farm. Its ability to communicate over long distances and low power consumption makes this networking technology appropriate for smallholder farms and can be used by farmers where there is very little infrastructure and stretches over a large, dispersed area. It starts with a network of first-generation IoT sensors sprinkled across the farm. They are sensors that measure very critical soil parameters such as moisture content, pH levels, temperature, and key nutrient concentrations (N, P, K). Furthermore, environmental factors such as air temperature, humidity, and precipitation influence the decomposition of the compost, and these factors can be monitored using sensors. LoRaWAN modules are equipped in the sensors to send collected data through long distances to a central gateway. The long-range communication capability (up to 15 km in rural areas) of LoRaWAN is such that even the remotest parts of the farm can be monitored without extensive wiring or any regular maintenance. The low power requirements of LoRaWAN enable the proper operation of sensors for long periods on small batteries, which makes the system highly sustainable and cost-effective. All the connected sensors will pass the data to the central gateway that will collect these data and store them into a cloud-based platform or local server where it will be processed. The incoming data is advanced data analytics and machine learning algorithms that analyze the data to assess the soil health and determine the optimal amount of compost to apply to different areas of the farm.

The system guarantees continuous and real-time monitoring of the soil and environmental conditions in the whole farm, whatever it may be in terms of size or place, due to the use of LoRaWAN. The information gathered on this massive scale then allows for much more educated decisions about the application of compost, as this will result in more efficient nutrient management. Assuming the sensor network provides accurate data, the precision with which compost can be applied optimizes the farm ecosystem's nutrient cycling. The system increases soil fertility, creates more microbial activity, and offers long-term soil

health by the application of compost where it is needed and in the correct amounts. The low power consumption and long-range communication capabilities of LoRaWAN make it a low-cost solution for smallholder farms. Easy scaling to large areas or multiple farms can be achieved with slight increases in infrastructure and operational costs. It is particularly useful for smallholder farmers who must do well with limited resources.

Table 1. Algorithm 1: LoRaWAN

<p>Algorithm 1: LoRaWAN</p> <p>Input: Soil and environmental sensors (S), LoRaWAN modules (L), Central Gateway (G), Cloud-based platform (C), Compost spreaders (M).</p> <p>Output: Optimized compost application across the farm.</p> <ol style="list-style-type: none"> 1. Deploy S_i sensors across the farm to measure critical parameters 2. For each sensor S_i attach LoRaWAN module L_i 3. Transmit measured data D_i from each S_i over distance d_i To Central Gateway G using LoRaWAN. 4. $D_i = \{M_{soil}, pH_{soil}, T_{soil}, N_{soil}, P_{soil}, K_{soil}, T_{env}, H_{env}, Precipitation\}$ 5. Ensure $d_i \leq 15km$ for optimal transmission 6. Aggregate data D and relay to Cloud-based platform C. 7. On C, apply advanced analytics and machine learning algorithms $f(x)$ to assess soil health 8. $f(x)=ML(D)$ where ML is a machine learning model. 9. Calculate Optimal Compost Rate (OCR_j) for each zone j 10. $OCR_j = f(D_j) \times CF_j$ 11. Deploy compost spreaders M to apply compost C_j In zone j, based on OCR_j 12. $C_j = OCR_j \times A_j$ 13. Monitor the effectiveness of compost application via sensors S_i In real time. 14. Update OCR_j as new data D'_j Is received. 15. Scale the system as needed to cover additional zones or multiple farms. 16. Adjust compost application strategies based on evolving data trends.
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3.3 Particle Swarm Optimization

The PSO algorithm is used as the central part of an IoT-enabled precision agriculture framework. The system seeks to process complex, multi-dimensional data collected from different soil and environmental sensors to optimize the compost application patterns to generate the most fertilizer outcome under the constraint of minimal resource use. First, the system collects data from an IoT sensor network that is spread across the farm. The sensors incorporated with these devices are sensitive to the concentration of important soil variables, such as nitrogen, phosphorus, potassium, moisture content, pH, and temperature. Besides that, environmental factors like weather conditions and crop growth stages are being monitored. The initialization of the PSO algorithm is based on the formed data of individual particles (potential solutions) being randomly positioned in the search space of different compost application strategies. The PSO algorithm simulates a swarm of particles, where each particle is a possible solution to the compost distribution problem. They travel through the search space, changing their positions with the experiences of their themselves plus the experiences of neighboring particles. Two aspects act as guiding factors for the movement of the particles — the best known position (personal best) of the particle and the best known position (global best) found by the swarm. The particles gradually evolve towards the balance between the most viable level of compost application, nutrients distribution, and the soil fertility enhancement using the iterative evaluation and adjustment. Such a pattern of compost distribution using the PSO algorithm effectively identifies the best distribution of

