

Utilization of Domestic Sewon Bantul Sewage Sludge as Raw Material for Granular Organic Fertilizer (GOF)

Ryan Bazaliel Alexandro Timpua* , Warsiyah, Endah Ayuningtyas, Rita Dewi
Triastianti

Institut Teknologi Yogyakarta, Indonesia

Email: ryan25timpua@gmail.com* , iwarity@gmail.com, endaha25@ity.ac.id,
rita.dewi0563@gmail.com

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Abstract

Domestic wastewater treatment plant (WWTP) sludge still contains organic matter and nutrients, indicating its potential for beneficial reuse. This study aimed to analyse the physicochemical characteristics of dried sludge from Sewon WWTP, Bantul Regency, and to evaluate its potential as a raw material for granular organic fertilizer through physical stabilisation without active composting. Dried sludge obtained from the sludge drying bed was formulated into four treatments: 100% sludge (F1), sludge combined with cattle manure (F2), sludge combined with fermented organic fertilizer mijongan (F3), and sludge combined with rice husk (F4), each at a 1:1 ratio. The processing stages included crushing, mixing, manual granulation using starch as a binder, and laboratory analysis of pH, moisture content, organic carbon, total nitrogen, total phosphorus, total potassium, and C/N ratio, with results compared against national solid organic fertilizer standards. The results showed that all formulations met the requirements for pH and organic carbon content. Variations were observed in moisture content, total nitrogen, and C/N ratio. Total phosphorus and potassium did not meet the minimum standard of $\geq 2\%$ across any of the formulations. The F4 formulation (sludge combined with rice husk) demonstrated the most balanced physicochemical quality, with a moisture content of 7.77%, total nitrogen of 2.15%, and a C/N ratio of 16.96. Overall, Sewon WWTP sludge shows potential as a raw material for granular organic fertilizer; however, further formulation optimisation is required to meet the minimum standards for phosphorus and potassium content.

INTRODUCTION

Here is the proofread passage with corrections applied, non-English and technical terms italicised, and paragraph form retained:

Domestic wastewater originates from household activities such as bathing, washing, toileting, and cooking. This wastewater contains organic matter, nutrients, detergents, and pathogenic microorganisms (Mousavi & Khodadoost, 2019). If discharged directly into the environment without adequate treatment, it can cause a decline in the quality of groundwater and surface water bodies, trigger eutrophication, and increase the risk of waterborne disease transmission, thereby endangering public health (Nelwan et al., 2003). The existence of an adequate and sustainable domestic wastewater treatment system is therefore a fundamental requirement for maintaining environmental quality and public health (Agarwal et al., 2022; Koul et al., 2022; Organization, 2021).

One of the by-products generated through the wastewater treatment process is WWTP (Wastewater Treatment Plant) sludge. This sludge is formed through physical, chemical, and biological treatment stages and still contains organic matter, nitrogen, phosphorus, and other

nutrients that theoretically have the potential for reuse. In practice, however, particularly in settlement-scale domestic wastewater treatment facilities, this sludge is still widely treated as final waste to be disposed of, creating an additional burden in its management and posing a risk of environmental pollution if not handled properly (Marsono, 2022).

Sewon Bantul WWTP is one of the largest domestic wastewater treatment facilities in the Special Region of Yogyakarta (Daerah Istimewa Yogyakarta/DIY), with sludge production reaching approximately $\pm 3,000$ m³ per year (Balai PIALAM, 2025). The majority of the processed sludge has thus far only been dried and disposed of at the Piyungan Final Disposal Site (Tempat Pembuangan Akhir/TPA), which has experienced capacity constraints and operational stoppages on several occasions (Rezky et al., 2025). This condition underscores the need for alternative sludge management approaches oriented not merely toward disposal but toward more productive and sustainable utilisation (Aryanfar et al., 2025; Choudhary et al., 2026; Joo et al., 2015).

