

Agronomic Response of Crape Jasmine (*Tabernaemontana divaricata*) to WUPA Wastewater Sludge Conditioned with Hybrid Conditioners: Soil Remediation Potential and Economic Feasibility

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Abstract - The sustainable management of sewage sludge remains a main environmental task due to increasing wastewater treatment activities worldwide. This study explored the agronomic response of Crape Jasmine (*Tabernaemontana divaricata*) cultivated on WUPA wastewater sludge conditioned with *Moringa oleifera* (MO) and cationic polyacrylamide (CPAM), as well as the economic feasibility of the conditioning process. Five different sludge treatments were evaluated: soil only (control), soil plus sludge, soil plus sludge plus MO, soil plus sludge plus CPAM, and soil plus sludge plus MO plus CPAM. Plant growth parameters including height, leaf number, bud number, flower number, and root length were monitored over eight weeks. The Soil + Sludge treatment produced the greatest plant height (45.68 cm), while the hybrid MO + CPAM conditioned sludge significantly increased leaf number (52.18), bud production (2.18), flower production (0.77), and root length (18.25 cm). Enhanced root development and reproductive growth showed improved nutrient availability and soil quality. Economic analysis showed that treatment of 2,000 kg of sludge using a 6:4 MO:CPAM blend resulted in a total cost of ₦528,000, equivalent to ₦264 kg⁻¹ sludge. Although MO alone represented the most economical option, hybrid conditioning produced superior agronomic benefits and greater resource recovery potential. The findings demonstrate that conditioned sewage sludge can be transformed into a valuable soil amendment suitable for ornamental horticulture and sustainable land restoration.

Keywords: Sewage sludge; Soil remediation; *Moringa oleifera*; Cationic polyacrylamide; Biosolids; Circular economy; *Tabernaemontana divaricata*.

1. INTRODUCTION

The rapid expansion of urban populations and wastewater treatment infrastructure has resulted in increased generation of sewage sludge globally. Disposal and management of sludge remain major environmental issues because conventional methods including landfilling, incineration, and ocean disposal are associated with substantial environmental and economic costs. Consequently, attention has shifted toward sustainable sludge management approaches that emphasize resource recovery and beneficial reuse. Sewage sludge contains valuable nutrients including nitrogen, phosphorus, potassium, organic carbon, and trace elements capable of improving soil fertility and supporting plant growth. When adequately treated and conditioned, sludge may serve as a soil amendment that improves soil structure, moisture retention, microbial activity, and nutrient availability. Its utilization in agriculture and horticulture therefore represents a promising strategy within the framework of circular economy principles. Dewatering and conditioning are critical steps in sludge management because they reduce sludge volume, lower transportation costs, improve handling characteristics, and enhance resource recovery. Synthetic polymers such as cationic polyacrylamide (CPAM) have been widely used as sludge conditioners because of their effectiveness in flocculation and dewatering operations. However, their high operational cost and environmental concerns have motivated research into sustainable alternatives. *Moringa oleifera* has emerged as a promising natural conditioner due to its biodegradable nature, non-toxicity, availability, and low cost. Proteins present in *Moringa* seeds possess coagulation properties capable of promoting particle aggregation and improving sludge dewatering efficiency. Combining natural conditioners with synthetic polymers can produce synergistic effects that improve dewatering performance while reducing chemical consumption.

Conditioning of sewage sludge (SS) has been pinpointed as a potential approach for improving its dewaterability and reducing its environmental impacts [1]. Cat-ionic polyacrylamide (CPAM) is a widely used polymer that is utilized as a conditioning agent for SS due to its ability to modify sludge dewaterability and lessen sludge volume [2]. Moringa oleifera (MO), on the other hand, is a natural conditioner/coagulant discovered to be effective in removing contaminants from wastewater. [3] Using Moringa oleifera not only aids in effective sludge conditioning but also enhances soil properties when applied as soil amendment. This method reduces reliance on synthetic chemicals, thereby mitigating environmental impacts with chemical sludge conditioners. Soil remediation using conditioned SS is a potential approach for restoring agricultural soils (Intensive farming nutrient depletion/acidic soil/alkaline soil).

Recently, interest has grown in using natural and biodegradable conditioning agents, such as plant-based polymers and bio flocculants. Moringa oleifera, a tropical plant, has been pinpointed as a potential source of natural coagulants and flocculants. The seeds of Moringa oleifera contain a water-soluble protein shown to have coagulation and flocculation properties [4].

Although several studies have investigated sludge conditioning technologies, limited information exists regarding the agronomic effectiveness of soils amended with sludge conditioned using hybrid MO-CPAM systems. Furthermore, information regarding their economic viability in developing countries remains scarce.

