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Remapping Soil Fertility: A Chemical Approach to Optimizing Agricultural Land in Urban Area of Bandulan Village, Malang City

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Abstract

This study explores soil fertility optimization strategies in Bandulan Village, Sukun District, Malang City, through a chemical analysis approach. The main focus of this study is to identify soil chemical parameters such as pH, nitrogen (N), phosphorus (P), and potassium (K), which affect agricultural productivity in urban areas with limited land. The methods used include laboratory testing and field observations to provide a comprehensive assessment of soil conditions. The results showed that soil fertility in the study area was at a moderate level, with pH varying from moderately acidic to slightly acidic, and N, P, and K contents ranging from low to moderate. These conditions can inhibit plant growth if not managed properly, especially in soils with a more acidic pH. This study offers recommendations for farmers and policy makers to improve efficient soil management through the use of organic fertilizers, technology-based soil fertility monitoring, and the adoption of environmentally friendly agricultural practices. Thus, it is expected to support the sustainability of agriculture amidst the pressures of urbanization and environmental change.

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Keywords:
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1. Introduction

Rapid urbanization in big cities in Indonesia has become a major driver of land conversion. Malang City, which has experienced significant development in the last few decades, is a prime example of this phenomenon. Land conversion from the agricultural sector to residential, infrastructure, and other uses has become commonplace along with the increasing need for space for development and economic growth. Bandulan Village, located in Sukun District, Malang City, is facing a real impact from this process. Based on data from the Malang City Central Statistics Agency (2020), the area of agricultural land in Bandulan Village has decreased significantly, from 961 hectares in 2015 to only 614 hectares in 2020 (Ivanka et al., 2024). This figure shows that almost a third of the agricultural land in this village has changed function in just five years. This phenomenon not only has an impact on the reduction of land available for agricultural activities, but also creates great pressure for local farmers to find innovative ways to manage increasingly limited land in order to remain productive and able to meet the needs of the local market and the ever-growing economy (Abriyantoro et al., 2024).

The conversion of agricultural land into residential and commercial areas in Malang City and other areas does not occur randomly, but rather is the result of various interrelated factors. The main factors that trigger this change in land use are rapid urbanization and rapid economic growth. Areas such as Bandung Regency, which also experienced similar urbanization, show a similar pattern where socio-economic factors, such as increasing population and the need for housing and infrastructure, cause agricultural land to be converted into non-agricultural land (Hasyim et al., 2024). This development cannot be separated from agrarian and agricultural policies in Indonesia which historically and contemporarily contribute to determining land use patterns. Agrarian reforms carried out by various government regimes in Indonesia, for example, have shaped land management practices that directly affect the availability of land for agriculture (Natadireja et al., 2024). With the changes that occur from time to time, agricultural policies continue to adapt, but are not always able to anticipate the pressures that come from increasingly intensive urbanization (Abriyantoro et al., 2024).

Land conversion caused by urbanization is often followed by various negative impacts on environmental quality, especially on soil quality. In urban areas, soil tends to experience degradation due to excessive human activities. Air pollution, industrial waste, and the use of chemicals in agricultural activities are some of the main factors that have an impact on the decline in soil quality and fertility. The accumulation of organic and inorganic pollutants, such as heavy metals and industrial by-products, can damage soil structure and reduce the quality of nutrients available to plants (Yamini et al., 2024). As a result, soil in urban areas often loses its ability to support optimal plant growth. This pollution can also have an impact on other ecological systems, including groundwater and soil biodiversity. On the other hand, intensive urbanization also triggers a decline in soil biodiversity, which can lead to disruption of natural ecosystem functions. This decline affects nutrient cycles and the activity of important microorganisms in the soil, which directly impacts overall soil fertility and productivity (Dixit et al., 2024).

In addition, urbanization accelerates the conversion of agricultural land to non-agricultural land. This impact is not only felt by the environment, but also increases pressure on farmers to increase productivity on the remaining land. Farmers in Bandulan Village, for example, are faced with the challenge of finding new, more innovative and efficient strategies to maintain agricultural productivity amidst land limitations. One solution that is often used is optimizing the use of fertilizers and more sophisticated agricultural technology to overcome the decline in soil quality (Biłozor et al., 2024). However, this solution requires a deep understanding of soil conditions and the factors that influence them. In the context of increasing land limitations, a comprehensive understanding of soil fertility conditions is becoming increasingly important. This is needed to formulate more adaptive and sustainable land management strategies, as well as to anticipate the negative impacts of increasingly rapid urbanization.

Previous studies have identified various soil chemical parameters that are important in assessing soil fertility and agricultural productivity. Some of the key parameters that are often used are pH, total nitrogen (N), available phosphorus (P), and available potassium (K). These parameters serve as important indicators in determining the ability of the soil to support optimal plant growth. For example, a neutral to slightly acidic soil pH is considered ideal because it supports soil microbial activity. These microbes play an important role in the decomposition process of organic matter which ultimately increases the availability of nutrients for plants (Zhang et al., 2024). Optimal microbial activity will increase the process of nutrient formation needed by plants to grow optimally. However, if the soil pH is too acidic, the availability of phosphorus in the soil can decrease due to the formation of insoluble compounds with aluminum. This condition results in phosphorus not being able to be absorbed effectively by plants, which ultimately reduces agricultural productivity (Abdi, 2024).