An internal study by Balai PIALAM (2025) indicates that Sewon WWTP sludge contains organic matter and nutrients of sufficient quality to warrant development as solid organic fertilizer or Granular Organic Fertilizer (GOF). This utilisation effort has been developed through multi-stakeholder collaboration involving DLHK DIY (the Regional Environment and Forestry Agency of DIY), BPDAS (the Watershed Management Agency), local governments, academics, and the community, in line with the principles of the circular economy through the conversion of sludge into value-added resources.

The use of sludge as organic fertilizer is also supported by a national regulatory framework (Christodoulou & Stamatelatu, 2016). Government Regulation Number 81 of 2012 encourages the reuse of organic waste prior to its disposal into the environment. In addition, the Decree of the Minister of Agriculture Number 261/KPTS/SR.310/M/4/2019 stipulates quality parameters for organic fertilizers — including moisture content, pH, C/N ratio, macronutrient content, and heavy metal limits — as technical references for product safety and quality (Arias et al., 2022; Cucina et al., 2021; Kominko et al., 2018; Sugurbekova et al., 2023).

This study was conducted to examine the physicochemical characteristics of Sewon WWTP sludge, to formulate granule variations with organic additives, and to evaluate the quality of the final product against applicable quality standards. The approach adopted is simple physical stabilisation without active composting, which is consistent with FAO (2020) and US EPA (2021) guidelines stipulating that sludge that has undergone biological treatment and drying in sludge drying beds may be categorised as partially stabilised biosolids and is suitable for further processing into organic fertilizer.

This research is expected to provide both theoretical and practical benefits. Theoretically, this study contributes to the development of knowledge in the fields of waste management and organic fertilizer technology, particularly regarding the use of domestic WWTP sludge as a raw material for granular organic fertilizer through simple physical stabilisation methods without active composting. The findings also enrich the literature on the circular economy approach in the context of domestic wastewater treatment. Practically, the results of this study can serve as a reference for the Sewon Bantul WWTP management and related stakeholders (DLHK DIY, BPDAS, and local governments) in developing sludge-based granular organic fertilizer products as an alternative to landfill disposal, thereby

reducing the burden on final disposal sites and generating economic value. Furthermore, this research provides initial formulation recommendations that can be further optimised by researchers and practitioners to improve the quality of the organic fertilizer produced, particularly with respect to phosphorus and potassium content, in order to meet national standards.

RESEARCH METHODS

Research Location and Time

The research will be carried out in 2025–2026 with sludge objects from domestic wastewater treatment from the Sewon Bantul WWTP, Special Region of Yogyakarta. Sampling was carried out at the Sewon WWTP sludge drying bed unit using the grab sampling method at one representative point with the driest sludge conditions visually. Laboratory analysis was carried out at the Environmental Quality Laboratory, Faculty of Civil Engineering and Planning, Islamic University of Indonesia.

Formulation Variations

The study used four variations of Sewon WWTP sludge-based granular organic fertilizer formulations with a total mixed weight of 150 grams per formulation:

F1 = 100% domestic sludge (control, no additives)

F2 = 50% domestic sludge + 50% manure (1:1 ratio)

F3 = 50% domestic sludge + 50% organic fertilizer (1:1 ratio)

F4 = 50% domestic sludge + 50% rice husk (1:1 ratio)

The entire process of mixing and forming the granules is carried out manually without the addition of bioactivators or advanced fermentation processes, according to the simple physical stabilization approach that is the focus of the research.

Granule Manufacturing Procedure

The stages of making granules are carried out as follows: (1) Manual destruction of dry WWTP sludge using a small shovel until a smaller and relatively uniform particle size is obtained; (2) Refining of additives, especially rice husks, using coffee grinder to reduce the particle size; (3) Weighing of ingredients according to the composition of the formulation that has been determined; (4) Manual mixing of ingredients in the mixing container until homogeneous; (5) The addition of adhesive material in the form of starch flour of 5% of the total dry weight of the material which is first dissolved with water in a limited amount; (6) Manual granule formation with hand pressure until the granule size ranges from ± 0.4 –1.0 cm; (7) Drying of granules naturally through drying at ambient temperature until stable conditions; and (8) Preparation of laboratory test samples by crushing granules into fine powders according to the requirements of analysis.

