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Utilization of Liquid Anaerobic Digestate using Recirculating Hydroponic Planting System

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Abstract. A hydroponic planting technique employing organically treated anaerobic digestion digestate liquid fertiliser is becoming popular. This study examines the biological treatment of digestate from food processing waste anaerobic digestion using Cosmoball® uncoated and activated carbon-coated plastic media. In a pilot-scale recirculating hydroponic system (RHS), ammonia-to-nitrate conversion and plant development were assessed at varying digestate ammonia concentrations. Bench tests suggest that AC-coated Cosmoball® successfully treats digestate. After 21 days, the nitrate level reached 80 ppm, and 100% ammonia elimination and over 90% of the carbon oxygen demand (COD) were observed. The RHS maintained 116-ppm nitrate but reduced COD treatment to only 62–66%. High pH at the start of the RHS trial required pH control until day 40, after which it stabilised at 6.8. 15-ppm ammonia additions caused a substantial pH drop. Maintaining the pH at 5.8 on the RHS boosted plant growth. Finally, AC-coated media improves nitrification and produces plant-growth nitrate.

Keywords: Activated Carbon, Ammonia, Anaerobic Digestate, Hydroponic, Plastic Media

INTRODUCTION

An appropriate and comprehensive approach to treating high-organic wastewater must be implemented efficiently, following the desired effluent standard set by environmental regulatory authorities. The researchers used an anaerobic digestion (AD) process to treat food-processing wastewater (FPW) containing high levels of organic, suspended, and dissolved solids (Mahat *et al.*, 2021). The digestate produced from this AD process still contains high concentrations of ammoniacal nitrogen (AN), ranging from 100 to 300 mg/L, and a chemical oxygen demand (COD) of 100 to 400 mg/L. Although the system utilises a membrane for post-treatment, the parameters listed above still do not comply with Standard B requirements under the Malaysian Environmental Quality (Industrial Effluent) Regulations (2009) (Department of Environment, 2009). This

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study proposes a treatment that utilises naturally available bacteria to support an environmentally friendly post-treatment process.

The traditional, natural, and cost-effective method for removing ammonia from digestate is nitrification; however, it is a slow process. Like the natural treatment process, the biological nitrification process utilises naturally occurring aerobic autotrophic bacteria to reduce ammonia to nitrate. Ammonia-oxidising bacteria (AOB), such as *Nitrosomonas* sp., consume ammonia (NH_3). and converted to nitrite (NO^{2-}). Then, nitrite-oxidising bacteria (NOB), such as *Nitrobacter* sp., will further oxidise nitrite to nitrate (NO^{3-}) (Li *et al*., 2022). Nitrate is the type of nitrogen plants use for growth, much better than ammonia (Tyson *et al*., 2004). New methods for improving agronomic utilisation levels have been studied over the past years, and one of them is converting biological waste into high-quality liquid fertiliser (Keskinen *et al*., 2020). Researchers have suggested using digestate as an alternative hydroponic nutrient solution or liquid fertiliser, provided that a portion of the digestate's ammonium is converted to nitrate (Van Rooyen and Nicol, 2022).

Hydroponics is a soilless method for growing crops that use water-soluble fertiliser as nutrients (Rosenbaum, 2020). The aquaponics system derives plant nutrients from fish waste containing ammonia, which undergoes biological treatment to produce nitrate. The nitrification process requires the naturally occurring bacteria to attach to a specific type of media. Examples of media include rocks, pebbles, LECA balls, and plastic, in different configurations, each with different efficacies for bacterial growth (Nelson, 2008). A medium with a high surface area can improve nitrification efficiency by providing more biofilm areas for bacteria to live in (Alves *et al*., 2025). Plastic media, such as bio-balls (Cosmoball®) coated with activated carbon, increase media surface area and are easy to clean and maintain, as they are larger than the media currently used in aquaponic systems (Omar *et al.,* 2023). With sufficient aeration in the system, the bacteria would not overgrow, which can help reduce clogging.