Longstanding conditioning methods, oftentimes do not attain adequate dewatering, resulting in high quantity of sludge which is costly to manage [5]. The utilization of cat-ionic Polyacrylamine Co-polymer (CPAM) for sludge treatment has constraints owing to extreme dose demands, significant issue to environment [6]. Limited comprehension of combined influences of CPAM and MO obstruct the progress of ideal sludge treatment techniques. This research aims to investigate a new framework using a combination of polyacrylamide based Super-absorbent Polymers (CPAM) and Moringa Oleifera seed to evaluate the optimal dosage and combination ratio of PAMS and MO seed for maximum removal of contaminants from sewage sludge, improve sludge conditioning for soil remediation and promote sustainable practices in wastewater treatment.

Crape Jasmine (*Tabernaemontana divaricata*) is a perennial ornamental shrub extensively cultivated in tropical and subtropical regions. Its rapid vegetative growth, continuous flowering behavior, and sensitivity to soil fertility make it a suitable indicator species for evaluating the agronomic performance of conditioned biosolids.

The present study therefore is aimed to:

- i. Conditioning of composite sludge samples from WUPA Wastewater Treatment Plant
- ii. Evaluate the growth response of *T. divaricata* cultivated in soil amended with conditioned WUPA wastewater sludge.
- iii. Compare agronomic performances of MO, CPAM, and hybrid MO-CPAM conditioned sludge.
- iv. Assess the potential of conditioned sludge for soil remediation.
- v. Determine the economic feasibility of hybrid sludge conditioning.

2. MATERIALS AND METHODS

2.1 Description of the Study Area

WUPA Sewage Treatment Plant is situated close to IDU industrial District, 900106, Abuja, Federal Capital Territory. Abuja is positioned in the geographical midpoint of Nigeria. The territory is an 8000km expanse of land. The plant is near the WUPA River and lies amid the latitude of $9^{\circ}02'20''$ and longitude $7^{\circ}38'21''$. It covers an area of 297,900 square meters and is designed to meet the necessities of 700,000 Population Equivalent (PE) denotation that the plant can house an average dry weather flow of 5,500 m³/hr. or 131,250 m³/day. It is also designed to treat sewage produced from phases I, II, III and IV of Abuja city. The plant was built to address the rising concern on discarding of sewage as Abuja transform into an intercontinental metropolitan [7].

Table 1: Various parameters of WUPA Sewage Treatment Plant [8]

1	Average dry weather flow	131,250 m ³ /day
2	Average hourly flow	5,500 m ³ /day
3	Peak flow	9,000 m ³ /day
4	BOD Load	4.2 ton/day
5	COD Load	8.4 ton/day

WUPA Basin sewage Treatment Plant is the biggest of its type in sub-Saharan Africa. It is renowned for its state-of-the-arts, high-tech and cutting-edge computerized components rating the plant at equivalence with the up-to-date treatment plants in the universe. The Treatment plant is environmentally friendly ensuring that the atmosphere of the town remains hygienic and

pleasing, guaranteeing improvement on the quality of underground water and streams as only treated water is discharged into its natural flow.