Parameters and Analysis Methods

The parameters analyzed included two groups: (a) Physical parameters, namely moisture content using the oven drying method at 105°C, as well as descriptive observation of color, odor, and texture; (b) Chemical parameters are pH using digital pH meter, C-organic using the CHNS method, total nitrogen (N-total) using the CHNS method, total phosphorus (P-total) using the X-Ray Fluorescence (XRF) method, total potassium (K-total) using the XRF method, and the C/N ratio is calculated mathematically from the value of C-organic divided by N-total. All test results were compared with the quality standards of SNI

7763:2018 and the Decree of the Minister of Agriculture Number 261/KPTS/SR.310/M/4/2019. Data analysis was carried out descriptively, quantitatively, and comparatively.

RESULTS AND DISCUSSION

Early Physical Characteristics of Sewon WWTP Mud

Sewon WWTP sludge taken from the sludge drying bed unit showed relatively stable physical conditions before formulation treatment. Visually, the mud is gray to brownish-gray with a pattern of cracks and hollow structures that resemble draining rice fields. The texture of mud is relatively dense and hard, not easily destroyed without mechanical treatment. Organoleptically, the mud does not show a pungent odor, but only smells of light soil typical of processed organic matter. This condition indicates that the sludge has experienced a significant decrease in moisture content and biological activity through the treatment process in the WWTP unit and natural drying in the sludge drying bed.

This physical character is in line with the concept of partially stabilized biosolids as stated by the US EPA (2021) and Metcalf & Eddy (2014) that sludge that has undergone aerobic biological treatment and drying in sludge drying beds can be categorized as sludge that has undergone partial stabilization. Thus, the sludge used in this study is not raw sludge, but a material that is ready to be further processed through the formulation and granulation stages.

Granule Formulation and Formation Results

The entire formulation can be formed into granules through a manual granulation process with granule sizes ranging from ± 0.4 –1.0 cm. The F2 formulation (sludge + manure) results in a relatively more uniform granule because the fine texture of the manure supports the particle union process. The F4 formulation (sludge + husk) produces a lighter and more porous granule due to the physical properties of the husk which is lignocellulose and low density. The F1 and F3 formulations produce granules with a degree of uniformity between the two formulations.

The use of starch flour as a 5% adhesive has been shown to be effective in improving cohesion between particles by forming a binding matrix that holds the sludge and additives together. The addition of starch-based adhesives helps to increase the resistance of the granules to mild compressive forces during initial handling (Haug, 2018). The process of smoothing husks using a coffee grinder also contributes to increasing the homogeneity of the mixture because it expands the surface area of contact between the husk and the sludge.

pH Test Results

pH testing is carried out to determine the acidity or alkaline level of each granular organic fertilizer formulation. The test results are presented in Table 1 below.

Table 1. pH Test Results

Yes	Formula	Actual pH	Quality Standards	Remarks
1	100% Sludge Granules (F1)	4,0	4 – 9	Meet
2	Sludge Granules + Manure (F2)	4,0		Meet

3	Mud Granules + Mijongan (F3)	4,0	Meet
4	Mud Granules + Rice Husks (F4)	4,5	Meet

Source: Primary Data (2025). Quality standards: SNI 7763:2018 and Ministry of Agriculture No. 261/2019.

pH value of the entire formulation (F1 = F2 = F3 = 4.0; F4 = 4.5) is within the quality standard range of 4–9, so all formulations meet the requirements. The small pH variation between formulations indicates that Sewon WWTP sludge as the main material has a stable buffer capacity. The natural drying process in the sludge drying bed plays a role in reducing the activity of organic acid-producing microorganisms, so that the pH tends to be constant (Metcalf & Eddy, 2014). Each additive makes a different contribution: manure tends to raise the pH due to the ammonia content, mijongan has a stable pH due to fermentation that has taken place, while husks are relatively chemically inert. The pH stability of the entire formulation supports the product's feasibility in terms of basic chemical safety and does not require additional correction treatment (Havlin et al., 2014).

