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Evaluation of vegetable waste-derived lactic acid from fermentation of selected vegetable wastes for faecal sludge treatment

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ABSTRACT

Safe disposal of faecal sludge remains a critical challenge in developing countries due to presence of harmful pathogens and odours. Current treatment methods are often inaccessible, ineffective, or costly, causing health and environmental risks. This study aimed to evaluate cabbage waste-derived lactic acid from fermentation of selected vegetable wastes for faecal sludge treatment as a low-cost and sustainable solution for faecal sludge management. Tomato, cabbage, and carrot wastes were fermented for six days at 37 °C with daily monitoring of pH and lactic acid concentrations. Four reactors with faecal sludge-to-lactic acid ratios of 1:1, 1:0.5, 1:0.35, v/v, and a control were set up and monitored for Escherichia coli, odour, total solids, and volatile solids reduction over 16 days. Cabbage-derived lactic acid was selected because the retention factor (Rf) was similar to the standard with no interfering organic acids. Reactor 1:1 eliminated E. coli within four days, achieving zero cfu/mL. TS decreased from 18.5 g/L to 14.5 g/L, while VS declined from 17.7 g/L to 7.6 g/L and 6.3 g/L in the 1:0.5 and 1:0.35 reactors, respectively. Odour reduction was also highest in this reactor, with a Threshold Odour Number (TON) of 7.3 compared to 25 in the control. These findings show that cabbage vegetable wastes can produce lactic acid that can lead to total E. coli elimination and significant odour elimination in faecal sludge. Studies should be carried out to explore feasibility of scaling up this method.

Introduction

Faecal sludge (FS) is the waste that arises from on-site sanitation systems and is not conveyed through a sewer. It typically exists as a partly digested or raw slurry or semi-solid form. It is generated through storing, collecting, or treating wastewater, including excreta and black water, either with or without grey water (*Shukla et al.*, 2023).

Globally, safe management of FS is crucial due to the significant health risks associated with exposure to unsanitised FS (*Chen et al.*, 2023). The Sustainable Development Goal (SDG) 6.2 addressing sanitation requires that everyone should have a safely-managed sanitation facility in which excreta can be securely disposed of on-site or processed off-site and that open defecation be eliminated by 2030 (*Hyun et al.*, 2019; Thevenon, 2020).

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As of 2024, global coverage of safely managed sanitation services stood at 58%, encompassing approximately 4.6 billion people. This marks a significant increase from 2015, when coverage was 48%, indicating a 10% rise over the nine years (United Nations Children's Fund & World Health Organization, 2024a). Despite this progress, 43% of the global population—about 3.5 billion people still lack access to safely managed sanitation services (United Nations Children's Fund & World Health Organization, 2024b). This includes 419 million individuals who practiced open defecation, which involves defecating in public places such as street troughs, bushes, or open water bodies (*Ubi et al*., 2021).

FS is a significant source of pathogens, containing numerous bacteria, protozoa, viruses, and helminths (*Schlosser-Brandenburg et al*., 2023). Water-borne, water-related, water-washed, and water-based diseases, e.g., intestinal parasitic infections, diarrheal diseases, skin and eye infections, are associated with a lack of proper faecal sludge disposal (*Chan et al*., 2021). Safe handling and treatment of FS are therefore key primary barriers in transmission pathways of such pathogens and protecting public health (Tortajada & Biswas, 2018).

Current FS treatment methods, such as anaerobic digestion, constructed wetlands, composting, and pyrolysis, have limitations. Anaerobic digestion and constructed wetlands require significant infrastructure and land, while composting and pyrolysis are energy-intensive and relatively expensive (*Abdel-Rahman et al*., 2013; Hube & Wu, 2021; Zuberer & Zibilske, 2021). These challenges highlight the need for innovative, cost-effective, and scalable solutions.

Lactic acid fermentation offers a promising FS treatment alternative. Lactic acid is a versatile organic acid and can be produced through the fermentation of carbohydrate-rich substrates by lactic acid bacteria (*Raman et al*., 2022). Recent studies have explored the use of organic waste such as food and agricultural waste as substrates for lactic acid production, combining waste valorisation with sustainable chemical production (*Odey et al*., 2018a). Vegetable waste, abundant and underutilized, is rich in carbohydrates, nutrients, and abundant lactic acid bacteria (LAB), making it an ideal substrate for lactic acid fermentation (*Wan-Mohtar et al*., 2023).

This study evaluated the feasibility of producing lactic acid through the fermentation of selected vegetable wastes and its application as a treatment method for FS. The specific objectives were to quantify the lactic acid produced through the fermentation of cabbage waste as a treatment agent for faecal sludge, enumerate the levels of Escherichia coli, total solids, and volatile solids in faecal sludge treated with varying ratios of cabbage waste-derived lactic acid and to evaluate the odour levels in faecal sludge treated with different ratios of cabbage waste-derived lactic acid to assess its effectiveness in odour mitigation.

Methods

Study site

Samples were collected at the Mitunguu Decentralized Treatment Facility in Mitunguu town Meru County, Kenya.

Faecal sludge sample collection

Faecal sludge was sourced from the Decentralised Treatment Facility (DTF). Sample size and sampling method were acquired according to the method described by (*Velkushanova et al*., 2021). Five kilograms of FS were obtained via a composite grab sampling technique, which involved taking equal sample portions from an exhauster track at set intervals during emptying. The portions were then mixed to obtain a homogenous mixture and transported in an air-tight, closed High Density Polyethene (HDPE) container to Meru University of Science and Technology, Sanitation Research Institute's laboratory, where the initial faecal sludge characteristics, such as pH, temperature, total solids, and Coliform Forming Units(CFUs), were studied and results noted prior to treatment.

Vegetable waste sample collection

Fresh cabbage, tomato, and carrot vegetable wastes serving as substrates for fermentation were sourced from Nkubu market, Meru County, Kenya, and transported to Meru University of Science and Technology laboratories, where size reduction was carried out by use of a kitchen knife and a heavy-duty commercial blender. One thousand grams of each substrate was mixed with 1000 mL of distilled water, and the mixture was homogenized. The wastes were then added to plastic containers and sealed to make them airtight and incubated at 37 °C for seven days, as described by (*Omar et al*., 2009).