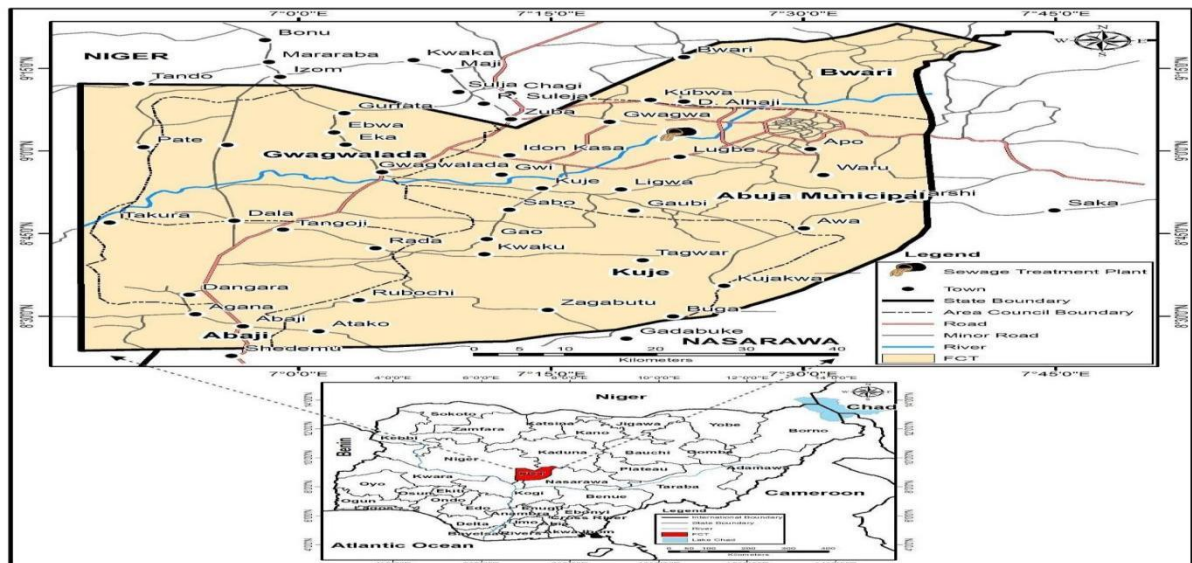


Figure 1: Map of Abuja showing the location of Wupa Basin Sewage Treatment Plant (WBSTP) Abuja and Wupa River. Sludge samples were obtained from the WUPA Wastewater Treatment Plant located in Abuja, Nigeria. The plant treats municipal wastewater generated from residential, institutional, and commercial activities within the Federal Capital Territory. The sampling method used is composite sampling where multiple samples were collected from different points in the reactor and combining them to create a representative sample.

2.2 Sludge Conditioning

Composite sludge samples from WUPA Wastewater Treatment Plant were conditioned using:

- MO (Moringa oleifera seed extract)
- CPAM (Cationic polyacrylamide)
- Hybrid MO + CPAM

2.3 Experimental Plant

Crape Jasmine (*Tabernaemontana divaricata*) was selected due to its ornamental importance, rapid vegetative response, and adaptability to different soil conditions.

2.4 Experimental Design

Table 2: A completely randomized design was adopted with five treatments:

Treatment	Description
T1	Soil only (Control)
T2	Soil + Sludge
T3	Soil + Sludge + MO
T4	Soil + Sludge + CPAM
T5	Soil + Sludge + MO + CPAM

Twenty percent conditioned sludge was mixed with eighty percent topsoil and placed into 3 kg pots.

2.5 Planting Procedure

Uniform six-week-old seedlings were transplanted into individual pots and maintained under identical environmental conditions. Plants were watered regularly and monitored for eight weeks.

Procedure for Planting and Monitoring of the Experimental Plant

- i. 6- weeks old seedling (shrubs) were bought in black nylon bags from nursery/garden centre in Industrial Estate Kukuaba FCT Abuja
- ii. Ten nos. of 3kg pots were filled with 20% sludge and 80% soil mix.
- iii. One plant was planted per pot in the evening hours.
- iv. The roots were checked and found to be settling around the pot, they were gently loosened to help them grow outwards into the container
- v. The plants were well positioned in the center of the container so that the first flare of roots was just below the surface of the soil. Care was taken not to bury the base of the stem
- vi. Ten pots containing the plants were positioned in the garden and watered regularly.
- vii. Growths of the plants were monitored and the parameters recorded weekly for 8 weeks.

2.6 Growth Assessment

The following parameters were measured weekly:

- Plant height (cm)
- Number of leaves
- Number of buds
- Number of flowers
- Root length (cm)

2.7 Economic Analysis

Economic evaluation considered:

- Cost of conditioning chemicals
- Treatment costs
- Cost-benefit relationships
- Scale-up implications

3.0 Results and Discussion

3.1 Growth Response of *Tabernaemontana divaricate*

The plant growth analysis was carried out in order to find the best treatment, explain the physiological mechanism and to link nutrient from sludge to plant function.

Table 3: Effect of conditioned sludge treatments on growth performance of *T. divaricata*

<i>Effect of sludge, MO, and PAMs on the vegetative characters of Crape Jasmine (Taberna Montana divaricate)</i>					
Treatment	Height (cm)	Leave No.	Bud No.	Flower No.	Root Length (cm)
Soil only (Control)	41.11 ^b	32.25 ^b	0.05 ^b	0.00 ^b	5.50 ^c
Soil + Sludge	45.68 ^a	36.57 ^b	1.14 ^{ab}	0.32 ^b	7.25 ^c
Soil + Sludge +MO	33.36 ^c	41.99 ^{ab}	0.50 ^b	0.14 ^b	13.50 ^b
Soil+ Sludge +PAM	42.28 ^{ab}	39.19 ^b	0.27 ^b	0.50 ^{ab}	9.50 ^{bc}
Soil+Sludge+MO+PAM	38.34 ^b	52.18 ^a	2.18 ^a	0.77 ^a	18.25 ^a