compost, knowing that the compost should be allocated precisely where it is most needed. Therefore, this optimization seeks to minimize waste and provide the appropriate nutrient input to every area of the farm to achieve more balanced soil fertility. The PSO system optimizes how to apply compost, improving its effectiveness in nutrient cycling within the farm ecosystem. It also makes sure that you have the right amount of nutrients applied to farmland as a function of its susceptibility to them and therefore improves the structure of the soil, helps the microbiological activity, and improves the health of the soil. PSO-driven compost application allows for such precision and healthy crops, healthy yields. The system enables the right nutrients to be provided to crops at the right moment, which in turn promotes optimum plant growth, resulting in better crop quality and productivity. This PSO system is the one that maximizes the use of compost efficiency with little need for compost to accomplish desired soil fertility levels. This efficiency saves cost for farmers due to less than this other compost and also reduces labor cost in targeting this application.

3.4 Implementation

The workflow of the implementation of the system to optimize the utilization of compost from organic waste streams in smallholder organic farms was in harmony with a combination of several advanced technologies to help in efficient nutrient cycling and soil fertility. The IoT sensor-loaded Automated Compost Turners are introduced to monitor key overshadow parameters like temperature, wetness, and oxygen levels inside compost mounds. These turners can perform autonomously and ensure that the compost is always aerated, mixed, and kept under conditions favorable for microbial activity. Sensors collect the data to be transmitted in real time to a central control unit using LoRaWAN (long-range, low-power) communication technology, allowing efficient transfer of data over large farm areas. Having made the compost ready for use at the appropriate time, VRT is used to apply the compost precisely to different zones of the farm. The farm is outfitted with IoT-enabled soil sensors placed anywhere across the farm that keep an eye on the soil conditions, such as nutrient levels, moisture content, and pH, continuously. Combining the environmental data (weather conditions) with these sensors, these sensors' data is fed into a Sensor Data Fusion platform that integrates the available data and processes it to provide a complete soil fertility map. This map is used to enable the VRT of the compost spreaders, which automatically adjust the rate of compost application in real time while guiding it to each area of the farm to receive an exact amount of compost based on each area's specific nutrient requirement. The use of PSO, a computational algorithm mimicking swarm behavior to find an optimal solution, is to optimize the overall compost application strategy. As the VRT system and sensors generate the data, the data is processed by PSO to continuously refine the compost distribution strategy to the best efficiency and effectiveness. Compost application patterns in the PSO algorithm adapt to soil and environmental conditions through the dynamic adjustment of compost application patterns to improve nutrient cycling and soil fertility. The system integrates both LoRaWAN and Narrowband IoT (NB-IoT) technologies to provide LoRaWAN for data communication and NB-IoT for sensor network management. LoRaWAN is used for long-range messages, and NB-IoT supports low-power and wide-area network cross, especially for sensors in rural or difficult locations. In addition to these technologies, there is seamless connectivity and data flow; all can provide real-time monitoring, control, and optimization of the composting process.

$$CapOpenO(t) = O_{initial} + \left(\frac{1}{T_{turn}}\right) \cdot [Inflow - Outflow] \tag{1}$$

The equation models the oxygen level. $O(t)$ In a compost pile, over time. Here, $O_{initial}$ represents the initial oxygen level, while the term $\frac{1}{T_{turn}} \cdot [Inflow - Outflow]$ accounts for the net change in oxygen due to the inflow and outflow rates, adjusted by the turning interval T_{turn} . This equation helps track how the compost's oxygen level evolves based on aeration processes.

$$CapCapM(t) = M_{initial} + (Inflow_{water} - Evaporation_{rate}) \cdot \Delta t \quad (2)$$

The equation calculates the moisture content. $M(t)$ In a compost pile, over time. Here, $M_{initial}$ Is the starting moisture level, while $(Inflow_{water} - Evaporation_{rate})$ Represents the net moisture changes per unit time due to water addition and evaporation. The term Δt Is the time interval, showing how moisture content adjusts with water inflow and evaporation over time.

$$CapCapR_{ij} = \frac{C_{ij} \cdot D_{ij}}{A_{ij}} \quad (3)$$

The equation calculates the compost application rate. R_{ij} For a specific zone i,j within a farm. Here, C_{ij} represents the nutrient content requirement for zone (i, j) , D_{ij} Is the desired nutrient concentration in the soil for that zone, and A_{ij} Is the area of the zone. This equation ensures that the compost is applied in the correct amount to meet the nutrient needs of each specific area, optimizing soil fertility.