Experimental setup

Thin Layer Chromatography qualitative test for lactic acid

TLC was carried out as described by (*Lee et al.*, 2001). Silica gel TLC plates (60 F254, Germany) were used in the experiment with a solvent system of acetone: water: chloroform: ethanol: ammonium hydroxide (60:2:6:10:22, v/v) (Loba Chemie, Gujarat, India). A series of 10% w/v, or v/v standard solutions containing equal concentrations of lactic acid, acetic acid, formic acid, oxalic acid, ascorbic acid, and citric acid (Rankem laboratory reagents, Gujarat, India), respectively, was prepared were used as standards.

Lactic acid recovery

The lactic acid was recovered using the method described by (*Getaneh et al.*, 2021). The incubated vegetable wastes were frozen overnight, followed by thawing in a drying oven at 60 for 2 to 3 h, followed by filtration and centrifugation at 6000 rpm for 10 min using a centrifuge (Hermule Labnet Z216 MK, USA)

Spectrophotometric quantification of lactic acid

Lactic acid was quantified using a spectrophotometric technique (*Borshchevskaya et al.*, 2016). A calibration curve was first prepared using a series of 2-fold dilutions of a lactic acid standard solution (1.2 g in 10 mL distilled water). The absorbance of the lactic acid-iron (III) chloride complex was measured at 390 nm using a spectrophotometer (Apel PD-UV-3000UV, Japan).

Assessment of lactic acid in the inactivation of E. coli in faecal sludge

Four reactors containing 1:1, 1:0.5, 1:0.35, FS to lactic acid, and a control were set up. Samples were collected from the reactors every 3–5 days for 16 days for pH analysis, volatile solids (VS), total solids (TS), and faecal coliform enumeration.

The ability of lactic acid to inactivate the faecal coliform was determined by evaluating the number of Colony Forming Units (CFU) of the E. coli as the indicator through a total viable plate count after plating on Violet Red Bile Agar (HIMEDIA), which is a selective medium for E. coli (Basavaraju & Gunashree, 2022; Digo, 2015).

The total solid content of the FS before and after treatment

Total solids (TS) and volatile solids (VS) content were analysed using the 2540E standard method for wastewater examination.

pH determination

The pH of the samples was measured using a pH meter (Model Bante902, Zhejiang, China) standardized using buffer solutions at pH 7, 10, and 4.

Odour evaluation

The odour strength of the faecal sludge was determined according to method 2150B of water and wastewater analysis (Threshold odour test).

Data analysis

Statistical analysis

The data obtained from each batch was first analysed using Excel by computing the averages of the three trials conducted per batch. The average values of the three batches were then calculated in order to generate the means, standard deviations, and standard errors.

Initial faecal Sludge characteristics	
pH	5.63
***E.Coli* (cfu/ml)**	10200
Total solids (g/L)	16.30
Volatile Solids (g/L)	13.00

Table 1: *Initial Faecal Sludge Characteristics*

Results and Discussion

The pH increased during fermentation.

The pH variation for carrot, tomato, and cabbage vegetable wastes fermented for 6 days at 37°C is illustrated in **Figure 1**.

The pH of the fermented waste decreased in all the vegetable wastes after the 6-day fermentation period. A decrease in the pH levels from 5.37±0.14, 4.36±0.15, and 5.90±0.05 to 3.20±0.16, 3.30±0.07, and 3.23±0.10 for carrot, tomato, and cabbage waste, respectively, showed that fermentation had occurred.

The drop in pH for all three vegetable wastes, as illustrated in the figure above, indicates the progress of lactic acid fermentation. During this process, lactic acid bacteria (LAB) convert sugars present in the

vegetables into lactic acid while causing a decline in pH (*Jabłońnska-Ryś et al.*, 2022; *Kaur et al.*, 2019). The initial rapid decrease in pH observed in the initial three days for all three vegetables suggests rapid fermentation activity, where LAB quickly utilizes the abundant fermentable sugars to produce energy while producing lactic acid as a metabolite, resulting in acidification. After which the pH levels stabilize, indicating that the fermentation process has stopped due to depletion of fermentable sugars (*Deshwal et al.*, 2021).

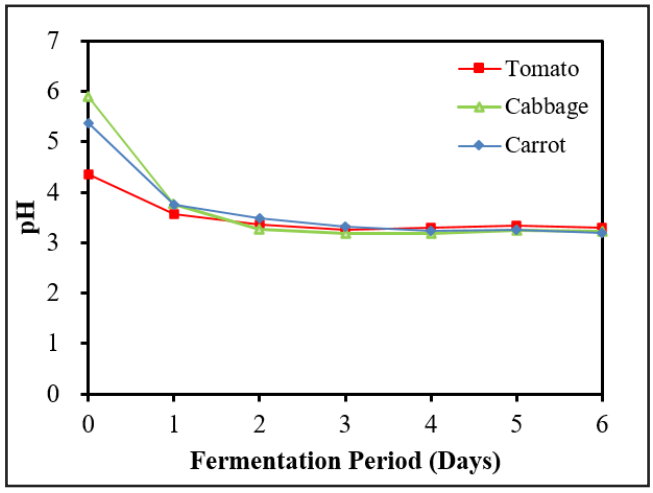

Figure 1: *pH changes over the fermentation period of the vegetable waste.*

The steady final pH of around 3.20 indicates a stable fermentation endpoint. Tomato waste had a lower starting pH, indicating more natural acidity. The pH stabilized around 3.30, showing effective fermentation but slightly less acidic than carrot and cabbage waste in the end, while cabbage waste starts with the highest pH, suggesting less initial acidity, the final pH stabilizes around 3.23, similar to carrots, indicating that despite starting with a higher pH, cabbage waste fermentation achieves a similar acidic environment. These results suggest that most of the fermentation process occurred earlier in the process, followed by a stabilization phase of three days, which is the period taken to achieve a stable pH. These results agree with findings earlier reported by (*Anderson et al.*, 2015; *Getaneh et al.*, 2021), which reported three days as the period during which the pH appears to stabilize.