In addition, low nitrogen and potassium content in the soil is often caused by leaching and evaporation processes, especially in areas with high rainfall such as Malang. Nitrogen is an important nutrient for plant growth because it plays a role in protein and chlorophyll synthesis, while potassium functions in the process of photosynthesis and nutrient transport in plants. In areas with high rainfall, rainwater can carry these nutrients out of the root zone, reducing their availability to plants (Siregar et al., 2024). Therefore, proper management is needed to prevent the loss of nitrogen and potassium from the soil, such as through the implementation of more efficient irrigation methods or the use of appropriate fertilizers.

In Bandulan Village, soil productivity faces various challenges, including the mismatch between the types of commodities planted and soil conditions. For example, in 2018 there was an incident of crop failure due to the lack of adjustment between plant needs and existing soil chemical conditions. This case shows the importance of a data-based approach in formulating appropriate agricultural strategies. The use of technology to monitor and analyze soil conditions in real-time can help farmers avoid similar mistakes in the future. A deep understanding of soil chemical parameters, such as pH, nitrogen, phosphorus, and potassium, will be very helpful in formulating more efficient and sustainable soil management strategies.

This study aims to evaluate the level of soil fertility in Bandulan Village by measuring several key chemical parameters such as pH, N, P, and K. The results of this study are expected to provide deeper insight into soil conditions in the area and become the basis for recommendations for more effective land management. Through an in-depth analysis of soil fertility conditions, this study also aims to provide concrete recommendations that can be applied by farmers in increasing the productivity of their land. In addition, this study is in line with efforts to maintain sustainable agriculture amidst increasing urbanization pressures. This pressure requires an approach that is not only efficient but also adaptive to environmental and economic changes.

In addition to providing data-based guidance for farmers, the results of this study are also expected to be a reference for policy makers in developing more effective land management strategies. This study also has the potential to enrich the literature on agricultural land management in urban areas and can be used as a reference in formulating policies that support sustainable agriculture. In the face of increasing urbanization pressures, sustainable land management is becoming increasingly important to maintain food security and ecosystem balance in urban areas.

By identifying soil chemical parameters and understanding their interactions with soil fertility in Bandulan Village, this study is expected to offer concrete solutions to overcome the challenges of agricultural productivity on increasingly limited land due to urbanization. In this context, the study aims to develop land management strategies that are not only effective in increasing agricultural yields, but also sustainable from an environmental and social perspective. One way to achieve this is by implementing a data-driven approach in decision-making related to land management.

Urbanization often brings complex challenges for farmers, especially in terms of adapting agricultural practices to changing soil and environmental conditions. Shrinking land availability forces farmers to maximize productivity from the remaining land. This creates an urgent need to understand soil characteristics in more detail, including how factors such as pH, nitrogen, phosphorus, and potassium interact to affect plant growth. For example, in soils that are too acidic, phosphorus availability can be very limited, ultimately limiting plant growth even when other parameters such as nitrogen and potassium are adequate. With the data-driven approach proposed in this study, farmers can more accurately predict and manage their soil needs, thereby avoiding mistakes in commodity selection or inefficient fertilizer use.

In addition, this study aims to investigate the potential long-term impacts of the use of technology in soil management. The use of soil sensors, soil testing devices, and information technology applications such as GIS (Geographic Information Systems) and IoT (Internet of Things) enable real-time land management. These technologies provide great opportunities to increase efficiency in monitoring changes in soil conditions, which can be caused by weather fluctuations or human activities, and provide timely recommendations for farmers to adjust their agricultural practices. These technologies also enable faster and more accurate decision-making in terms of fertilizer management, irrigation, and crop rotation, all of which play a vital role in maintaining soil fertility and agricultural productivity in the long term.

This research is also expected to contribute to the formulation of public policies that support sustainable agriculture in urban areas. With strong data on soil fertility conditions in Bandulan Village, policy makers can formulate more appropriate strategies to support farmers, such as providing organic fertilizer subsidies, agricultural technology training, or building supporting infrastructure that can facilitate the use of data-based technology. Policies that support innovation in the agricultural sector are essential to maintain a balance between economic growth and environmental sustainability, especially in areas experiencing intensive urbanization such as Malang.

On a broader scale, the results of this study can be a reference for other urban areas facing similar challenges due to urbanization pressures. Bandulan Village, as part of the developing city of Malang, is a clear example of an area where urbanization pressures have a direct impact on the sustainability of agricultural practices. Therefore, a better understanding of the dynamics of soil fertility in this area will not only benefit local farmers but also policymakers and academics working to develop sustainable agricultural solutions in big cities in Indonesia.

Overall, this research not only focuses on the technical aspects of soil fertility but also attempts to offer a more holistic approach to addressing the challenges caused by urbanization. By combining scientific analysis of soil chemical parameters with modern technology and supportive policies, this research is expected to provide comprehensive guidance for managing agricultural land in urban areas in a more adaptive and sustainable manner.

2. Methods

Research methods

This study uses a quantitative descriptive method to evaluate soil fertility in Bandulan Village, Sukun District, Malang City. The quantitative descriptive approach was chosen because this method allows researchers to measure and analyze soil fertility conditions systematically through the collection of numerical data that can be interpreted statistically. This method is effective in describing the main characteristics of soil conditions, such as pH, cation exchange capacity (CEC), and organic carbon content, which are important indicators of soil fertility (Nabilah et al., 2024) . The main focus of this method is to identify chemical parameters that affect agricultural productivity in areas facing urbanization pressures, allowing for more appropriate adjustments to land management strategies (Lubis et al., 2024) .