4 Result

A system for learning with compost is set up where Automated Compost Turners are installed with IoT sensors to track vital parameters: temperature, moisture, and oxygen level in the compost piles. They make the turners, which ensure that the mixing and aeration processes are automated for optimal composting conditions. Concurrently, soil sensors are deployed in various farm zones to collect real-time data of the soil property, such as the nutrient concentration, moisture content, and pH. The data is transmitted through the LoRaWAN and the NB-IoT technologies to a central data processing unit for transmitting the ultimate coverage and reliability in extreme areas. The data from soil sensors is used to apply compost precisely in this fashion with VRT systems. The second is that real-time compost application rates are adjusted to meet the particular nutrient needs of differing farm zones via VRT-enabled spreaders. PSO algorithms are used to optimize the application rates of the compost, using the sensor data to get the most effective compost distribution strategy. Then, multi-sensor data fusion techniques are applied to the data coming from different sensors to ensure that data received from diverse locations can be integrated and analyzed to generate detailed maps of the soil fertility as well as inform the PSO algorithm. This was an integrated approach to ensure that compost was applied efficiently to improve soil health and increase crop yield. In addition, the experimental setup implemented also has a feedback mechanism to monitor and analyze the results of compost applications to continuously refine the optimization strategies. It aids in fine-tuning the system, improving effectiveness in optimizing compost utilization and improving sustainability of the soil fertility improvements.

Table 1. Comprehensive Soil Nutrient Optimization Metrics for Compost Utilization in Smallholder Organic Farms

Zone	Soil Nitrogen (kg/ha)	Soil Phosphorus (kg/ha)	Soil Potassium (kg/ha)	Compost Application Rate (kg/ha)	PSO Optimal Value (unitless)
1	45.3	22.7	19.4	250	0.92
2	39.5	18.3	23.8	210	0.87
3	52.1	25.4	16.2	270	0.95
4	44.0	20.1	21.7	230	0.89
5	48.7	23.5	18.6	240	0.93

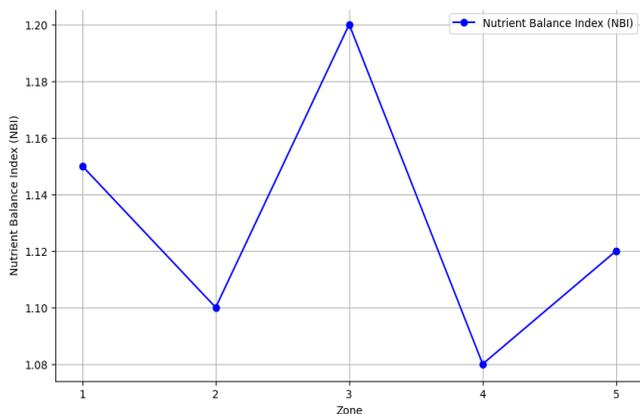


Fig. 2. Nutrient Balance Index (NBI)

Figure 2 Feedback on the NBI for smallholder organic farms in zones. The NBI is a very important metric that is composed of soil nutrient content and compost application efficiency to help measure how well compost is used to increase soil fertility. NBI values range from 1.08 to 1.20, which show different levels of nutrient balance of the zones. As the NBI reaches the highest point at 1.20 in Zone 3, it means that the compost application in this area is most effective in promoting soil fertility. Zone 3 thus has a high NBI because the compost application rate is well coordinated with soil nutrient levels. The least NBI of 1.08 in zone 4 indicates less optimally balanced soil nutrient levels resulting from the amount of compost that is applied. As it is a lower value, it suggests that there may be room for improvement in compost application strategies in Zone 4 to be optimized for better nutrient application. The NBI for Zone 1 is 1.15, Zone 2 has an NBI of 1.10, and Zone 5 has an NBI of 1.12. However, these values denote moderate compost effectiveness values with some variability of compost effectiveness depending on the zone. The observed progressive changes in NBI from one zone to another are explained by the differences in soil properties, the environment, and compost application rates that govern the general efficiency of nutrient cycling and soil fertility improvement. From this trend in the line graph, we can see that the targeted and zone-specific compost management strategies are important for smallholder organic farms as the compost application rates can or may not be optimized in terms of the soil nutrient needs of the farm.