Moisture Content Test Results

Moisture content testing is carried out to determine the percentage of water content in each formulation. The test results are presented in Table 2 below.

Table 2. Moisture Content Test Results

Yes	Formula	Units	Up Air	Quality Standards	Remarks
1	100% Sludge Granules (F1)	%	9,62	8 – 25	Meet
2	Sludge Granules + Manure (F2)	%	33,20		Not Fulfilled
3	Mud Granules + Mijongan (F3)	%	12,68		Meet
4	Mud Granules + Rice Husks (F4)	%	7,77		Meet

Source: Primary Data (2025). Quality standards: SNI 7763:2018 and Ministry of Agriculture No. 261/2019.

There is considerable variation in moisture content between formulations, ranging from 7.77% (F4) to 33.20% (F2). The F4 formulation (sludge + husk) shows the lowest moisture content due to the lightweight, porous, and high aeration capacity and low hygroscopic properties, thus accelerating water evaporation during processing (Stevenson, 1994). In contrast, F2 formulations (sludge + manure) have the highest moisture content which is associated with the ability of manure to absorb and retain moisture due to the content of fine organic matter that is hygroscopic (Haug, 2018). Based on the quality standard of 8–25%, F1, F3, and F4 formulations meet the requirements, while F2 does not meet and requires advanced drying before it can be used as a stable solid organic fertilizer. Too high a moisture content can trigger continuous decomposition, cause unpleasant odors, and reduce the shelf life of fertilizers (BSN, 2018).

C-Organic Testing Results

C-organic testing is carried out using the CHNS method to determine the organic carbon content of each formulation. The test results are presented in Table 3 below.

Table 3. C-Organic (C) Testing Results

No	Formula	Units	C-Organic (C)	Quality Standards	Remarks
1	100% Sludge Granules (F1)	%	55,40	≥ 15	Meet
2	Sludge Granules + Manure (F2)	%	59,72		Meet
3	Mud Granules + Mijongan (F3)	%	34,30		Meet
4	Mud Granules + Rice Husks (F4)	%	36,47		Meet

Source: Primary Data (2025). Quality standards: SNI 7763:2018 and Ministry of Agriculture No. 261/2019.

The C-organic content of the entire formulation is well above the minimum limit $\geq 15\%$, with the highest value at F2 (59.72%) and lowest at F3 (34.30%). The high C-organic content reflects the dominance of the fraction of organic matter in the Sewon WWTP sludge as the main material. The F2 formulation shows the highest value because manure contains a high fraction of activated organic carbon. The F4 formulation shows 36.47% C-organic because the rice husk is rich in lignocellulose which contributes to structural carbon. The F3 formulation shows the lowest value because fermented mijongan has a content of volatile carbon fractions that have been reduced during the previous fermentation process. The high C-organic content of all formulations supports the role of fertilizers in improving the physical and biological properties of soils, including increased cation exchange capacity (CEC), soil aggregation, and soil's ability to hold water (Brady & Weil, 2016).

Total Nitrogen Test Results

Total nitrogen testing was performed using the CHNS method. The test results are presented in Table 4 below.

Table 4. Total Nitrogen Test Results (N)

No	Formula	Units	N-Total (N)	Quality Standards	Remarks
1	100% Sludge Granules (F1)	%	3,00	≥ 2	Meet
2	Sludge Granules + Manure (F2)	%	3,23		Meet
3	Mud Granules + Mijongan (F3)	%	1,25		Not Fulfilled
4	Mud Granules + Rice Husks (F4)	%	2,15		Meet

Source: Primary Data (2025). Quality standards: SNI 7763:2018 and Ministry of Agriculture No. 261/2019.