The effects of sludge, moringa, and PAM on growth of the vegetative character are presented on table 3. The table displayed a significant difference ($p \leq 0.05$) on the vegetative characters. The results showed that the mixture of soil + sludge (45.68) significantly produced the highest plant height when compared with the control, soil only (41.11) and the remaining treatments soil +sludge + PAMs (42.28), soil +sludge +MO+PAM (38.34) respectively. The least significant difference at ($p \leq 0.05$) was recorded in the mixture of soil +sludge + MO (33.36). However, in terms of the mean number of leaves, soil amendment; soil +sludge +MO+PAM (52.18) significantly produced the highest mean number of leaves at ($p \leq 0.05$) when compared with soil

amendment, soil +sludge +MO (41.99), and the remaining treatments. The result from the table also presented that soil amendment treatment soil +sludge +MO/PAM (2.18) significantly produced the highest number of buds at ($p \leq 0.05$), when compared to soil amendment soil +sludge (1.14). The minimum mean number of buds was recorded at soil amendment treatment soil +sludge +MO (0.5), soil +sludge +PAM (0.25) and the control group, soil only (0.05) respectively. Furthermore, soil amendment; soil +sludge +MO+PAM (0.77) significantly produced the maximum number of flowers at ($p \leq 0.05$) when compared to soil amendment soil +sludge +PAM (0.05). This was followed by soil mixture, soil + sludge (0.32) and soil+ sludge +MO 0.14) respectively. Maximum roots length was obtained in soil mixture soil + sludge +MO+PAM (18.25), which is significantly higher at ($p \leq 0.05$) compared to soil amendment soil +sludge +MO (13.50). This was followed by soil amendment soil +sludge +PAM (9.50) which is significantly higher at ($p \leq 0.05$) than soil +sludge (7.25) and the control, soil only (5.50) [9].

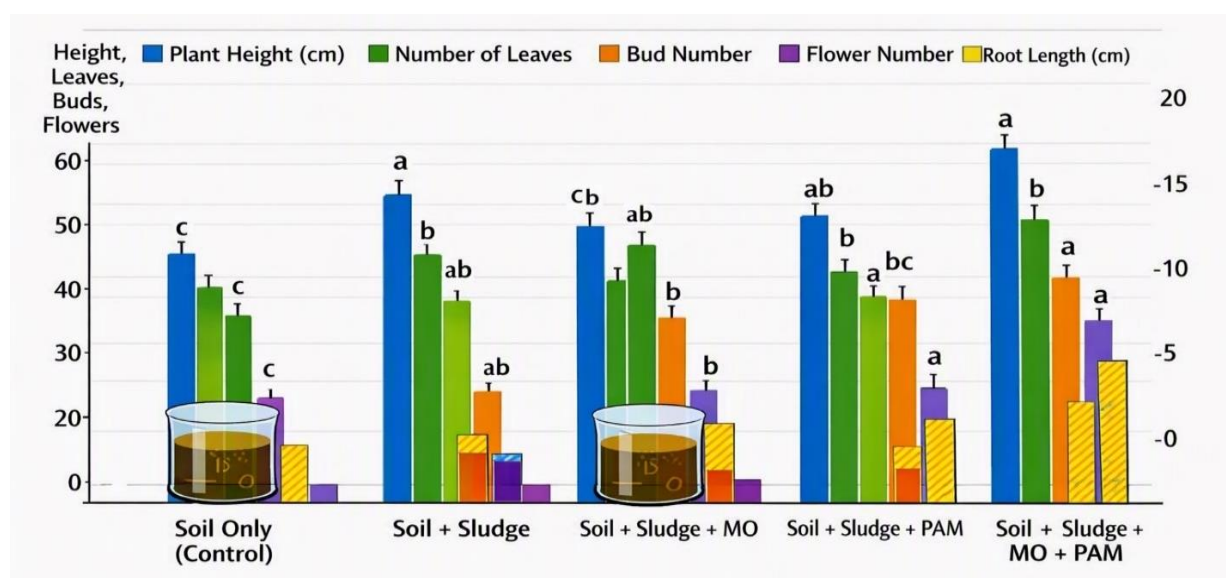


Figure 2: Effect of sludge, MO, and PAM on the vegetative characters of Crape Jasmine