It is essential to study the AD food waste digestate and its nutrient potential, as it can nitrify ammonium to nitrate, helping avoid toxic levels of ammonium in plants and optimising yield and crop quality. Different organic fertilisers derived from the digestate of various sources will have different characteristics (Bergstrand *et al*., 2012). Some researchers used AD digestate as a liquid fertiliser with or without nitrification, but with limited success (Shaji *et al*., 2021). The plant growth was inferior compared to the hydroponic system utilising inorganic fertiliser (Lind et al., 2021). Many factors, such as pH, nitrate, ammonia, and dissolved oxygen, can affect nitrification. pH has a significant impact on the nitrification process because it influences not only bacterial growth rates but also the acid-base balance of NO^{2-}/HNO^{2} and NH^{4+}/NH^{3}, thereby affecting the availability of substrates for ammonia-oxidising bacteria (AOB) and nitrite-oxidising bacteria (NOB) (Ni *et al*., 2023). During nitrification, ammonium is oxidised to nitrite, which lowers pH (Lind *et al*., 2021). The pH changes in the hydroponic systems using digestate were caused by the digestate's pH, nitrification, and the plants' ability to take up nutrients (Lind *et al*., 2021). Exudation of carbonate ions and hydroxide ions occur during plant nitrate-nitrogen uptake, raising the nutrient solution's pH. Due to the generally high pH of digestate, feeding it to a soil-less system raises the pH, but plant uptake of ammonium causes proton excretion from the roots, lowering the pH of the nutrient solution. The optimum pH for nitrification is 7.0 to 8.2, while the suitable pH for plant nutrient uptake is 5.8 to 6.8 (Gentili *et al.*, 2018). Stabilising pH within the range suitable for both processes is critical.

Thus, this study aims to assess the effectiveness of uncoated and activated carbon-coated Cosmoball® plastic media for biological treatment of digestate from AD of food processing waste. The chosen plastic media was then used in a pilot-scale recirculating hydroponic system to evaluate its effectiveness in nitrifying digestate at different ammonia concentrations to produce optimal nitrate for plant growth.

MATERIALS AND METHODS

Raw Materials

Fresh digestate was sourced from a food processing wastewater (FPW) anaerobic digester (Mahat *et al.,* 2021). A local plant in Kuala Lumpur, Malaysia, that produces fast-food products such as nuggets, burgers, and sausages, provided the raw FPW. The ammoniacal-nitrogen concentration of the digestate ranged from 100 to 300 ppm. The COD concentrations ranged from 80 to 380 ppm. The *Alternanthera sissoo* (Brazilian spinach) plant stem cuttings (around 10 cm) were rooted in tap water for 4-5 days before being transferred to the Deep Flow Technique (DFT) system.

Preparation of Plastic Media – Activated Carbon-coated Cosmoball®

The Cosmoball® media was made of durable high-density polyethylene (HDPE). It was light in weight (75 kg/m^3), so its floats make it easy to remove and clean. Figure 1(a) shows the spherical uncoated Cosmoball®, where the outer and inner diameters are 85 and 75 mm, respectively. The surface design includes crossed and longitudinal fins on the inside and outside of the ball, resulting in a specific surface area of 160 m^2/m^3. Granulated activated carbon from coconut shell (100–500 µm) was coated to the Cosmoball® using epoxy resin following the paint-spray-dry method of Shahot *et al.* (2019). Figure 1(b) shows the finished activated carbon (AC)-coated Cosmoball®. Durability tests were done by immersing the AC-coated Cosmoball® in distilled water and shaking using an incubator shaker (Innova 4000) for 28 days at 200 rpm and 35ºC.