Total nitrogen values vary from 1.25% (F3) to 3.23% (F2). F1, F2, and F4 formulations meet the minimum limit of $\geq 2\%$, while F3 does not. The highest nitrogen content in F2 can be explained by the manure's rich properties of protein compounds and amino acids as a source of organic nitrogen (Havlin et al., 2014). The low nitrogen in F3 is likely due to a previous fermentation process that causes some readily available nitrogen to be degraded or released in the form of volatilization of ammonia during fermentation (Bernal et al., 2009). Rice husks have a low nitrogen contribution because they are composed predominantly by lignocellulose and silica. Nitrogen is the main macronutrient that plays a role in the formation of chlorophyll, amino acids, and proteins, so its content determines the agronomic value of organic fertilizers (Marschner, 2012).

Total Phosphorus Test Results

Total phosphorus testing was carried out using the X-Ray Fluorescence (XRF) method. The test results are presented in Table 5 below.

Table 5. Total Phosphorus Test Results (P)

Yes	Formula	Units	P-Total (P)	Quality Standards	Remarks
1	100% Sludge Granules (F1)	%	0,81	≥ 2	Not Fulfilled
2	Sludge Granules + Manure (F2)	%	0,77		Not Fulfilled
3	Mud Granules + Mijongan (F3)	%	0,88		Not Fulfilled
4	Mud Granules + Rice Husks (F4)	%	0,90		Not Fulfilled

Source: Primary Data (2025). Quality standards: SNI 7763:2018 and Ministry of Agriculture No. 261/2019.

The total phosphorus content of the entire formulation ranges from 0.77–0.90%, which is below the national standard minimum limit $\geq 2\%$. As such, all formulations have not met the total phosphorus requirements. The low phosphorus content indicates that the Sewon WWTP sludge is not the dominant source of phosphorus, and the additives used are not able to significantly increase the phosphorus content. Manure generally contains phosphorus from feed residues and animal metabolism, while mijongan stores a certain amount of organic phosphate fractions, but neither is sufficient to push the total P content beyond the minimum limit of 2%. Rice husks are relatively poor in phosphorus, so their contribution is very limited. Strengthening of phosphorus elements through the addition of natural phosphate sources is required for further research (Brady & Weil, 2016).

Total Potassium Test Results

Total potassium testing was performed using the X-Ray Fluorescence (XRF) method. The test results are presented in Table 6 below.

Table 6. Total Potassium Test Results (K)

Yes	Formula	Units	K-Total (K)	Quality Standards	Remarks
1	100% Sludge Granules (F1)	%	0,43	≥ 2	Not Fulfilled
2	Sludge Granules + Manure (F2)	%	1,79		Not Fulfilled
3	Mud Granules + Mijongan (F3)	%	0,75		Not Fulfilled
4	Mud Granules + Rice Husks (F4)	%	0,47		Not Fulfilled

Source: Primary Data (2025). Quality standards: SNI 7763:2018 and Ministry of Agriculture No. 261/2019.

The total potassium content of the entire formulation ranges from 0.43–1.79%, all of which are below the national standard minimum limit $\geq 2\%$. The F2 formulation showed the highest potassium value (1.79%) because manure naturally contains potassium from feed residues and animal metabolism, but the value still does not meet the standard. The F4 formulation showed the lowest potassium value (0.47%) because rice husks are composed predominantly by silica and lignocellulose which are very low in potassium. WWTP sludge as the main ingredient is not a significant source of potassium, so the variation of potassium in the final product is more determined by the composition of the additives. Potassium plays a role in regulating plant water balance, enzyme activation, and increasing resistance to environmental stress and disease (Marschner, 2012), so a strategy for adding potassium sources is needed to improve the nutritional quality of products.