Figure 2 shows that Soil + Sludge + MO + PAM portrayed the maximum total development with leaf number (52.18), bud number (2.18), flower number (0.77), and root length (18.25 cm) performing more than other treatments indicating robust vegetative potency. Soil + Sludge + MO remarkably boosted root elongation (13.5 cm), displaying *Moringa*'s bio-stimulating outcome. Soil + Sludge + PAM enhanced flowering (0.50) and sustained reasonable vegetative development, Soil + Sludge improved height (45.68 cm) nevertheless had inadequate propagative /reproductive growth. Soil only control exhibited minimum vegetative growth across entire factors [9]. The maximum plant height of 45.88 cm was recorded in Soil + Sludge treatment, while the minimum height of 38.34 cm was recorded in Soil + Sludge + MO + PAM, indicating that sludge alone favored shoot elongation. The number of leaves increased progressively from 32.25 in Soil Only to 52.18 in Soil + Sludge + MO + PAM, showing that the combined application of sludge, microorganisms and PAM significantly enhanced vegetative growth. The highest number of buds at 2.18 was observed in Soil + Sludge + MO + PAM compared to zero in the control, while the highest number of flowers at 1.14 was observed in Soil + Sludge, indicating that the full amendment favors bud initiation. Root length increased from 5.50 cm in Soil Only to 18.25 cm in Soil + Sludge + MO + PAM, demonstrating that the synergistic effect of sludge, MO and PAM greatly improved root development. Overall, Soil + Sludge + MO + PAM was the most effective growing medium for improving leaf production, bud formation and root growth of Crape Jasmine, while Soil + Sludge alone was best for plant height which shows an agreement with the finding of [9].

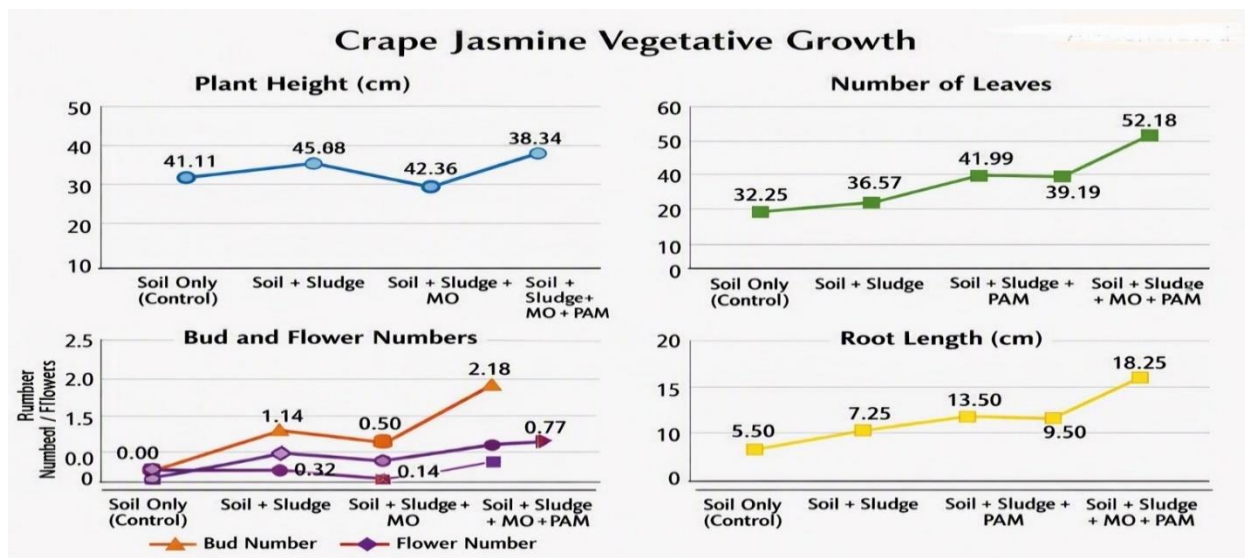


Figure 3: Vegetative growth under different treatments

Figure 3 shows crape jasmine vegetative growth under different treatments where plant height peaked with soil+sludge (455.08), while leave number (52.18), bud number (2.18), flower number (0.77) and root length (18.25cm) were highest under the combined soil+sludge+MO+PAM treatment. The synergistic interaction between MO proteins and PAM molecules contributed to improved sludge flocculation and dewatering performance, resulting in greater nutrient stability and gradual nutrient release following soil incorporation. Improved soil organic matter levels also enhance microbial activity, promoting nutrient cycling and plant nutrient uptake. These findings support previous reports that organic amendments derived from treated biosolids improve soil quality, plant productivity, and ecosystem restoration outcomes [10,11]. The use of hybrid-conditioned sludge therefore represents an environmentally sustainable pathway for beneficial sludge reuse