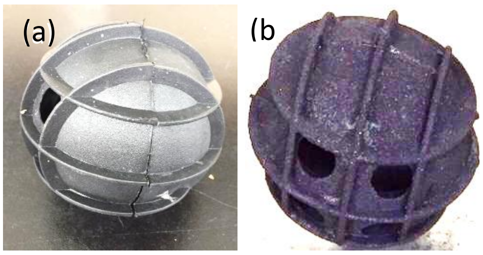

Fig. 1: Pictures of (a) original Cosmoball® and (b) Activated-carbon coated Cosmoball®

Digestate Treatment with Different Media and Ammonia Concentration

Two non-coated and AC-coated Cosmoball® were placed in 3-litre beakers filled with 2-litre digestate of 120 ppm (AN) concentration. A beaker without plastic media served as the control. Air was supplied via 5 W aquarium air pumps (SOBO, SB348A), ensuring dissolved oxygen content above 4 ppm. Next, five concentrations of digestate (20, 35, 65, 90, and 110 ppm; prepared by diluting with distilled water) corresponding to the initial ammonia concentration were treated using AC-coated Cosmoball®. The same setup applied. The runs were done in duplicates. Samples were analyzed for NH_3-N (APHA Method 4500-C) and pH (pH-80, HM Digital) every three to four days. COD (APHA

Method 5220C), nitrate test kit (API®), and nitrite test kit (API®) were checked once a week. Two samples (digestate and water in RHS with 4 ppm TAN addition) were analyzed for total nitrogen (Elemental Analyzer) and P and K as P_2O_5 and K_2O using ICP-OES after wet digestion.

Pilot-scale recirculating hydroponic system setup and experimental procedure

Figure 2 displays the schematic diagram of the pilot-scale RHS setup utilized in this study. It consists of a 100-litre influent tank, a 50-litre tank filled with 50 pieces of AC-coated Cosmoball® media, a 50-litre radial filter tank to remove the solids, a 50-litre sump tank to house a 32-watt (2000 L/hr) submersible pump (BLS DoPhin, PC2000), and six rectangular UPVC pipes (5 x 10 x 100 cm) with six-5 cm holes on each pipe to place the netpots for the plants (DFT system). The air in the biological tank was supplied using a 4 L/hr output air pump (SOBO, SB-988) with a dissolved oxygen level of 4 ppm. LECA balls held the plant stem cuttings in the net pot.

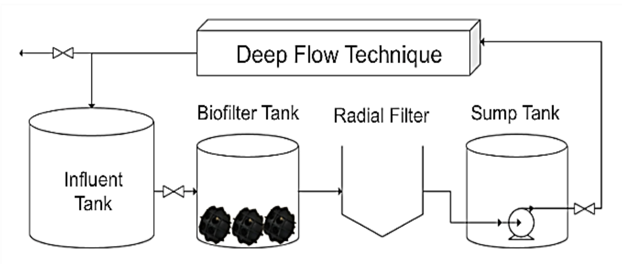

Fig. 2: Schematic diagram of the pilot-scale RHS

The start-up phase used 70 L of the AD digestate with an ammoniacal-nitrogen concentration of 60 ppm. No plants were added to the DFT system during this phase. The pH, total ammonia nitrogen (TAN) (API®) – a measure of NH_3 and NH^{4+}, nitrite, and nitrate was monitored. Once the TAN concentration reached zero, digestate was added to reach around 20 ppm. Once the nitrate reaches 80 ppm, the system is ready for transplanting the rooted stem cuttings. Henceforth, digestate batches were added in increments of TAN concentration (2, 4, 6, 8, 10, 12, and 15 ppm) at a few-day interval, depending on the nitrate value. In general, the nitrate concentration was maintained at 80 ppm. The plants' height, weight, and number of leaves in each net pot were measured on the first and final days of the experiment.