C/N Ratio Calculation Results

The C/N ratio is calculated from the C-organic value divided by the total nitrogen in each formulation. The results of the calculation are presented in the following Table 7.

Table 7. C/N Ratio Calculation Results

Yes	Formula	Units	C/N Ratio	Quality Standards	Remarks
1	100% Sludge Granules (F1)	%	18,47	≤ 25	Meet
2	Sludge Granules + Manure (F2)	%	18,49		Meet
3	Mud Granules + Mijongan (F3)	%	27,44		Not Fulfilled
4	Mud Granules + Rice Husks (F4)	%	16,96		Meet

Source: Primary Data (2025). Quality standards: SNI 7763:2018 and Ministry of Agriculture No. 261/2019.

The C/N ratio varies from 16.96 (F4) to 27.44 (F3). Formulations F1 (18.47), F2 (18.49), and F4 (16.96) meet the maximum limit of ≤25, while F3 (27.44) does not. The C/N F4 ratio in the range of 15–20 indicates relatively stable organic matter conditions and supports gradual nitrogen mineralization without causing immobilization (Havlin et al., 2014). The high C/N F3 ratio reflects the dominance of carbon relative to nitrogen due to the low N content in the formulation, which has the potential to cause nitrogen immobilization by soil microorganisms when applied to the soil (Bernal et al., 2009). The variation in the C/N ratio between formulations is influenced by the combination of carbon and nitrogen sources in the mixture: husks rich in structural carbon but poor in nitrogen produce a lower C/N ratio when combined with sludge that is quite rich in N, while mijongan with low N produces the highest ratio.

Recapitulation of Quality Parameter Conformity to National Standards

All results of testing the quality parameters of granular organic fertilizer based on Sewon WWTP are summarized and evaluated for conformity to national standards (SNI 7763:2018 and Ministry of Agriculture No. 261/2019) as presented in Table 8 below.

Table 8. Recapitulation of Conformity of Granular Organic Fertilizer Quality Parameters to National Standards

Parameter	Units	F1 (100% Lumpur)	F2 (+ Cage)	F3 (+ Mijongan)	F4 (+ Husk)	Quality Standards	Status
pH	-	4,0	4,0	4,0	4,5	4 – 9	All ✓
Up Air	%	9,62	33,20	12,68	7,77	8 – 25	F2 ✗
C-Organic	%	55,40	59,72	34,30	36,47	≥ 15	All ✓
N-total	%	3,00	3,23	1,25	2,15	≥ 2	F3 ✗
P-total	%	0,81	0,77	0,88	0,90	≥ 2	All ✗
K-total	%	0,43	1,79	0,75	0,47	≥ 2	All ✗
C/N Ratio	%	18,47	18,49	27,44	16,96	≤ 25	F3 ✗

Source: Primary Data (2025/2026). ✓ = fulfill; ✗ = not fulfilled. Reference: SNI 7763:2018 and Ministry of Agriculture No. 261/KPTS/SR.310/M/4/2019.

Based on the recapitulation in Table 8, there are two parameters that are met by all formulations, namely pH and C-organic. The moisture content parameters were met by F1, F3, and F4, while F2 did not meet the high moisture content (33.20%). The total nitrogen parameters are met by F1, F2, and F4, while F3 does not meet (1.25%). The parameters of

total phosphorus and total potassium were not met by all formulations, indicating systemic limitations in the content of these two elements in the Sewon WWTP sludge and the organic additives used. The C/N ratio parameters are met by F1, F2, and F4, while F3 does not meet the consequences of too high a ratio (27.44).

Determination of the Best Formulation

Based on a thorough evaluation of all quality parameters, there is no single formulation that meets all the requirements of national standards simultaneously. However, the F4 formulation (sludge + rice husk) showed the most proportional balance of parameters and was determined as the best formulation in this study based on: (1) the fulfillment of four of the seven parameters tested (pH, moisture content, C-organic, N-total, and C/N ratio); (2) the lowest moisture content (7.77%) which supports storage stability; (3) the optimal C/N ratio (16.96) which is in the range of 15–20 according to Havlin et al. (2014); and (4) a balance between physical and chemical properties that is more proportionate than other formulations.