Primary data collection was carried out through two main stages: field measurements and laboratory testing. Field measurements are essential to obtain direct data on soil chemical parameters such as pH, total nitrogen (N), available phosphorus (P), and available potassium (K) at various sample points, which capture the spatial variability of soil properties (Gyawali et al., 2023). Laboratory testing was carried out using a colorimetric method implemented through the Paddy Soil Testing Device (PUTS), a method that has been validated for accurate soil nutrient analysis and is comparable to traditional laboratory spectrophotometers (Singh et al., 2023). Data obtained from these two stages were then quantitatively evaluated to assess the soil fertility status at the study site, including nutrient concentration and uptake (Rakotoson et al., 2023).

Table 1. Color Chart of P, K, and pH Tests for Paddy Field Soil

Soil Parameter	Status	Recommendations
SP-36 Fertilizer	Low	100 kg SP-36/ha
	Current	75 kg SP-36/ha
	High	50 kg SP-36/ha
KCl + KCl Fertilizer	Low	100 kg KCl/ha + 5 t straw/ha
	Current	50 kg KCl/ha + 5 t straw/ha
	High	5 t straw/ha (no KCl)
Soil pH	< 4	Lime interrupted, 1-2 t lime/ha after urea
	4-5	Use urea with lime
	5-6	Conventional fertilizers
	6-7	Continue conventional system
	> 7	2 t gypsum/ha + precautionary salt

Source: Processed Data by Researchers

This table synthesizes the essential guidelines for managing soil nutrients and pH as depicted in the infographic. It provides a concise view suitable for referencing in reports or publications.

Research Design

This research is designed as an in-depth case study in Bandulan Village, Sukun District, Malang City, an urban area that has experienced significant urbanization pressure in recent years. The case study approach was chosen because it provides flexibility and the ability to explore complex phenomena in a specific context, such as changes in agricultural land use due to urbanization. In this case, the study focuses on the condition of agricultural soil fertility in an area that continues to experience land conversion from agriculture to non-agricultural sectors, including residential and commercial. This case study also provides an opportunity for researchers to study the relationship between environmental conditions, land management practices, and socio-economic factors that influence agricultural productivity. With this approach, the study is expected to provide a more comprehensive and in-depth picture of the various aspects that influence soil fertility in urban areas.

Bandulan Village was chosen as the research location because of its representation as an urban area experiencing high land conversion pressure. In this context, the case study approach allows researchers to analyze the specific impacts of urbanization on agricultural soil fertility in the area. This research is not only limited to the technical aspects of soil fertility, but also takes into account other factors such as socio-economic dynamics, changes in land use policies, and climate change that can affect the sustainability of agricultural practices in urban areas. Through this approach, the research is expected to provide a more comprehensive understanding of the factors that affect soil fertility and how they relate to the increasing pressure of urbanization.

Observational Design

This study uses an observational design that combines direct field observation with laboratory analysis to gain a deeper understanding of soil fertility conditions in Bandulan Village. Field observations were conducted to collect empirical data on soil chemical parameters, especially pH, nitrogen (N), phosphorus (P), and potassium (K). Data collected in the field were then analyzed in the laboratory to identify the content of soil nutrients available to plants. This method allows researchers to obtain accurate and representative primary data on real conditions in the field. The combination of field observation and laboratory analysis is very important to ensure that the data obtained reflects actual conditions and can be used as a basis for formulating appropriate policy recommendations.

Figure 2. Research Location Map
Source: (Kota, 2019)

This approach provides advantages in terms of data accuracy and validity. By using modern measurement technology such as soil meters and laboratory test equipment, researchers can ensure that important soil parameters such as pH, nitrogen, phosphorus, and potassium content can be measured accurately. In addition, with more in-depth analysis through laboratory testing, the results obtained can be used to provide a more complete picture of the soil fertility conditions in the area. The data collected will not only be used for scientific analysis, but also to provide practical recommendations that can be implemented by farmers and local policy makers.

Population and Sample

The population of this study covers all agricultural land in Bandulan Village, Sukun District, Malang City. To ensure that the results of this study are representative and can be applied generally, soil samples were taken purposively from eight points that were considered to best represent the variation in agricultural land conditions in the area. Sample selection was carried out by considering various variables such as geographic location, physical condition of the soil, and type of land use. With this approach, researchers can ensure that the samples taken provide an accurate picture of the variation in soil fertility throughout the Bandulan Village area.

Stratified random sampling method was used for soil sampling. This method was chosen because of its ability to ensure that each soil subpopulation in the study area is proportionally represented in the samples taken. In its implementation, each sampling point was selected based on certain predetermined criteria, such as differences in soil texture, altitude, and types of crops planted. Soil samples were then taken using special tools to avoid contamination and maintain sample quality. After the samples were collected, each soil sample was sent to the laboratory for further analysis.

Data collection technique

Data were collected through two main techniques: direct field observation and laboratory testing.