RESULTS AND DISCUSSION

Treatment Performance using Non-coated and AC-coated Cosmoball®

Ammoniacal-nitrogen concentration in all the treatments followed a decreasing trend, fastest in the treatment with AC-coated media and slowest in the control experiment, as shown in Figure 3. AC-coated, non-coated media, and control treatment achieved a Standard A discharge below 10 ppm (Department of Environment, 2009) on days 11th, 19th, and 21st, respectively. This downward trend aligns with the rise in nitrite observed on days 14, 11, and 7 for control, non-coated, and AC-coated media, indicating that nitrification has begun. Nitrate began to appear on day 14th and reached a higher concentration of 80 ppm in the AC-coated samples, consistent with the higher nitrite concentration of 0.375 ppm on day 11th. The addition of Cosmoball® media provided a suitable surface for faster biofilm growth, similar to the findings of Sharipuddin and Awang (2021), who treated domestic wastewater. Shahot *et al.* (2019) similarly found that the addition of activated carbon-coated Cosmoball® media increases the specific surface area and surface roughness, promoting faster biofilm formation. More rapid ammonia removal via denitrification at the beginning of the experiment can also be attributed to the addition of activated carbon.

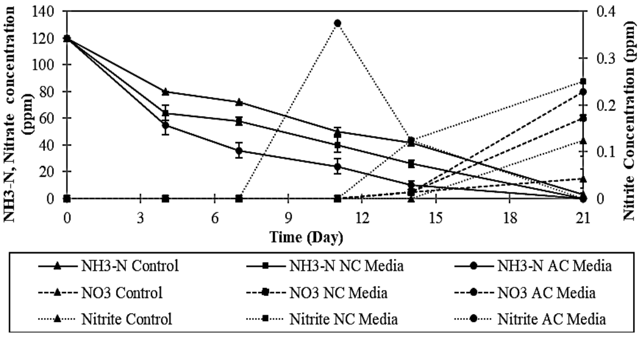

Fig. 3: Ammoniacal-nitrogen, nitrate, and nitrite concentration profile in digestate treatment using Cosmoball®

The pH fluctuated between 7 and 9 across all media and control experiments, rising from 7.5 to 9 within 7 days before plummeting back to approximately 7.5 on day 14. The initial increment could be due to carbon dioxide stripping from aeration (Cheng *et al.,* 2023). The AOB bacteria convert ammonia into nitrite, which lowers pH. As shown in Figure 3, a higher nitrite concentration led to a higher pH, as more H+ ions were produced (Tyson *et al.,* 2004). On the 21st day, during treatment with AC-coated media, the pH increased to 8.3, contrary to the expectation that higher nitrate levels would decrease the water pH. This suggests that NOB favors a higher pH, thereby increasing nitrate production. The activity of nitrifying bacteria increased with increasing pH (Tyson *et al.,* 2004) and reached its optimum at 8.0 (Pfeiffer and Ott, 2023). Because a high amount of ammonia remained in the control experiment, ammonia oxidation led to a further pH reduction to 7.2.

All digestate-treated achieved a Standard A discharge limit of COD below 50 ppm on the 21st day. Better treatment with AC-coated media achieved this as early as day 7. Digestate treatment aided by AC-coated Cosmoball® media successfully removed the highest COD (91.7%), compared to 83.4% and 75.2% for non-coated and control experiments, respectively. Shahot *et al.* (2015) also achieved Standard A discharge COD with uncoated Cosmoball® media during municipal wastewater treatment. Coating the Cosmoball® media with activated carbon (Stoknes *et al.,* 2016) resulted in improved treatment performance. Hence, Cosmoball® media, especially the AC-coated ones, are suitable for biological wastewater treatment, especially during polishing steps.