Lactic acid concentration increased during fermentation.

A calibration curve was constructed from which the lactic acid concentration was calculated. **Figure 2** below shows the calibration curve for the quantification of lactic acid. The curve plots absorbance (y-axis) against concentration (x-axis) in milligrams per millilitre (mg/mL).

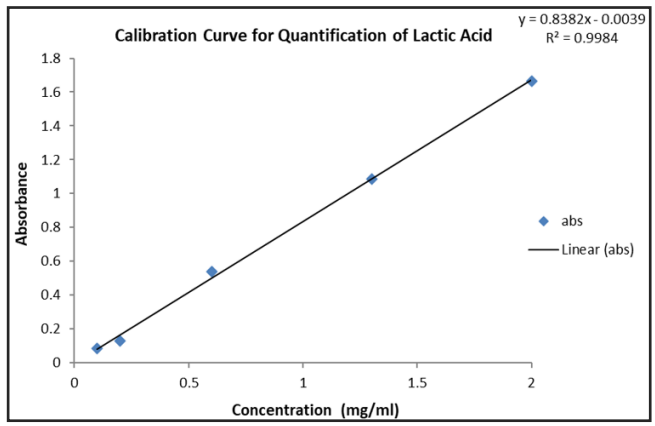

Figure 2: *Lactic acid calibration curve*

Figure 3 below shows the concentration of lactic acid in the three vegetable waste substrates (carrot, tomato, and cabbage) over six days during fermentation at 37°C.

During the initial 3 days of fermentation, the three vegetable wastes showed an increase in lactic acid concentration, indicating the onset of fermentation. This is characterized by the activity of lactic acid bacteria that start converting sugars into lactic acid. Although carrot waste showed a higher absorbance indicating a higher concentration of lactic acid, TLC results indicated formation of other organic acids that might have had a similar absorbance as lactic acid.

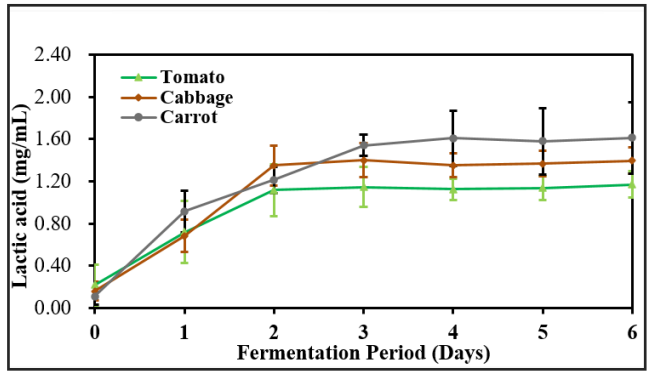

Figure 3: *Lactic acid concentration over a 6-day fermentation period*

Lactic acid production was monitored over a period of six days, and statistical differences in mean concentrations across the days were evaluated using Tukey's Honest Significant Difference (HSD) post hoc test following a one-way ANOVA. The results revealed significant variations in lactic acid production

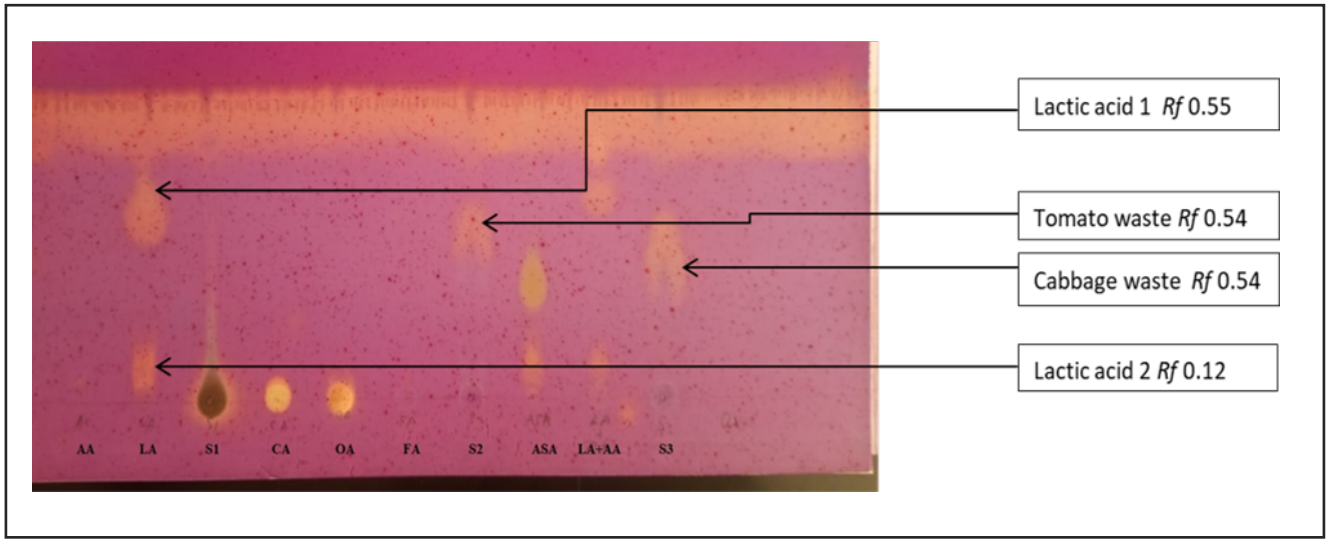

Figure 4: *TLC analysis of the presence of lactic acid.*

during the fermentation period.

As shown in **Figure 3** above, lactic acid concentrations increased markedly between Day 0 and Day 2, followed by a plateau from Day 3 onwards. The Tukey HSD test confirmed that the lactic acid production on Day 0 was significantly lower ($p < 0.001$) than all subsequent days, indicating fermentation and acid accumulation within the first 24 hours. This finding highlights the critical initiation phase of microbial activity immediately after fermentation onset.