3.2. Economic Feasibility Analysis Economical Analysis MO and CPAMS Result

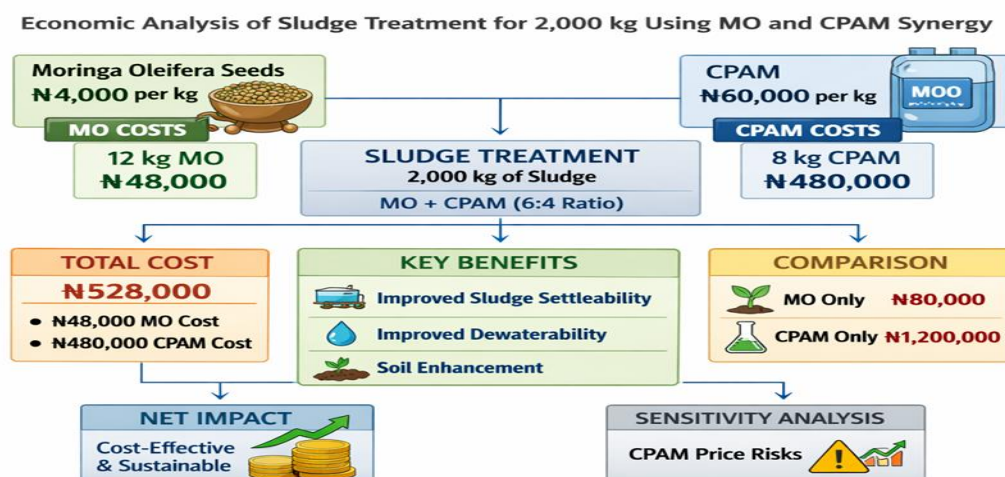


Figure 4. Economic analysis of Sludge Treatment using MO and CPAM Synergy

Figure 4 shows the economic analysis for the treatment of 2,000kg sludge using a synergistic blend of MO and CPAM at a ratio of 6:4 shows a total treatment cost of ₦528,000, this comprises 12kg of MO at ₦4,000 per kg (₦48,000) and 8kg of CPAM at ₦60,000 per kg (₦480,000), giving a unit cost of ₦264 per kg of sludge. Compared to the alternative treatment options, the MO + CPAM synergy is cost-effective. The use of MO alone costs ₦80,000 but is ineffective in terms of settle-ability and dewaterability, while the use of CPAM alone costs ₦1,200,000. The combined approach therefore results in a cost saving of ₦672,000 relative to CPAM alone. In addition to cost savings, the synergy provides key benefits including improved sludge

settleability, dewaterability and soil enhancement due to the organic nature of MO. The net impact is that the treatment is both cost-effective and sustainable. However, sensitivity analysis indicates that the model is vulnerable to CPAM price volatility, as CPAM accounts for approximately 91% of the total cost, making the overall economics highly sensitive to fluctuations in CPAM market price.

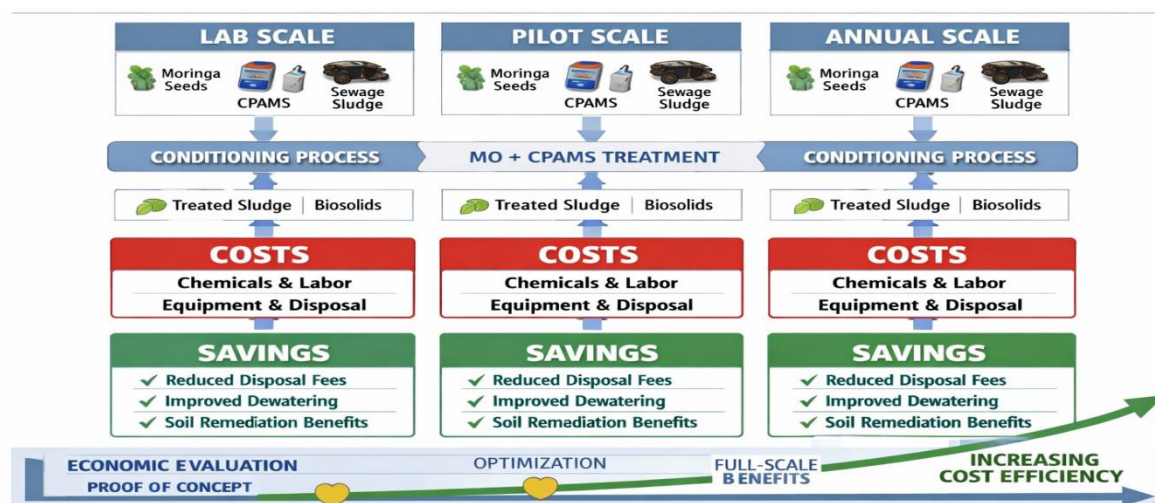


Figure 5: Economic Analysis of Conditioning Sewage Sludge with MO and CPAMS

Figure 5 presents the scale-up pathway and economic evaluation of sludge treatment using MO + CPAMS from laboratory to full industrial scale as viz;