Treatment Performance using AC-coated Cosmoball® at Increased TAN Concentration

A study on different initial TAN concentration (20–110 ppm) using AC-coated Cosmoball® media showed a similar pattern of TAN concentration reduction, with higher TAN concentrations reaching the Standard A discharge limit later. pH ranged from 6.6 to 7.6, within the suitable range for nitrification. Nitrate appeared starting on day 12 for higher initial TAN concentrations of 65, 90, and 110 ppm. Meanwhile, it took 18 days for lower concentrations (20 and 35 ppm) to produce nitrate. By day 22, all TAN had reached a nitrate concentration of 80 ppm, except at 90 ppm, where the initial TAN was reduced from 60 to 20 throughout the experiment. The initial TAN treatment on the 29th day registered a concentration of 160 ppm. COD removal was only 50-67%, as the initial COD was high at 380 ppm for an initial TAN of 110 ppm. This shows that the AC-coated Cosmoball® media batch setup used in this experiment is better suited for the polishing step in wastewater treatment.

Pilot-scale Recirculating Hydroponic System (RHS)

The RHS used AC-coated Cosmoball® for the treatment of digestate, as better nitrification was observed in the initial bench study and in Brazilian spinach planting. pH ranged between 6.8 and 7.8, which is suitable for nitrification. The start-up phase lasted 21 days, as indicated by the nitrate level reaching 80 ppm. The experimental phase commenced after the plants were transplanted into the system. The RHS successfully maintained 80-100 ppm nitrate throughout TAN additions of 2 ppm (18 days) and 4 ppm (15 days), as shown in Figure 4. After that, TAN levels were increased to 8, 10, 12, and 15 ppm at 6-7-day intervals to assess their effects on RHS performance and plant growth. Nitrate concentration ranges between 80 and 140 ppm, with an average of 116.4 ppm. The absence of nitrite indicates that it was converted to nitrate within 24 hours of adding the digestate. An analysis of the nutrient (NPK) revealed that the total N in the feed was slightly higher at 1.87% as compared to the water in the system when 4 ppm TAN was added (1.53%). Meanwhile, the same low P and K values were found in both samples at 0.01% and 0.02%, respectively.

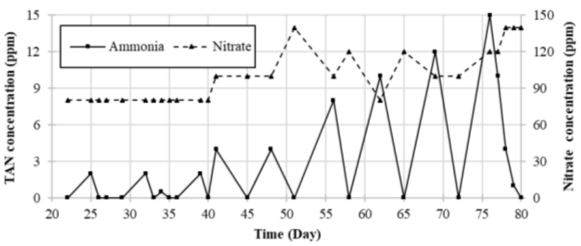

Fig. 4: Nitrate concentration in the pilot-scale recirculating hydroponic system at different amounts of digestate additions

Figure 5 shows the pH values in the pilot-scale RHS experiment. A high pH of 7.96 at the start of a plant transplant required the addition of phosphoric acid to improve nutrient uptake. Additional phosphoric acid was required on days 32 and 39, along with digestate to control pH. Despite adding the maximum amount of digestate to yield 15 ppm TAN, the pH eventually stabilised around 6.8. No further addition of phosphoric acid was required. The water in the system may already have reached its buffering capacity. A study by Galiart (2023) using digestate in their RHS showed a similar trend in pH, with values ranging from 6.8 to 8.2. In contrast, Lind *et al.* (2021) observed considerable pH fluctuations after each digestate addition, possibly due to the high volume of each addition (2 litres in a working volume of 9). Unfortunately, the pH plummeted to 5 two days after the addition of 15-ppm TAN digestate. The experiment was stopped due to the toxic effect of the low pH on nitrifying bacteria, despite no observed negative effects on nitrate concentration or plants. TAN values of around 8–10 ppm are advisable for future studies. COD removal remained around 62–66% for all TAN levels. It is possible that only the biological process on the AC-coated Cosmoball® media contributed to the reduction in COD, not phytoremediation.