Similarly, the mean concentration on Day 1 was significantly lower than those observed on Days 2 through 6 ($p < 0.001$), suggesting that a substantial increase in lactic acid production occurred between Day 1 and Day 2. The difference between Day 1 and Day 2 was statistically significant with a mean difference of 0.395 mg/ml ($p = 0.001$). However, no statistically significant differences ($p > 0.99$) were observed between Days 2, 3, 4, 5, and 6. Cabbage waste derived lactic acid was therefore selected since there was no significant difference in production between the fermented cabbage and tomato waste.

Thin-layer chromatography indicated the presence of lactic acid.

TLC was used as a qualitative method to determine the formation of lactic acid in the fermented vegetable wastes. **Figure 4** above shows the separation of organic acids on a 20×20 cm TLC plate in an acetone, water, chloroform, ethanol, and ammonium hydroxide mobile phase in the ratio of 60:2:6:10:22.

Lactic acid standard appeared as a yellow spot on the chromatogram with an RF of 0.55 and 0.12, while carrot waste marked as S1 appeared as a single spot with an unclear spot that aligned with those of ascorbic acid, lactic acid standard, and oxalic acid. Tomato and cabbage waste samples marked as Sample 2 and 3, respectively, appeared as a single spot with an RF of 0.54. These results indicate that there was the formation of lactic acid in all the fermented samples. Carrot waste produced a spot with unclear Rf displaying production of a mixture of other organic acids while cabbage waste was selected for FS treatment because it produced a single, clear TLC spot with an Rf value closely matching that of the lactic acid standard.

pH Decreased during treatment of FS with lactic acid

Figure 5 below shows a comparative analysis of pH in the reactors. The control showed a steady increase in pH from slightly acidic 6.13 to moderately alkaline 8.20. This increase could be attributed to natural biochemical processes in the faecal sludge, such as ammonia production due to urea breakdown (*Chang et al.*, 2015).

Reactor 1:1 had the highest pH decline by Day 4, with a slight increase thereafter from 6.13 to 4.35. The reactor exhibited a significant drop in pH, indicating a high concentration of lactic acid. The slight increase after Day 4 suggests some buffering capacity or metabolic changes in the sludge that partially counteract the acidity. These results are in agreement with (*Getaneh et al.*, 2021), which reported a decrease in pH to 4.05 by day five of treatment.

In reactor 1:0.5, the initial pH (Day 0) was 6.13 while the final pH was 5.85. Reactor 1:0.5 exhibited a moderate decrease in pH compared to reactor 1:1. This suggests that the lower lactic acid concentration allowed for some neutralizing processes within the sludge. Reactor 1:0.35 showed the least change in pH, with a minor depression followed by a rise to slightly basic levels. These results suggest that lactic acid concentration significantly influenced the pH of faecal sludge.

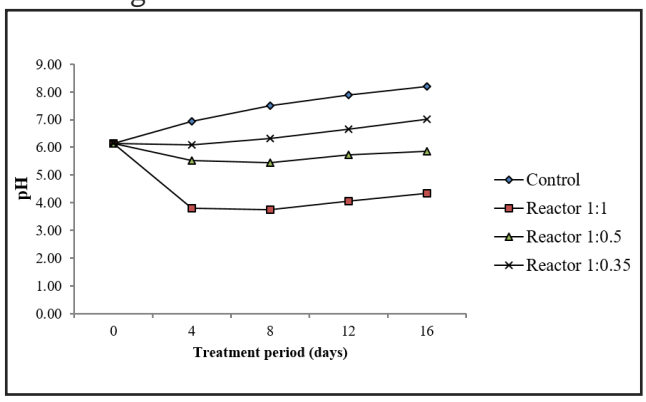

Figure 5: *pH variation in reactors containing different lactic acid to FS ratios*

There was E. coli inactivation in some lactic acid treatment reactors

E. coli concentration (cfu/mL) results over a treatment period of 16 days for a faecal sludge sample treated with 1:1, 1:0.5, and 1:0.35 FS to lactic acid (v/v) and a control are illustrated in **Figure 6** below.

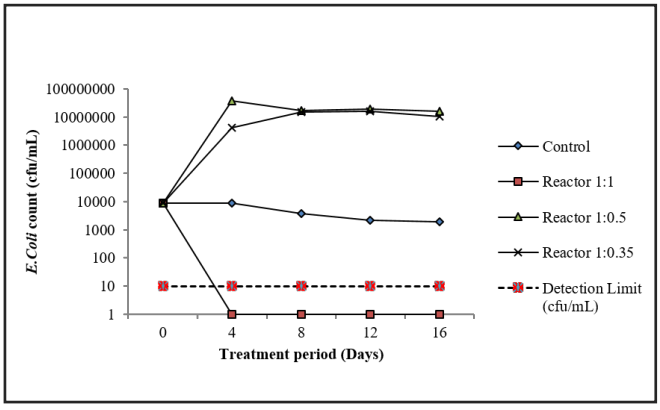

Figure 6: *E. coli variations in reactors containing different ratios of lactic acid to FS.*

The following observations were noted. E. coli concentration decreased steadily over the 16 days in the control. Starting at 8.9×103 cfu/mL on Day 0, the CFU decreased to 2.0×103 cfu/mL by Day 16. This indicated that in the control setup, conditions were not conducive for E. coli survival or growth over time due to factors such as high pH or depletion of nutrients, thus resulting in a natural die-off of E. coli (Malambo, 2014; *Van den Bergh et al.*, 2016).

In reactor 1:1, the E. coli concentration dropped and remained at zero by Day 4 and throughout the treatment period. This indicated that the conditions in Reactor 1:1 were highly effective in eliminating E. coli. This is in agreement with similar results by *Anderson et al.* (2015), which concluded that at pH levels of around 4.0, E.coli growth is hindered by the ability of lactic acid to reduce the intracellular pH of bacteria by penetrating bacterial cells and decreasing their internal pH, ultimately disrupting cellular functions.