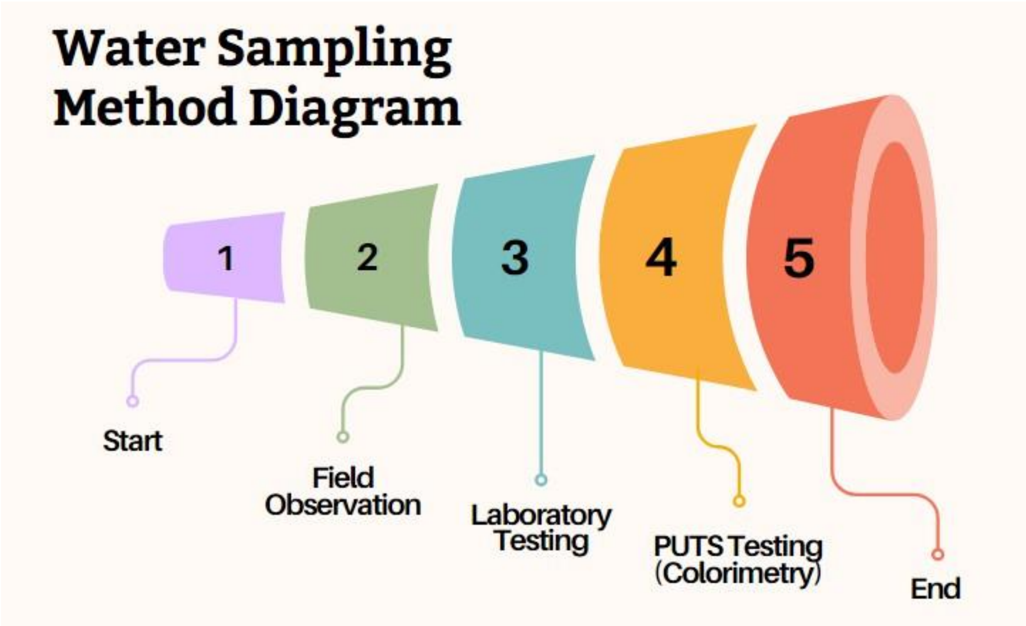

Figure 3. Water Sampling Method Diagram
Source: Processed Data by Researchers

1. **Field Observation:** Observations were conducted using a soil pH meter, such as a 4 in 1 soil meter, which is capable of measuring pH parameters quickly and accurately. These measurements were conducted at each predetermined sample point to obtain a direct picture of the soil fertility conditions at the research location. . Each sampling point is marked using GPS coordinates to ensure repeatability of future measurements and minimize the possibility of sampling errors. These observations are important to provide primary data used as a basis for further analysis.
2. **Laboratory Testing:** After field measurements are carried out, the soil samples that have been taken are taken to the laboratory for further testing using the Paddy Field Soil Testing Device (PUTS). In this test, the colorimetric method is used to identify the nutrient content of the soil, such as nitrogen, phosphorus, and potassium. This colorimetric technique involves a chemical reaction between the soil sample and certain reagents, which then results in a color change. The color that appears is then evaluated visually using a standard color scale to determine the level of nutrients available in the soil. This laboratory test provides more detailed and accurate results regarding the nutrient content in the soil, which will be used as a basis for making recommendations for better soil management.

The colorimetric method was chosen because of its simplicity and efficiency in detecting soil nutrient concentrations under field conditions. The PUTS tool allows researchers to perform testing quickly and at a relatively low cost compared to more complex laboratory methods. The speed and simplicity of this test are well suited to field research that requires immediate and practical results .

Justification of Methods and Techniques

The selection of quantitative descriptive method in this study is based on the need to obtain objective and measurable data on soil fertility conditions in urban areas that are increasingly under pressure from the urbanization process. By using observational techniques and laboratory testing, researchers can obtain primary data that can be analyzed statistically and quantitatively. This is important because it provides a strong scientific basis for recommendations that will be made at the end of the study. This approach also ensures that the results obtained are relevant and can be applied to real situations in the field.

The combination of these two techniques provides a more comprehensive view of the soil conditions in the study area. Direct field observations allow researchers to understand the actual conditions of the studied environment, while laboratory testing provides more detailed data on the chemical composition of the soil. With this approach, the study is expected to make an important contribution to the management of agricultural land in urban areas, as well as offering data-based recommendations that can be implemented by farmers and local policy makers. This data-driven approach is also expected to help address the challenges posed by urbanization and promote more sustainable agricultural practices in urban areas.

3. Results and Discussion

Results

1. Soil Fertility Analysis Based on Chemical Parameters

Soil fertility is a crucial factor that determines the productivity of agricultural land, especially in urban areas such as Bandulan Village, which faces strong pressure from changes in land use due to urbanization (Agustian & Simanjuntak, 2018). In urban areas, soil often experiences a decline in quality due to intensive human activities, such as construction, pollution, and the use of chemicals. Therefore, a deep understanding of soil fertility conditions in Bandulan Village is important to determine the right land management strategy.

Table 1. Soil Fertility Status Based on pH, N, P, and K Parameters

Sample	pH	N Total	P Available	K Available
1	6.0	Medium	Medium	Medium
2	6.2	Medium	Medium	Medium
3	6.5	Medium	Medium	Low
4	6.2	Medium	Medium	Medium
5	5.8	Low	Medium	Low
6	5.8	Low	Low	Medium

Source: Processed Data by Researchers

This study shows that the soil in Bandulan Village has a moderate level of fertility. Analysis of soil chemical parameters including pH, total nitrogen (N), available phosphorus (P), and available potassium (K) revealed several important findings:

1. **Soil pH:** Soil pH measurements show a variation in values between 5.8 and 6.5. This value indicates that the soil is in the moderate to slightly acidic pH range. This pH range is considered optimal for most plants because soil microorganisms tend to be active in this range, supporting the decomposition of organic matter and increasing the availability of essential nutrients (Stewart, 1987). However, slightly acidic soil pH can inhibit the availability of phosphorus (P) because this element can bind with iron (Fe) and aluminum (Al) in more acidic soils, forming insoluble compounds that are difficult for plants to absorb (McKerrel et al., 1971). This indicates the need for proper soil pH management to maintain nutrient balance (Scholes et al., 1994).
2. **Nitrogen (N):** As one of the essential elements for plant growth, nitrogen plays a role in the synthesis of proteins and enzymes required for photosynthesis. The results of the study showed that nitrogen levels in the soil in Bandulan Village varied from low to moderate. Nitrogen in the soil can be lost through several processes, including leaching, volatilization, and uptake by plants (GARDNER, 1991). Leaching is a particular problem in areas with high rainfall such as Malang, where rainwater can carry nitrate from the root zone, reducing the availability of nitrogen for plants (Scholes et al., 1994). Therefore, it is important to consider the efficient use of nitrogen fertilizers and soil management techniques that can reduce nitrogen loss (Inubushi, 2014).
3. **Phosphorus (P):** Phosphorus is an important element in plant growth, playing a role in the process of photosynthesis, root formation, and fruit development. Research results show that phosphorus levels in the soil vary from low to moderate. In acidic soil conditions, phosphorus tends to bind with aluminum and iron, forming compounds that cannot be absorbed by plants (McKerrel et al., 1971). To overcome this, the application of proper phosphate fertilizer can increase the availability of phosphorus in the soil and improve plant growth (Scholes et al., 1994).

4. **Potassium (K):** Potassium is also an essential nutrient that is important for various plant physiological processes, including protein and carbohydrate synthesis, as well as increasing resistance to disease and drought (Inubushi, 2014). The results of the study showed that potassium levels in the soil of Bandulan Village varied from low to moderate. Potassium loss can occur through harvesting, erosion, or leaching, especially in sandy or light-structured soils (GARDNER, 1991). It is important for farmers to monitor potassium levels regularly and adjust the use of potassium fertilizers according to the specific needs of their soil (Scholes et al., 1994).

berdasarkan nilai pH yang diperoleh dapat disusun peta sebaran nilai pH pada lahan pertanian ditunjukkan pada gambar 1.

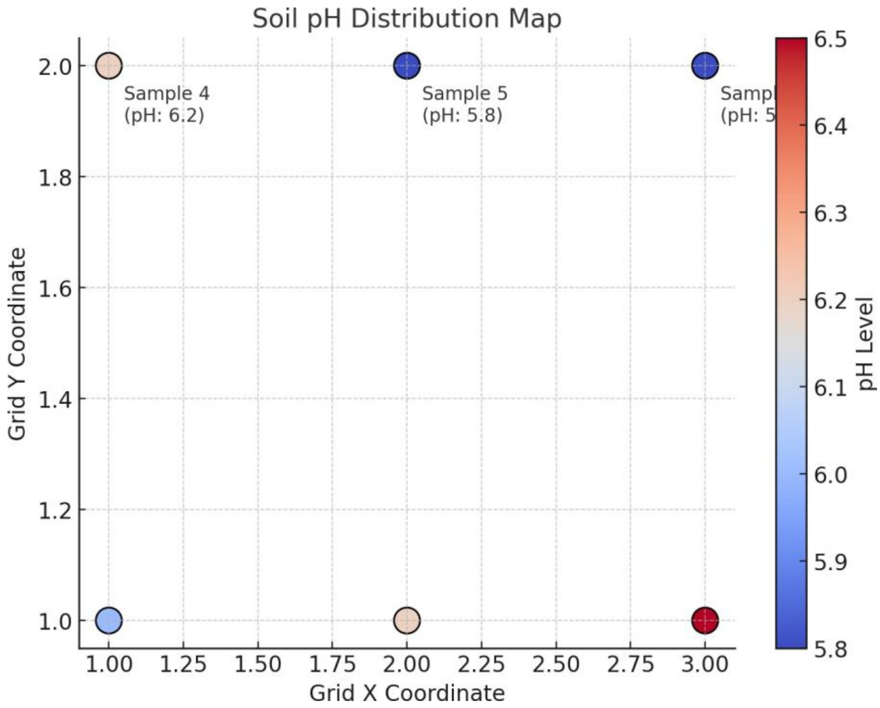

Figure 4. Soil pH Distribution Map
Source: Processed Data by Researchers

The soil pH distribution map reveals a moderate variation in pH levels across the sampled area, ranging from 5.8 to 6.5, indicating that the soil is generally in the mildly acidic to neutral range. Samples with lower pH values (5.8) are concentrated in the second row of the grid, suggesting a slightly more acidic condition in that part of the field. Meanwhile, higher pH values are observed in the first row, with the highest being 6.5 at Sample 3. These variations in pH could impact nutrient availability, particularly for crops sensitive to soil acidity, and may indicate the need for localized soil management practices.

2. Impact of Urbanization on Soil Fertility

Urbanization has a significant impact on the quality of agricultural land, both directly and indirectly. The reduction in agricultural land area in Bandulan Village, from 961 hectares in 2015 to 614 hectares in 2020, is a clear example of the impact of changes in land use due to urbanization (Lehmann, 2006). As urbanization progresses, agricultural land is often converted into residential and commercial spaces, limiting the area available for farming. This conversion reduces access to fertile land, forcing farmers to maximize productivity on increasingly smaller plots. However, this pressure often leads to intensive agricultural practices, which, if not managed properly, can further degrade the soil quality and reduce its long-term sustainability (Hazelton et al., 2009).