Lab scale: Conducted as a proof of concept using small quantities of MO, CPAMS and sewage sludge. The materials undertook a conditioning process to produce treated sludge and biosolids. At this stage, costs are incurred for chemicals and labor, as well as equipment and disposal while savings are achieved through reduced disposal fees, improved dewatering and soil remediation benefits

Pilot scale: This represents the optimization phase, using larger quantities of the same materials. The treatment followed the MO + CPAMS treatment route to produce treated sludge and biosolids, the cost and saving components remain the same as the lab scale, but the process is refined to improve efficiency.

Annual scale: This represents full scale implementations, it follows the same conditioning process as the lab scale to generate treated sludge and biosolids with identical cost components and savings.

The overall economic evaluation shows a progression from proof of concept at lab scale, to optimization at pilot scale to full scale benefits at annual scale. As the project scales up, there is a trend of increasing cost efficiency indicating that the cost of chemicals, labor, equipment and disposal persist at all scales, the savings from reduced disposal fees, improved dewatering and soil remediation benefits become more significant making the MO + CPAMS treatment increasingly economically viable at large scale.

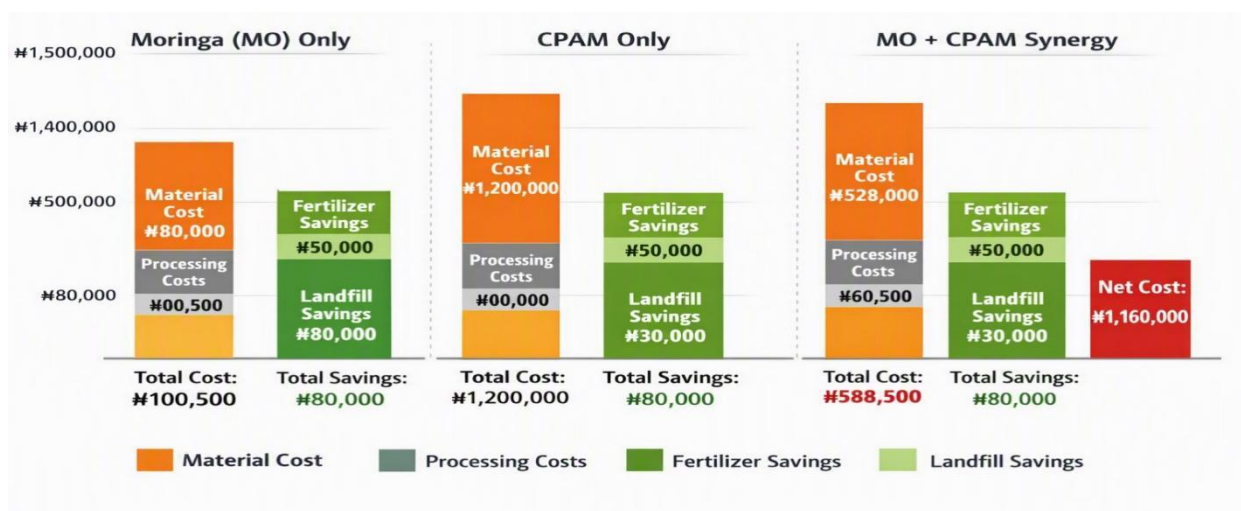


Figure 6: Cost benefits analysis of sludge conditioning

Figure 6 presents a comparative cost benefits analysis of three conditioning regimes. The MO incurred the lowest total processing cost of ₦100,500, comprising ₦80,000 material cost and ₦20,500 processing cost. This generated total saving of ₦80,000 (₦50,000 from fertilizer value and ₦30,000 from avoided landfill costs). CPAM was found to be the most expensive with a total cost of ₦1,200,000 driven entirely by high material cost of ₦1,200,000 while yielding the same ₦80,000 savings. The synergy between MO + CPAM shows an intermediate total cost of ₦588,500 (₦528,000 material plus ₦60,500 processing cost), also offset by ₦80,000 total saving. The economical evaluation reveal that MO based conditioning is significantly more cost effective than conventional CPAM, aligning with finding by [12].