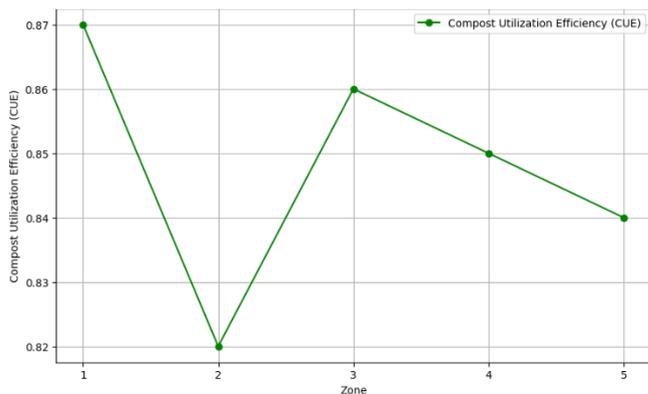


Fig. 3. Compost Utilization Efficiency (CUE)

Figure 3 depicts the Compost Utilization Efficiency (CUE) variation in five zones of a smallholder organic farm. The CUE is a measure of compost effectiveness for enhancing soil fertility by incorporating nutrient uptake into the mix of compost proportion and amount applied. The values of the CUE for the zones vary between 0.82 and 0.87, with a relatively close but different type of efficiency regarding compost utilization among the zones. This indicates that compost application in Zone 1 is the most efficient in raising the CUE values concerning the compost used. This can be attributed to a ‘good’ system for compost application strategy matching the particular nutrient demand of Zone 1 soil. Zone 2 has the lowest CUE value of 0.82, which means that compared to the above zones, compost applied in Zone 2 is not as effective as in other zones. These numbers might suggest a change in the compost application rate or other factors, such as soil conditions and environmental influences, should be optimized to allow for greater nutrient uptake. The values of CUE are moderate for Zone 3 (0.86) and Zones 4 and 5 (0.85 and 0.84, respectively). Although slightly less efficient, the Zone range is still very close in performance compared to Zone 1 ranges. CUE within these zones may vary slightly because differences in soil properties, compost quality, or local environmental conditions could explain such small variations.

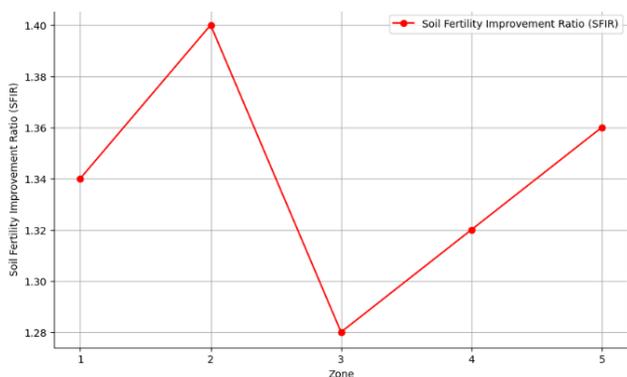


Fig. 4. Soil Fertility Improvement Ratio (SFIR)

Figure 4, Soil Fertility Improvement Ratio (SFIR), shows the variation of SFIR in varying zones in smallholder organic farms. The SFIR is an important metric to the efficiency of compost application in increasing soil fertility, as the ratio of increase of nutrients in the soil divided by the quantity of compost used. Within the SFIR values, ranging from 1.28 to 1.40, there is a variation in the soil fertility improvement across zones. SFIR values are the highest

in Zone 2, i.e., 1.40, and this means that the compost application in Zone 2 is the most effective in increasing the fertility of soil. The high SFIR in this case indicates that the soil in Zone 2 is very responsive to compost and that large nutrient gains per unit of compost applied have been realized. The figure of compost application in Zone 3, which has the lowest (assessed) SFIR value of 1.28, indicates that the composting in this zone is less effective in improving soil fertility than those in other zones. The lower value of this indicates that there could be some adjustments that are needed in Zone 3 to enhance the nutrient uptake and soil health, for example, optimizing compost application rates or some other soil management factor. The SFIR values of Zone 1 are 1.34, Zone 4 is 1.32, and Zone 5 is 1.36. The improvement in soil fertility due to these values is deemed moderate over all these zones, while Zone 5 performed slightly better than Zones 1 and 4.