The F2 formulation (sludge + manure) excels in C-organic content (59.72%) and total nitrogen (3.23%), but the very high moisture content (33.20%) lowers the physical stability of the product and is the main limiting factor. The F3 formulation (mud + mijongan) shows the lowest nitrogen (1.25%) and the highest C/N ratio (27.44) that exceeds the standard limit, thus having a weakness in the carbon and nitrogen balance. F1 formulations (100% sludge) have good organic and nitrogen content as control ingredients, but do not show an increase in P and K elements compared to mixed formulations.

These findings also show that the first hypothesis of the study (H_1) is proven, namely that the dry sludge of the Sewon WWTP meets most of the basic parameters of solid organic fertilizer raw materials. However, the second hypothesis (H_2) is not fully proven, because the F2 formulation (sludge + manure) that is predicted to be the optimal formulation does not show the most stable overall performance due to the high moisture content. The best formulation must consider the balance of all quality parameters, not just the dominance of one particular nutrient.

CONCLUSION

Based on the results of the study on the use of Sewon Bantul WWTP sludge as a raw material for Granular Organic Fertilizer (GOF) through simple physical stabilisation, the following conclusions were drawn.

The physicochemical characteristics of the dried sludge from Sewon WWTP demonstrate its potential as a raw material for solid organic fertilizer. Chemically, the sludge achieved full compliance with the parameters of pH (4.0), C-organic (55.40%), total nitrogen (3.00%), and C/N ratio (18.47) in accordance with national standards. However, the phosphorus content (0.81%) and potassium content (0.43%) remain below the minimum threshold of $\geq 2\%$, necessitating enrichment of P and K elements for the product to fully meet the applicable standards.

The formulation and granulation process yielded varying quality across the four formulations. The F4 formulation (sludge combined with rice husk) demonstrated the most balanced and stable parameter profile, with the lowest moisture content (7.77%), compliant total nitrogen (2.15%), an optimal C/N ratio (16.96), and adequate C-organic content

(36.47%). All formulations met the pH and C-organic parameters; however, none met the standards for phosphorus (0.77–0.90%) or potassium (0.43–1.79%). Compositional optimisation to increase P and K content is therefore required for the product to meet national standards in their entirety.

Based on these findings, several recommendations are proposed. Further research should incorporate natural phosphate sources — such as rock phosphate or bone meal — and potassium-rich materials — such as wood ash or potassium salt — into the formulations in order to raise total P and K levels above the minimum standard of $\geq 2\%$. For the F2 formulation (sludge combined with cattle manure), an extended drying period or mechanical dewatering should be applied to reduce moisture content to within the acceptable range of 8–25%. Pilot-scale production and field application trials are recommended to evaluate the agronomic effectiveness of the best-performing formulation (F4) in terms of plant growth and soil health. Finally, regulatory bodies may consider developing specific technical guidelines for organic fertilizers derived from domestic WWTP sludge to facilitate their safe and sustainable reuse.