In addition to land conversion, soil conditions in urban areas are often degraded by human activities such as industrial operations, transportation, and construction. These activities generate pollutants, including hazardous chemicals and heavy metals, which accumulate in the soil and disrupt its structure and chemical balance (Meuser, 2010). Pollutants like lead, mercury, and cadmium are particularly harmful, as they can become embedded in the soil and affect its fertility over time. The disruption of the soil's chemical balance due to these contaminants impacts its ability to support plant life, reducing agricultural productivity. This degradation is more pronounced in urban environments compared to rural areas, where pollution levels are typically lower (Meuser, 2010).

Climate change also exacerbates the degradation of soil in urban areas by altering weather patterns, such as rainfall, temperature, and humidity. Changes in these environmental factors can accelerate the decomposition of organic matter and increase nutrient leaching, further reducing soil fertility (Rodríguez-Espinosa et al., 2021). In areas with unpredictable or extreme weather conditions, soil management becomes even more challenging. The combined effect of climate change and urban pollution puts immense pressure on the soil's ability to recover naturally. Thus, proactive soil management strategies are essential to mitigate these negative impacts and maintain soil health.

Air pollution in urban areas not only affects air quality but also contributes to the degradation of soil through the deposition of harmful substances onto the ground. The increased concentration of heavy metals such as lead, mercury, and cadmium in urban soils can damage soil structure and reduce its fertility (Meuser, 2010). These pollutants can enter the food chain, posing risks to human health as well. Studies have shown that urban soils contain higher levels of pollutants compared to rural soils, which affects not only plant health but also the potential for sustainable agriculture. This makes it essential to monitor soil quality in urban areas regularly and implement measures to reduce pollution.

Managing urban soil, despite its challenges, can still offer environmental and infrastructural benefits. Urban soils, when managed properly, can contribute to stormwater management, reducing the risk of flooding and improving water quality. Strategies such as the use of Technosol, an engineered soil made from waste materials, are being explored to maintain the ecosystem functions of soil in urban environments (Rodríguez-Espinosa et al., 2021). These innovative approaches can help preserve soil health while allowing for continued urban development. It is critical to balance the demands of urban expansion with the need for sustainable soil management practices to ensure long-term ecological and agricultural viability.

3. Soil Fertility Optimization Strategy

To overcome the challenges of soil fertility in urban areas such as Bandulan Village, a comprehensive and sustainable land management strategy is needed. Some strategies that can be applied include:

1. Increasing Soil Organic Matter Content: One effective way to increase soil fertility is by increasing organic matter content through the use of organic fertilizers or compost. Organic fertilizers significantly improve soil structure, enhance the soil's capacity to store water and nutrients, and provide a more sustainable source of nutrients for plants (Mubeenuddin et al., 2024). Long-term studies have shown that organic amendments increase soil organic carbon levels, which in turn boosts soil fertility. However, organic fertilizers alone may not supply all essential nutrients, suggesting a combined approach with inorganic fertilizers for optimal results (Titirmare et al., 2023). The use of green manure and mulch is also recommended to maintain soil moisture and reduce erosion, while also improving the soil's physical properties and supporting plant growth (Arunprasath et al., 2023).
2. Application of Soil Monitoring Technology: Tools such as the Paddy Soil Testing Device (PUTS) enable farmers to regularly and accurately monitor soil chemical parameters, allowing them to adjust fertilizer types and dosages based on specific soil needs. This targeted approach helps in early identification of soil fertility issues and allows for timely corrective measures (Dandasena et al., 2024). Regular monitoring is crucial in ensuring that farmers can maintain an optimal balance of nutrients in the soil for plant health and productivity.
3. Information Technology-Based Soil Management: The implementation of digital soil mapping and IoT (Internet of Things) sensors has been proven effective in increasing agricultural productivity by improving soil monitoring efficiency. IoT-based systems enable real-time soil condition monitoring, facilitating better decision-making regarding nutrient management (Reddy et al., 2023). These technologies have been shown to enhance crop yields, especially in urban agricultural settings, by optimizing irrigation and nutrient application through automated systems. Despite the benefits, initial costs and technical expertise required to implement advanced soil monitoring technologies may pose challenges for some farmers,

indicating the need for tailored approaches depending on local agricultural contexts (Arunprasath et al., 2023; Titirmare et al., 2023).

4. **Developing Policies that Support Urban Agriculture:** Governments and policymakers need to actively support the adoption of modern, environmentally friendly agricultural technologies. Policies that promote the use of digital technologies, such as IoT-based soil monitoring and precision agriculture tools, can significantly enhance the efficiency and sustainability of urban farming (Reddy et al., 2023). Additionally, providing incentives for sustainable agricultural practices, such as subsidies for organic fertilizers or tax breaks for adopting green technologies, can encourage farmers to implement practices that improve soil fertility while minimizing environmental impact (Arunprasath et al., 2023). Furthermore, investment in infrastructure, including reliable access to technology and digital tools, will help farmers tackle the challenges posed by soil fertility in urban environments (Titirmare et al., 2023). These supportive policies are crucial for ensuring long-term agricultural productivity and sustainability in urban areas.

By implementing these strategies, it is expected that agricultural land productivity in Bandulan Village can be increased despite the increasingly strong urbanization pressures. These strategies also offer a sustainable and data-based approach to land management, which is very important in maintaining the sustainability of agriculture in dense urban areas.

Discussion

The findings of this study indicate that soil fertility in Bandulan Village is in the moderate category, which means that agricultural land in this area requires more attention in managing soil nutrients and pH. Soil with moderate to slightly acidic pH is ideal for most plants because it supports microbial activity that is important in the decomposition of organic matter. However, this condition also risks reducing the availability of phosphorus in the soil, as phosphorus can react with aluminum and iron in acidic soil, forming insoluble compounds (Bhupenchandra et al., 2024). When phosphorus binds to these elements, it becomes difficult for plant roots to absorb, which can inhibit plant growth and reduce productivity. Therefore, it is important to consider appropriate pH management strategies, such as the use of lime to increase soil pH to a more neutral level and increase the availability of phosphorus in the soil (Dash et al., 2023; Sara et al., 2024).