In reactor 1:0.5, the E. coli concentration increased significantly by Day 4, to 3.8×107 cfu/ml. It remained relatively high, fluctuating slightly but still in the range of 1.6×107 to 1.9×107 cfu/mL from Day 8 to Day 16. This suggests that in reactor 1:0.5, the growth conditions of E. coli were promoted. In reactor 1:0.35, similar to reactor 1:0.5, there was a significant increase in E. coli levels by Day 4 to 4.2×106 cfu/ml. The concentration remained high with values of 1.1×107 to 1.6×107 cfu/ml, from Day 8 to Day 16 of treatment. The conditions in Reactor 1:0.35 also appeared to support E. coli growth. These findings are in agreement with (Malambo, 2014), who reported an initial increase in E. coli count for the treatment reactors within the initial four days of treatment.

E. coli thrives at pH levels between 4.5 and 9 (*Rodrigues et al.*, 2020). Over this pH range, E. coli preserves enzyme activity, as well as protein and nucleic acid stability, by maintaining the cytoplasmic pH in the range of 7.2 to 7.8 (*Slonczewski et al.*, 1981). Low lactic acid concentrations can also break down complex organic compounds in the FS into simpler, more accessible nutrients, resulting in the growth of bacteria like E. coli (*Wang et al.*, 2021).

These findings suggest that reactors 1:0.5 and 1:0.35 conditions did not contain the threshold lactic acid amount or acidification levels required to eliminate or significantly lower the E. coli levels to acceptable levels. Reactor 1:1 had the best conditions for E. coli elimination.

The volatile solids decreased during treatment.

Volatile solids are the organic matter content in the sludge, which can be decomposed through microbial activity (Chynoweth & Pullammanappallil, 2020). Monitoring the reduction in VS provides in-

sight into the efficiency of biodegradation processes. **Figure 7** above shows the trend of volatile solids during the 16-day treatment period of faecal sludge and different ratios of lactic acid.

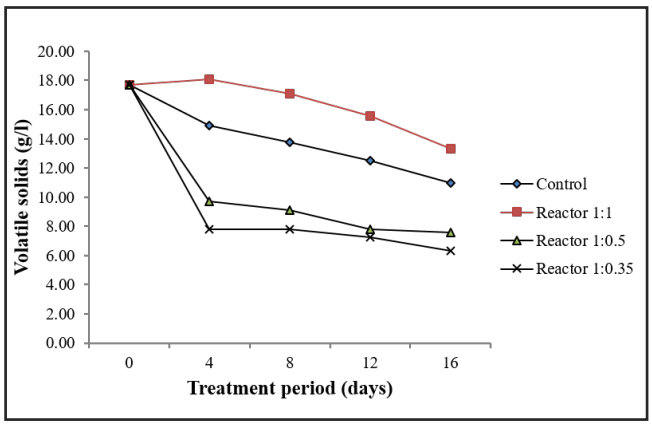

Figure 7: *Volatile solids in faecal sludge treated with different lactic acid ratios.*

The results revealed a decrease in VS in all the reactors. The control showed a gradual reduction in VS concentration over the 16 days, from 17.70 g/l to 10.95 g/l. This reduction is expected due to natural microbial activity and degradation processes occurring in the sludge without any additional treatments. At the same time, in reactor 1:1, the VS concentration initially increases slightly from 17.70 g/l to 18.08 g/l by Day 4. This was attributed to low initial microbial activity, leading to low breakdown of complex organic materials. After Day 4, there is a gradual reduction in VS, reaching 13.35 g/l by Day 16. This pattern indicated a slower but steady decomposition process compared to other reactors.

Reactor 1:0.5 showed a significant and rapid reduction in VS concentration from 17.70 g/l to 9.73 g/l within the first four days, followed by a more gradual decline to 7.59 g/l by Day 16. This rapid initial decrease suggested a highly efficient microbial degradation process due to an optimal environment for microbial activity and organic matter breakdown.

Reactor 1:0.35, similar to reactor 1:0.5, demonstrated a sharp decline in VS from 17.70 g/l to 7.81 g/l by Day 4, indicating a highly effective reduction in organic matter. The concentration stabilized around 7.80 g/l from Day 4 to Day 8 and decreased slightly to 6.32 g/l by Day 16. The sharp initial drop followed by slower degradation suggested that the conditions in reactor 1:0.35 maximized the microbial efficiency. The high microbial load in reactor 1:0.5 and 1:035, as shown in **Figure 4** above, led to the rapid decrease in VS due to the increased microbial activity.

The efficiency of VS reduction in faecal sludge treatment is critical for reducing the sludge's volume and potential environmental impact (*Zewde et al.*, 2021). Effective treatment results in lower organic load, making the remaining sludge more stable and less odorous (*Demirbas et al.*, 2017). High microbial activity and optimal environmental conditions, such as appropriate moisture content, temperature, and pH, facilitate the breakdown of organic matter in faecal sludge (*Cofie et al.*, 2016). The results highlight the effectiveness of different reactor setups in reducing volatile solids in faecal sludge. Reactors with a lower concentration of lactic acid, i.e., 1:0.5 and 1:0.35, displayed more rapid initial VS reduction. This can be attributed partially to the low pH in the reactors, indicating more efficient microbial degradation.

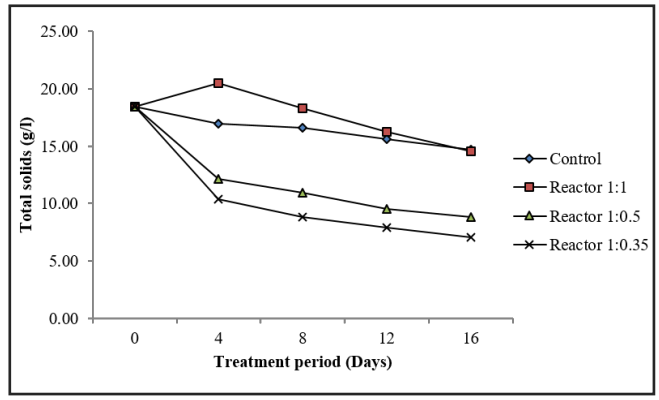

Figure 8: *Total Solids analysis in faecal sludge treatment*

The control TS concentration gradually decreased from 18.47 g/l to 14.67 g/l over the 16-day treatment period. The steady decline indicated natural microbial degradation of solids without additional treatment. The reduction is consistent with typical sludge stabilization processes observed in untreated or minimally treated faecal sludge (Strande & Brdjanovic, 2014).