REFERENCE

- Agarwal, S., Darbar, S., & Saha, S. (2022). Challenges in management of domestic wastewater for sustainable development. In *Current directions in water scarcity research* (Vol. 6, pp. 531–552). Elsevier.
- Arias, O., Pulgar, J. A., & Soto, M. (2022). Application of organic wastes to soils and legislative intricacies in a circular economy context. *Clean Technologies and Environmental Policy*, 24(6), 1871–1888.
- Aryanfar, Y., García Alcaraz, J. L., Keçebaş, A., Fernandez, J. B., Arslan, B., Ilbas, M., Algarni, S., Alqahtani, T., & Irshad, K. (2025). Transforming food industrial sludge into sustainable resources: Innovations in waste management and renewable energy recovery. *Business Strategy and the Environment*, 34(3), 3672–3700.
- Balai PIALAM. (2025). Pengelolaan lumpur IPAL dan IPLT menjadi granular organic fertilizer (GOF) berbasis multistakeholder. Balai PIALAM.
- Brady, N. C., & Weil, R. R. (2016). *The nature and properties of soils* (15th ed.). Pearson Education Limited.
- Choudhary, J. K., Polavarapu, M. P., Singh, A. K., Shukla, S. K., & Kumar, M. (2026). Recent advances in sewage treatment technologies and sustainable sludge management practices. In *Municipal sewage and sludge: Treatment and disposal strategies: Management of sewage and sludge* (pp. 345–365).
- Christodoulou, A., & Stamatelatu, K. (2016). Overview of legislation on sewage sludge management in developed countries worldwide. *Water Science and Technology*, 73(3), 453–462.
- Cucina, M., De Nisi, P., Sordi, S., & Adani, F. (2021). Sewage sludge as N-fertilizers for crop production enabling the circular bioeconomy in agriculture: A challenge for the new EU regulation 1009/2019. *Sustainability*, 13(23), 13165.
- FAO. (2020). *Guidelines for sustainable production and use of organic fertilizers*. Food and Agriculture Organization of the United Nations.
- Haug, R. T. (2018). *The practical handbook of compost engineering* (2nd ed.). CRC Press.
- Havlin, J. L., Tisdale, S. L., Nelson, W. L., & Beaton, J. D. (2014). *Soil fertility and fertilizers: An introduction to nutrient management* (8th ed.). Pearson.
- Joo, S. H., Dello Monaco, F., Antmann, E., & Chorath, P. (2015). Sustainable approaches for minimizing biosolids production and maximizing reuse options in sludge

- management: A review. *Journal of Environmental Management*, 158, 133–145.
- Kominko, H., Gorazda, K., Wzorek, Z., & Wojtas, K. (2018). Sustainable management of sewage sludge for the production of organo-mineral fertilizers. *Waste and Biomass Valorization*, 9(10), 1817–1826.
- Koul, B., Yadav, D., Singh, S., Kumar, M., & Song, M. (2022). Insights into the domestic wastewater treatment (DWWT) regimes: A review. *Water*, 14(21), 3542.
- Marschner, P. (2012). *Marschner's mineral nutrition of higher plants* (3rd ed.). Academic Press.
- Marsono, M. R. (2022). Pemanfaatan lumpur IPAL komunal Asrama Dinas Lingkungan Hidup Jagakarsa Kota Jakarta Selatan sebagai bahan dasar pupuk organik [Tesis magister, Universitas Pertamina].
- Metcalf & Eddy. (2014). *Wastewater engineering: Treatment and resource recovery* (5th ed.). McGraw-Hill Education.
- Mousavi, S. A., & Khodadoost, F. (2019). Effects of detergents on natural ecosystems and wastewater treatment processes: A review. *Environmental Science and Pollution Research*, 26(26), 26439–26448.
- Rezky, A. P., Al Khalidi, S. M., Firdaus, A., & Saputri, A. (2025). Waste management challenges in Yogyakarta: A study using multiple perspective analysis. *Jurnal Ilmiah Administrasi Publik*, 11(2), 173–186.
- Sugurbekova, G., Nagyzbekkyzy, E., Sarsenova, A., Danlybayeva, G., Anuarbekova, S., Kudaibergenova, R., Frochot, C., Acherar, S., Zhatkanbayev, Y., & Moldagulova, N. (2023). Sewage sludge management and application in the form of sustainable fertilizer. *Sustainability*, 15(7), 6112.
- World Health Organization. (2021). *Progress on wastewater treatment: Global status and acceleration needs for SDG indicator 6.3.1*. World Health Organization.