Figure 7: Pilot scale cost benefits analysis of conditioning sewage sludge with MO and CPAMS

Figure 7 illustrates the cost benefit analysis of the integrated MO and CPAM conditioning system for the treatment of 2,000kg of sludge. The input costs comprise material costs of ₦48,000 for MO, ₦440,000 for CPAM, plus labour and equipment costs of ₦350,000 each giving a total cost of ₦878,000. On the return side, the system generated total savings of ₦750,000 consisting of ₦400,000 from avoided disposal costs, ₦200,000 from dewatering efficiency gains and ₦150,000 from soil amendment benefits of the biosolids produced. The result of the net balance of -₦128,000 indicate a near breakeven position. The negative margin of only 14.6% of total cost suggests the process is economically viable with high optimization potential to active positive savings through bulk sourcing of MO, dose optimization and valorization of treated biosolids as fertilizer [13].

3.3 Numerical Cost Benefit Result

At laboratory scale, the synergistic dosage of MO and CPAM was established at 10 g/L of sludge, with a ratio of 6:4. For 2000 kg of sludge, this deciphers to 12 kg of MO and 8 kg of CPAM. With market prices of ₦4,000/kg for MO and ₦60,000/kg for CPAM, the total conditioning cost is ₦528,000. Comparatively, MO-only conditioning costs ₦80,000, while CPAM-only conditioning costs ₦1,200,000. These figures demonstrate that synergy is significantly cheaper than CPAM-only treatment, however more exorbitant than MO-only treatment. However, synergy suggests greater conditioning effectiveness and soil remediation potential, extenuating its higher upfront charge.

3.4 Life Cycle Costing

Life-cycle costing outspreads the analysis outside instant material charges to comprise upstream, midstream, and downstream aspects. Upstream, MO farming entails seed gathering, drying, and crushing, whereas CPAM comprises importation and supply. Midstream costs comprise labor, dosing equipment, and energy inputs. Downstream, synergy decreases sludge volume for disposal, drops landfill costs, and improves soil fertility when sludge is reprocessed. When cut-rate cash flow procedures are used synergy reveals longstanding economic feasibility by counterbalancing higher upfront charges with downstream reserves in waste managing and agricultural participation.

3.5 Environmental Economic Valuation

Environmental economics offers a background for appreciating circumvented externalities. By diverting sludge from landfill, synergy diminishes methane emissions and leachate pollution. The addition of MO contributes organic matter to soils, enhancing fertility and reducing reliance on synthetic fertilizers. These avoided costs can be quantified using shadow pricing, where landfill disposal is valued at ₦2,000 per ton and fertilizer substitution at ₦5,000–₦10,000 per hectare. Therefore, the environmental profits of synergy outspread beyond direct financial savings, contributing to Nigeria's climate and sustainability goals.

3.6 Socio-economical Impact Analysis

The socio-economic impacts of synergy are substantial. MO cultivation produces rural income streams, authorizing local farmers and expanding agricultural markets. Employment chances arise in sludge-to-soil programs, predominantly in processing and delivery. Moreover, reduced dependence on imported CPAM saves foreign exchange, consolidation Nigeria's economic flexibility. These effects align with national urgencies in poverty decrease, food security, and sustainable expansion, making synergy not only a technical resolution but also a socio-economic approach.

3.7. Sensitivity and Risk Analysis

Sensitivity analysis reveals that MO price fluctuations have minimal impact on total conditioning costs, while CPAM price volatility significantly affects economics. For example, a 50% increase in MO price raises total cost by only 4.5%, whereas a 33% increase in CPAM price raises total cost by 30%. Risk analysis further highlights vulnerabilities in CPAM supply chains, including import disruptions and global petrochemical market instability. Climate variability affecting MO yields also poses risks, though these can be mitigated through local cultivation programs. Scenario analysis demonstrates that synergy remains economically viable under most conditions, but policy support is essential to buffer against CPAM volatility.

4. CONCLUSIONS

Conditioned WUPA wastewater sludge significantly improved the growth performance of *Tabernaemontana divaricata*. While sludge alone promoted maximum plant height, the hybrid MO-CPAM treatment produced the highest leaf number, root length, flowering response, and bud formation. The study demonstrates that hybrid conditioning enhances the agronomic value of wastewater sludge and supports its utilization as a sustainable soil amendment. Economic evaluation confirmed that although Moringa-only treatment remains the least expensive option, the hybrid MO-CPAM system provides the best balance between treatment efficiency, environmental sustainability, and agronomic performance.

The findings support the adoption of hybrid sludge conditioning technologies for large-scale wastewater management, soil remediation, and circular resource recovery programs.

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