In addition to pH management, nitrogen also requires special attention. The results of the study showed that nitrogen levels in the soil of Bandulan Village varied from low to moderate. This indicates that nitrogen in the soil tends to be easily lost through leaching (washing by rainwater), volatilization (evaporation), or taken up by plants. Areas with high rainfall such as Malang often experience nitrogen leaching problems, where rainwater carries nitrate away from the root zone, causing plants to lack the nitrogen needed for growth (Zhou et al., 2024)). Therefore, more efficient use of nitrogen fertilizers is needed to prevent the loss of this important nutrient. One strategy that can be applied is the use of slow-release fertilizers, which can help maintain nitrogen availability over a longer period of time (Luo et al., 2024). In addition, practices such as crop rotation and planting legumes that can bind nitrogen from the air can also be natural solutions to increase nitrogen availability in the soil (Kurniawan et al., 2023).

Phosphorus, an essential nutrient for photosynthesis and root formation, is also found in moderate to low levels. In soils with a more acidic pH, phosphorus tends to bind with heavy metals such as aluminum and iron, resulting in the formation of insoluble compounds (Négrel et al., 2024). To overcome this, the addition of phosphate fertilizers can help increase the availability of phosphorus in the soil. However, it is important to remember that excessive fertilization can also cause environmental problems such as groundwater pollution (Fatima et al., 2024). Therefore, it is crucial to regularly monitor phosphorus levels in the soil and apply fertilizers in the right doses according to plant needs. The use of organic fertilizers containing natural phosphorus can also be a more environmentally friendly alternative, as the release of nutrients tends to be slower and more sustainable in the long term (Liu et al., 2024). Additionally, using phosphate-solubilizing microbes provides an eco-friendly alternative to enhance phosphorus uptake (Marpaung et al., 2023).

Potassium, found in low to moderate levels in the soil of Bandulan Village, is an essential nutrient for various physiological functions of plants, including protein synthesis, photosynthesis, and increasing plant resistance to disease and drought. Potassium also helps regulate water balance within plant cells, which is essential for maintaining healthy plant conditions, especially in stressful environments such as urbanization (Johnson et al., 2022; Mostofa et al., 2022). Potassium loss can occur through harvesting, erosion, or leaching, especially in sandy or loosely structured soils (Das et al., 2022). Therefore, regular monitoring of potassium levels is essential to ensure that plants are getting enough of this nutrient. If potassium levels are too low, farmers need to adjust the use of potassium fertilizers to suit their soil conditions. In addition, the use of organic mulch can help retain soil moisture and prevent erosion, which is often the main cause of potassium loss from the soil (Das et al., 2022).

Urbanization also has a significant impact on soil fertility in Bandulan Village. Along with the increasing population and expansion of infrastructure, agricultural land is decreasing, and soil quality in urban areas is often degraded due to pollution, industrial activities, and the use of chemicals. The rapid urbanization process causes the soil to become less fertile and requires more intensive management efforts to remain productive (Dixit et al., 2024). In addition, changes in land use from agriculture to housing and commercial areas cause farmers to have to maximize productivity from increasingly limited land (Ihenetu et al., 2024). This creates a major challenge for local farmers, who need to implement more efficient and sustainable farming techniques to maintain productivity. Urban farming also emerges as a potential solution, allowing the optimization of small spaces for food production, thereby enhancing local food security and environmental health (Giyarsih et al., 2024).

Modern technology can be one solution to address these challenges. The use of devices such as the Paddy Soil Testing Device (PUTS) allows farmers to monitor soil chemical conditions regularly and more accurately. This technology helps farmers adjust the dosage of fertilizers and the types of nutrients needed according to soil conditions, optimizing crop productivity. In addition, the adoption of information technology such as digital mapping applications and Internet of Things (IoT) sensors allows for real-time soil monitoring, providing accurate data for more timely decision-making (Haqim Azman et al., 2023). The implementation of this technology can help farmers address soil fertility issues more quickly and efficiently, increasing their yields, even in areas with high urbanization pressures (Jyothi, 2024; Madhuri et al., 2024).

To support the success of these strategies, the government and policymakers also need to play an active role in providing adequate support to farmers. Policies that encourage the adoption of digital technology in agriculture, provide incentives for sustainable agricultural practices, and improve agricultural infrastructure can help farmers face the challenges of soil fertility in urban areas (Johan et al., 2024). With good collaboration between farmers, the government, and experts, agricultural land productivity in areas such as Bandulan Village can be maintained or even increased, despite the increasing pressure of urbanization (Limpamont et al., 2024; Modjo et al., 2024).

4. Research Implications

Practical Implications

This study reveals a number of significant practical implications for farmers and policymakers in Bandulan and similar urban areas. The findings highlight the importance of a more adaptive and data-driven approach to soil management to address the soil fertility challenges faced by farmers in urban areas. Rapid urbanization in the region has resulted in major changes in land use, forcing farmers to work on smaller and often poorer plots of land. In this context, farmers would benefit greatly from increasing the use of organic matter and green manures. The use of organic manure or compost, for example, not only improves soil structure and increases water retention capacity but also provides essential nutrients to plants in a more sustainable manner. In addition, the use of green manures and mulches can help retain soil moisture and prevent erosion, especially on steeper and more degraded lands.