In reactor 1:1, TS concentration initially increased from 18.47 g/l to 20.48 g/l by Day 4. Following this peak, the TS gradually decreased to 14.53 g/l by Day 16, indicating on going microbial degradation. The spike at Day 4 suggests temporary microbial activity or aggregation of solids due to lactic acid's inhibitory effects on initial microbial metabolism (Paul & Liu, 2012).

The data indicate that the treatment reactors (1:0.5 and 1:0.35) were significantly more effective in reducing total solids compared to the control and reactor 1:1. The reactor 1:0.35 consistently showed

the greatest reduction in TS, demonstrating its potential for optimizing faecal sludge treatment.

The steady decline in TS suggests efficient biodegradation, likely due to optimal pH and lactic acid concentration favourable for microbial growth. This is supported by previous findings indicating that low lactic acid concentrations minimize microbial inhibition, thereby promoting increased microbial activity (*Cofie et al*., 2016). These results agree with those of *Odey et al*. (2018), who reported a final TS of 33% in the 1:1 (FS: lactic acid) reactor, which was higher than the control (13%) and the 1:2 reactor (19.2%).

In this study, it was noted that while reactors 1:0.5 and 1:0.35 achieved the greatest reduction in TS and VS, they also showed the least efficiency in pathogen and odour control. This highlights the potential inhibitory effect of lactic acid at high concentrations on microbial activity responsible for solids degradation. Future studies should investigate an optimized lactic acid quantity that balances both pathogen elimination and stabilization.

Odour levels reduced in faecal sludge treated with different lactic acid ratios.

High TON levels indicate a significant presence of odour, suggesting the need for effective odour management strategies, while a low TON indicates effective odour treatment.

Table 2 below presents the mean Threshold Odour Number (T.O.N) levels measured during a faecal sludge treatment process. The data includes the initial T.O.N level and the levels observed in a control and three different reactor ratios (1:1, 1:0.5, and 1:0.35).

RATIO	MEAN (T.O.N) LEVEL
Initial	37.33
Control	25.00
Ratio 1:1	7.33
Ratio 1:0.5	42.67
Ratio 1:0.35	26.67

Table 2: *TON levels*

The initial faecal sludge odour level was relatively high (37.33 TON). This acted as the reference point measurement against which the other treatments were compared.

The control condition demonstrates a decrease in odour levels to 25.00 TON. This reduction from the initial condition indicates some level of odour reduction.

The 1:1 ratio reactor showed a significant decrease in odour levels, reaching 7.33 TON, the lowest among all reactors. This suggests that the 1:1 ratio was highly effective in controlling and reducing odours. The odour reduction was likely due to the low pH and the high concentration of lactic acid in the reactor, which inhibited the growth of bacteria that degrade proteins, such as sulphur-reducing bacteria. These bacteria typically produce odorous compounds, including dimethyl trisulfide, hydrogen sulphide (H_2S), dimethyl disulphide, methyl mercaptan, and dimethyl sulphide (*Choudhury et al*., 2024; Newman, 2023). Low pH in the range 3-4.5 has been reported to reduce urea hydrolysis to ammonia (another odorous compound) by inactivating urease-producing bacteria (*Ray et al*., 2018).

The ratio 1:0.5 reactor exhibited an increased odour level to 42.67 TON, which was even higher than the initial condition. This indicated that this ratio was ineffective for odour control and might even contribute to the growth of odour-causing bacteria. Possible reasons could have been due to the low lactic acid concentration and the relatively high pH that allowed E. coli and other microorganisms to persist at high levels throughout the treatment period (*Anderson et al*., 2015; *Andreev et al*., 2017). Continued microbial activity led to the breakdown of organic material, thereby producing large amounts of odour-causing compounds (*Zewde et al*., 2021).

The ratio 1:0.35 reactor indicated an odour level of 26.67 TON, which was lower than the initial condition but higher than the control. This indicated a moderate level of effectiveness in odour reduction. While it was better than the initial condition, it did not perform as well as the control or the ratio 1:1 reactor. Similar results were reported by *Anderson et al*., (2015); *Getaneh et al*., (2021); *Odey et al*., (2018), who reported decreased odour levels in higher lactic acid concentrations and higher odour levels in lower lactic acid concentrations.

These findings are in agreement with those of *Anderson et al*., (2015), who demonstrated that lactic acid lowers FS pH and suppresses pathogenic growth. Similarly, *Getaneh et al*., (2021) observed higher urea stabilization and pathogen inactivation at low pH values. However, unlike *Odey et al*., (2018b), who focused primarily on odour control and patho-

gen elimination, this study also evaluated solid content reductions, revealing a key disadvantage: while high lactic acid concentrations eliminated E. coli and odour, they suppressed microbial activity required for VS and TS reduction.

Conclusion

This study showed that considerable lactic acid amounts can be produced via spontaneous fermentation of cabbage, tomato, and carrot waste. Although carrot waste exhibited a higher absorbance, cabbage waste was selected since it produced a clear spot with an Rf similar to that of pure lactic acid, as confirmed by thin-layer chromatography. There was also no significant difference in lactic acid produced in cabbage and tomato waste on the final day of fermentation. This highlights the potential of vegetable waste as a low-cost, renewable resource for lactic acid production.