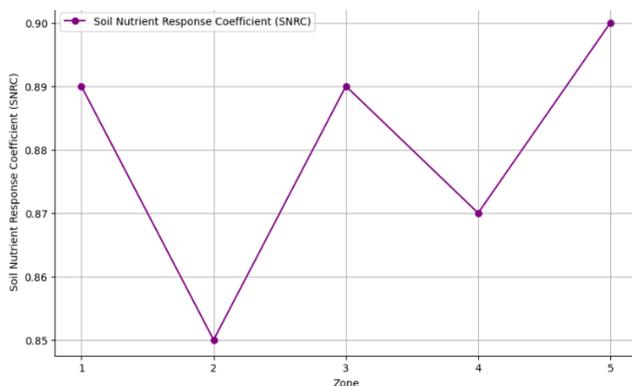


Fig. 5. Soil Nutrient Response Coefficient (SNRC)

The Soil Nutrient Response Coefficient (SNRC) is depicted in Figure 5. The SNRC provides a measure of responsiveness of soil nutrient levels to the application of compost adjusted for factors affecting nutrient availability. The values of SNRC fall in the range of 0.85 to 0.90, which reflects different responses of soil nutrients to the application of compost in different zones. The highest SNRC value at 0.90 is observed in Zone 5, which suggests that the application of compost in this zone achieves the largest increase in soil nutrients as compared to other areas. The compost applied in Zone 5 has had a great effect in enhancing the levels of soil nutrients, based on influencing factors, thus suggesting a higher SNRC. The lowest value of SNRC for Zone 2 indicates that compost application in Zone 2 is less efficient in improving the soil nutrient level than Zones 1 and 3. Factors such as soil or compost quality, in this case, may be constrained from reducing the potential for compost effectiveness in Zone 2 because of this lower coefficient. The SNRC values for Zones 1, 3, and 4, respectively, are 0.89, 0.89, and 0.87. These are relatively close values and, therefore, represent moderate and similar responses to compost application in these zones. SNRC Values show that most zones have some aspects of compost's usefulness in enhancing soil nutrients but varied from site to site in potential effectiveness.

5 Conclusion

The NBI values varying from 1.08 to 1.20 reflect different levels of optimizing the ratio of nutrients among different zones of the soil. In Zone 3, with NBI of 1.20, which signifies optimal nutrient balance, composting application is considered the most effective because the compost used has the highest nutrient level. Alternatively, Zone 4, with an NBI of 1.08, is an area in which nutrient balancing may not be efficient, and compost application could be

adjusted to enhance performance. Compost shows an efficiency of 0.82 to 0.87 of CUE values in enhancing soil fertility. The highest CUE of 0.87 is found in Zone 1, implying the most efficient use of compost. Whereas Zone 2, with a CUE = 0.82, indicates changes in the use, performance, or both of compost that might be improved through better application practice or other interventions. Varying from 1.28 to 1.40, SFIR indicates compost's effectiveness in improving soil fertility. The highest SFIR of 1.40 has been reached in Zone 2, which implies the largest beneficial effect on soil fertility. Conversely, Zone 3, with the lowest SFIR of 1.28, implies that soil fertility could be further refined in terms of compost application. Based on these results, the SNRC values (0:85 to 0:90) reflect the responsiveness of soil nutrients to the application of compost. Compost is an especially effective nutrient supply source because zone 5, with the highest SNRC of 0.90, reveals the greatest nutrient response. Nutrient response could be maximized in some areas of Zone 2 (the SNRC of lowest 0.85), where nutrient response could be enhanced through the modification of ΔP application. Future improvements that can optimize compost utilisation by smallholder organic businesses could include the insertion of advanced sensors and IoT technologies facilitating real-time viewing of soil nutrient status and compost inclusion. Machine learning algorithms for predictive analytics can implement compost application rates more precisely than is currently achieved through static application rates to compound dynamic soil and environmental factors. In addition, the utilization of biochar in combination with compost may further enhance the fertility and the retention of nutrients in the soil. Other benefits of this research will include expanding research on the best compost formulations for various soil types and crops with more effective cycling of nutrients. Practical improvements and the adoption of these innovations can instead be driven by cooperative efforts with local farmers to stand up and test these innovations on site.

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