Furthermore, the results of this study indicate the need to adopt modern technologies for real-time soil fertility monitoring. Technologies such as IoT (Internet of Things) sensors and GIS (Geographic Information System) applications can provide more accurate and timely data on soil conditions, enabling farmers to make faster and more informed decisions regarding fertilizer use, irrigation, and other soil management actions. With these technologies, farmers can continuously monitor changes in soil conditions, such as fluctuations in pH levels or nutrient content, and immediately adjust their strategies according to the specific needs of their land. These technologies can also reduce the cost and time required for manual soil monitoring, increasing overall production efficiency.

From a policymaker perspective, this study emphasizes the importance of policy support to encourage the adoption of innovative agricultural technologies. Policies that support the use of digital technologies, such as IoT sensors and GIS applications, can play a significant role in improving the efficiency and effectiveness of land management in urban areas. Providing financial incentives, such as subsidies for purchasing agricultural technologies or low-interest loans, can motivate farmers to adopt more modern and efficient practices. In addition, adequate infrastructure development, such as access to a stable internet network and training for farmers in the use of digital technologies, is also important to ensure that these technologies can be implemented effectively in the field.

This study also highlights the need for collaboration between the government, research institutions, and farming communities to develop programs that support the implementation of environmentally friendly and sustainable agricultural technologies. Thus, it is hoped that agricultural productivity in urban areas can be maintained or even increased, even amidst the increasing pressure of urbanization.

Theoretical Implications

Theoretically, this study makes an important contribution to the existing literature on soil management and agriculture in urban areas. The findings of this study reinforce the concept of the importance of data-driven soil management in the context of urban agriculture. In situations where agricultural land is increasingly limited and soil conditions tend to change rapidly due to environmental factors and human activities, a deep understanding of soil chemistry becomes crucial. This study shows that the use of appropriate technologies, such as soil sensors and soil testing devices, can help farmers to monitor and manage soil fertility more effectively, maintaining agricultural productivity even under challenging conditions.

In addition, this study also adds new insights into soil fertility optimization, especially in the context of rapid urbanization. The study highlights that technology-based and adaptive approaches are more likely to succeed in addressing dynamic soil fertility challenges, caused by complex interactions between environmental factors and human activities. By integrating information technology into agricultural practices, farmers can obtain real-time data that allows them to respond quickly to changes in soil conditions, weather, and other factors that affect soil fertility.

Furthermore, the findings of this study also underscore the importance of a holistic approach to soil management, which does not only focus on one aspect (e.g., increasing soil nutrient levels) but also considers various other factors such as soil structure, water retention capacity, and the environmental impact of agricultural practices. This approach is in line with the principles of sustainable agriculture, which emphasizes the importance of maintaining ecosystem balance while still achieving optimal productivity.

Thus, this study makes a significant contribution to our understanding of how to optimize soil fertility in urban areas experiencing urbanization pressures. This study also opens up opportunities for further studies on the application of more sophisticated and sustainable agricultural technologies, as well as the development of policies that support farmers' adaptation to changing environmental conditions.

5. Conclusion

This study shows that the soil in Bandulan Village, Sukun District, Malang City, has a moderate level of fertility based on key chemical parameters such as pH, nitrogen, phosphorus, and potassium. The soil pH value ranging from moderate to slightly acidic supports the activity of microorganisms that are important for the decomposition process of organic matter. However, the nutrient content such as nitrogen, phosphorus, and potassium which varies from low to moderate highlights the need for more efficient and data-based soil management to improve agricultural productivity in this area.

Urbanization in the region has put significant pressure on agricultural land use, reducing the available land area and affecting the quality of the remaining land. Rapid urbanization has led to the conversion of agricultural land to settlements and infrastructure, which not only reduces land area but also has the potential to damage soil quality through pollution and chemical use. Therefore, more innovative and adaptive land management approaches are needed to maintain agricultural productivity in these increasingly challenging conditions.

This study highlights the importance of collaboration between farmers, policymakers, and academics to develop more effective soil management strategies. Farmers can be encouraged to adopt environmentally friendly practices, such as the use of organic fertilizers, compost, and green manures, which can improve soil structure and increase the soil's capacity to retain water and nutrients. In addition, modern technologies such as IoT sensors, soil testing devices, and GIS applications enable real-time monitoring of soil conditions, providing more accurate data for timely decision-making on soil management and fertilizer use.

From a policymaker perspective, the study highlights the importance of supporting the adoption of modern agricultural technologies. Providing financial incentives, such as subsidies for technology purchases or low-interest loans, can motivate farmers to adopt more efficient practices. Developing adequate infrastructure, such as access to the internet and training farmers in the use of digital technologies, is also important to ensure that these technologies can be implemented effectively in the field.

Academics also have a role to play in supporting further research that helps understand the most effective data-driven soil management practices in urban environments. This further research can provide guidance for farmers and policymakers to design appropriate approaches to optimize soil fertility.

Overall, this study emphasizes the importance of sustainable land management in urban areas experiencing urbanization pressures. Technology-based and adaptive approaches allow for increased agricultural productivity on limited land while maintaining ecosystem balance and environmental sustainability. The results of this study can form the basis for developing more effective agricultural policies and practices in other urban areas facing similar challenges. Thus, the success of maintaining agricultural productivity in urban areas depends heavily on adapting to dynamic conditions and integrating local knowledge with advanced technological innovations.

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