The 1:1 ratio of FS to lactic acid achieved complete elimination of E. coli (0 cfu/mL) within four days, demonstrating greater pathogen inactivation compared to lower ratios (1:0.5, 1:0.35) and the control. It was noted that in higher lactic acid concentrations (1:1), volatile solids were not reduced due to microbial inhibition, while lower ratios (1:0.5, 1:0.35) showed rapid VS and TS degradation, indicating enhanced microbial activity at lower acidity.

The 1:1 lactic acid ratio significantly reduced odour, achieving a Threshold Odour Number (TON) of 7.3, compared to the control (TON = 25). These results indicated that lower ratios (1:0.5 and 1:0.35) exacerbated odour, likely due to the growth of odour-producing bacteria. This highlights the importance of optimal lactic acid concentration for effective odour control.

These findings confirm lactic acid from vegetable waste as a viable, eco-friendly solution for FS treatment, aligning with circular economy principles by valorising vegetable waste into sanitation resources. The 1:1 lactic acid ratio proved optimal for pathogen elimination and odour reduction; however, it showed a reduced efficiency in both TS and VS reduction. This necessitates further studies to find an optimal lactic acid concentration that can result in pathogen elimination, odour elimination, and TS and VS elimination.

Conflict of Interest

The author declares no conflict of interest.

Ethics Statement

Free and informed consent of the participants or their legal representatives was obtained, and the study protocol was approved by the National Commission for Science, Technology, and Innovation (NACOSTI) under research permit NACOSTI/P/25/415907. The approval was granted in accordance with national research regulations in Kenya.

References

Abdel-Rahman, M. A., Tashiro, Y., & Sonomoto, K. (2013). Recent advances in lactic acid production by microbial fermentation processes. Biotechnology Advances, 31(6), 877–902.

Anderson, C., Malambo, D. H., Gonzalez Perez, M. E., Nobela, H. N., De Pooter, L., Spit, J., Hooijmans, C. M., Van De Vossenberg, J., Greya, W., & Thole, B. (2015). Lactic acid fermentation, urea and lime addition: Promising faecal sludge sanitizing methods for emergency sanitation. International Journal of Environmental Research and Public Health, 12(11), 13871–13885.

Andreev, N., Ronteltap, M., Boincean, B., & Lens, P. N. (2017). Treatment of source-separated human faeces via lactic acid fermentation combined with thermophilic composting. Compost Science & Utilization, 25(4), 220–230.

Basavaraju, M., & Gunashree, B. (2022). Escherichia coli: An overview of main characteristics. Escherichia Coli-Old and New Insights. http://dx.doi.org/10.5772/intechopen.105508

Borshchevskaya, L., Gordeeva, T., Kalinina, A., & Sineokii, S. (2016). Spectrophotometric determination of lactic acid. Journal of Analytical Chemistry, 71, 755–758.

Chan, E. Y. Y., Tong, K. H. Y., Dubois, C., Mc Donnell, K., Kim, J. H., Hung, K. K. C., & Kwok, K. O. (2021). Narrative review of primary preventive interventions against water-borne diseases: Scientific evidence of health-EDRM in contexts with inadequate safe drinking water. International Journal of Environmental Research and Public Health, 18(23), 12268.

Chang, Y., Deng, C., Dore, A. J., & Zhuang, G. (2015). Human excreta as a stable and important source

of atmospheric ammonia in the megacity of Shanghai. PLoS One, 10(12), e0144661.

Chen, Y., Feng, Q., & Zhang, Z. (2023). Innovative disposal technology and management practice for medical waste. Springer.

Choudhury, A. R., Singh, N., Lalwani, J., Rao, M. G., Konyala, B. P., Nadella, C., Nayakwadi, A., & Palani, S. G. (2024). A comparative assessment of biomethane potential of fresh fecal matter and fecal sludge and its correlation with malodor. Environmental Science and Pollution Research, 31(21), 31619–31631.

Chynoweth, D. P., & Pullammanappallil, P. (2020). Anaerobic digestion of municipal solid wastes. Microbiology of Solid Waste, 71–113.

Cofie, O., Nikiema, J., Impraim, R., Adamtey, N., Paul, J., & Koné, D. (2016). Co-composting of solid waste and fecal sludge for nutrient and organic matter recovery (Vol. 3). IWMI.

Demirbas, A., Coban, V., Taylan, O., & Kabli, M. (2017). Aerobic digestion of sewage sludge for waste treatment. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 39(10), 1056–1062.

Deshwal, G. K., Tiwari, S., Kumar, A., Raman, R. K., & Kadyan, S. (2021). Review on factors affecting and control of post-acidification in yoghurt and related products. Trends in Food Science & Technology, 109, 499–512.

Digo, C. A. (2015). Isolation and characterization of lactic acid bacteria and their inhibitory/safety potential in traditionally fermented milk, mursik in Kenya.

Getaneh, Z., Love, N. G., Desta, A., & Nigussie, A. (2021). Lactic acid from food waste enhances pathogen inactivation and urea stabilization in human urine. International Journal of Water Resources and Environmental Engineering, 13(3), 196–205.

Hube, S., & Wu, B. (2021). Mitigation of emerging pollutants and pathogens in decentralized wastewater treatment processes: A review. Science of the Total Environment, 779, 146545.

Hyun, C., Burt, Z., Crider, Y., Nelson, K. L., Prasad, C. S., Rayasam, S. D., Tarpeh, W., & Ray, I. (2019). Sanitation for low-income regions: A cross-disciplinary review. Annual Review of Environment and Resources, 44, 287–318.

Jabłońska-Ryś, E., Sławińska, A., Skrzypczak, K., & Goral, K. (2022). Dynamics of changes in pH and the contents of free sugars, organic acids and LAB in button mushrooms during controlled lactic fermentation. Foods, 11(11), 1553.

Kaur, P., Ghoshal, G., & Jain, A. (2019). Bio-utilization of fruits and vegetables waste to produce β-carotene in solid-state fermentation: Characterization and antioxidant activity. Process Biochemistry, 76, 155–164.

Lee, K.-Y., So, J.-S., & Heo, T.-R. (2001). Thin layer chromatographic determination of organic acids for rapid identification of bifidobacteria at genus level. Journal of Microbiological Methods, 45(1), 1–6.

Malambo, D. H. (2014). Sanitizing faecal sludge using lactic acid bacteria in the context of emergency situations.

Newman, S. (2023). Unmaking waste: New histories of old things. University of Chicago Press.

Odey, E. A., Li, Z., Zhou, X., & Yan, Y. (2018a). Locally produced lactic acid bacteria for pathogen inactivation and odor control in fecal sludge. Journal of Cleaner Production, 184, 798–805.

Odey, E. A., Li, Z., Zhou, X., & Yan, Y. (2018b). Locally produced lactic acid bacteria for pathogen inactivation and odor control in fecal sludge. Journal of Cleaner Production, 184, 798–805.

Omar, F. N., Rahman, N., Hafid, H. S., Yee, P. L., & Hassan, M. A. (2009). Separation and recovery of organic acids from fermented kitchen waste by an integrated process. African Journal of Biotechnology, 8(21).

Paul, E., & Liu, Y. (2012). Biological sludge minimization and biomaterials/bioenergy recovery technologies. Wiley Online Library.

Raman, J., Kim, J.-S., Choi, K. R., Eun, H., Yang, D., Ko, Y.-J., & Kim, S.-J. (2022). Application of lactic acid bacteria (LAB) in sustainable agriculture: Advantages and limitations. International Journal of Molecular Sciences, 23(14), 7784.

Ray, H., Saetta, D., & Boyer, T. H. (2018). Characterization of urea hydrolysis in fresh human urine and inhibition by chemical addition. Environmental Science: Water Research & Technology, 4(1), 87–98.

Rodrigues, J. F., Lourenço, R. F., Maeda, D. L. N. F., de Jesus Cintra, M., Nakao, N., Mathias-Santos, C., Luiz, W. B., & de Souza Ferreira, L. C. (2020).

Strain-specific transcriptional and posttranscriptional regulation of heat-labile toxin expression by enterotoxigenic Escherichia coli. Brazilian Journal of Microbiology, 51, 455–465.

Schlosser-Brandenburg, J., Midha, A., Mugo, R. M., Ndombi, E. M., Gachara, G., Njomo, D., Rausch, S., & Hartmann, S. (2023). Infection with soil-transmitted helminths and their impact on coinfections. Frontiers in Parasitology, 2, 1197956.

Shukla, A., Patwa, A., Parde, D., & Vijay, R. (2023). A review on generation, characterization, containment, transport and treatment of fecal sludge and septage with resource recovery-oriented sanitation. Environmental Research, 216, 114389.

Slonczewski, J. L., Rosen, B. P., Alger, J. R., & Macnab, R. M. (1981). pH homeostasis in Escherichia coli: Measurement by 31P nuclear magnetic resonance of methylphosphonate and phosphate. Proceedings of the National Academy of Sciences, 78(10), 6271–6275.

Strande, L., & Brdjanovic, D. (2014). Faecal sludge management: Systems approach for implementation and operation. IWA publishing.

Thevenon, F. (2020). Sustainable Sanitation Systems: Health, Environment and Governance Challenges.https://www.sidalc.net/search/Record/oai:wedocs.unep.org:20.500.11822-33366/Description

Tortajada, C., & Biswas, A. K. (2018). Achieving universal access to clean water and sanitation in an era of water scarcity: Strengthening contributions from academia. Current Opinion in Environmental Sustainability, 34, 21–25.

Ubi, A., Njoku, L. A., Oyalabu, S., Emurotu, A., Kwaskebe, J., & Uwaoma, A. N. (2021). Ethico-medical implications of open defecation in a multi-religious society: A study of three communities in Ibadan, Oyo State, Nigeria. Sapientia Foundation Journal of Education, Sciences and Gender Studies, 3(4).

United Nations Children's Fund & World Health Organization. (2024a). Progress on household drinking water, sanitation and hygiene 2000-2022: Special focus on gender. World Health Organization.

United Nations Children's Fund & World Health Organization. (2024b). Progress on household drinking water, sanitation and hygiene 2000-2022: Special focus on gender. World Health Organization.

Van den Bergh, B., Michiels, J. E., Wenseleers, T., Windels, E. M., Boer, P. V., Kestemont, D., De Meester, L., Verstrepen, K. J., Verstraeten, N., & Fauvart, M. (2016). Frequency of antibiotic application drives rapid evolutionary adaptation of Escherichia coli persistence. Nature Microbiology, 1(5), 1–7.

Velkushanova, K., Brdjanovic, D., Koottatep, T., Strande, L., Buckley, C., & Ronteltap, M. (2021). Methods for faecal sludge analysis. IWA publishing.

Wang, Y., Wu, J., Lv, M., Shao, Z., Hungwe, M., Wang, J., Bai, X., Xie, J., Wang, Y., & Geng, W. (2021). Metabolism characteristics of lactic acid bacteria and the expanding applications in food industry. Frontiers in Bioengineering and Biotechnology, 9, 612285.

Wan-Mohtar, W. A. A. Q. I., Khalid, N. I., Rahim, M. H. A., Luthfi, A. A. I., Zaini, N. S. M., Din, N. A. S., & Mohd Zaini, N. A. (2023). Underutilized Malaysian Agro-Industrial Wastes as Sustainable Carbon Sources for Lactic Acid Production. Fermentation, 9(10), 905.

Water, Sanitation and Hygiene (WASH) Practices and the Incidence of WASH Related Diseases Within the Tamale Metropolitan Area (2020).

Zewde, A. A., Li, Z., & Xiaoqin, Z. (2021). Improved and promising fecal sludge sanitizing methods: Treatment of fecal sludge using resource recovery technologies. Journal of Water, Sanitation and Hygiene for Development, 11(3), 335–349.

Zuberer, D. A., & Zibilske, L. M. (2021). Composting: The microbiological processing of organic wastes. In Principles and applications of soil microbiology (pp. 655–679). Elsevier.