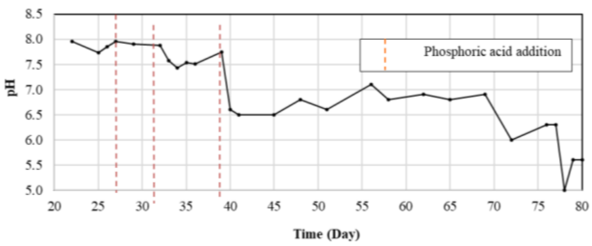

Fig. 5: pH trend in the pilot-scale recirculating hydroponic system

pH Control Strategy via Interval Digestate Addition

The system performance and plant growth were further tested by adding digestate at intervals and in varying amounts to maintain a pH of 6.5 or lower. The pH range of 5.8-6.8 is ideal for nutrient solutions used in soilless cultures (Gentili *et al.*, 2018). Although pH 6.5 falls within the lower end of the optimal pH range for nitrification, it still maintains a balance between nitrification and plant nutrient uptake. Since 8 ppm of ammonia addition in the previous experiment did not show adverse effects on nitrate concentration, pH drop, or pH rise, it was chosen for the maximum pH 6.5 study. Figure 6 shows the trend of pH and nitrate upon ammonia addition. pH fluctuated between 5.1 and 6.6 during this study, with pH raised slightly after each addition. Digestate was added to the 8-ppm ammonia concentration on days 3, 10, and 39. Meanwhile, 4 ppm ammonia digestate was added on the 26th. This ensures the pH does not exceed 6.5. However, the laboratory was closed for the semester break, resulting in missing data for days 26-30. Therefore, digestate was not added during this time. The drops in pH during the experiment indicate nitrification; meanwhile, the rises are due to digestate addition and possibly plant nutrient uptake (Lind *et al.,* 2021). The lowest observed pH of 5.1 on day 11th, a day after digestate addition, is primarily due to rapid nitrification, as previously discussed in Section A, or to ammonium uptake by plants, given its high concentration during these digestate additions (Singh *et al.,* 2019). Ammonium uptake releases protons (H^+), increasing the proton concentration around the roots and decreasing pH, as clearly observed at lower nitrate concentrations (around 90–100 ppm).

Nitrate concentrations remained around 100 ppm and only shot up to 160 ppm on day 15, 5 days after the second 8-ppm ammonia digestate addition. This can be proven that the nitrification rate was high. The high nitrate value persisted for 8 days, although the pH favours high nutrient levels (nitrate as a nitrogen source) rather than optimal nitrification conditions. The height and number of leaves registered rapid increases during this period (Figure 7).

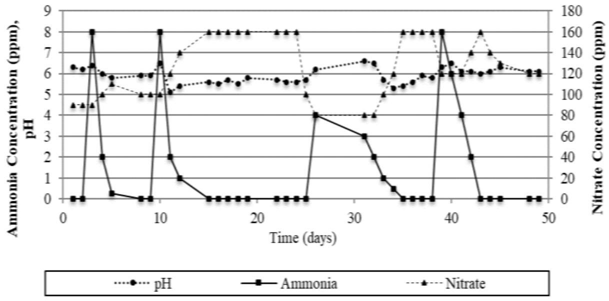

Fig. 6: Nitrate concentration and pH trend in a pilot-scale recirculating hydroponic system at digestate additions to control pH below 6.5

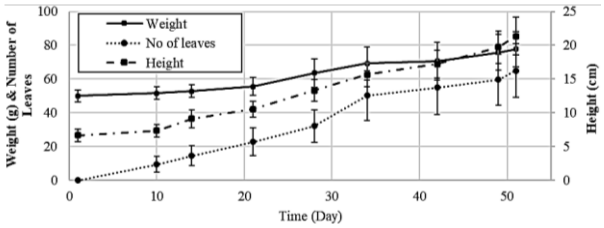

Fig. 7. Plant growth performance in a pilot-scale recirculating hydroponic system added with digestate to control pH below 6.5

The plant simultaneously takes up nitrate concentrations above 160 ppm, thereby maintaining a constant concentration. The drop in nitrate concentration to 100 ppm on day 25 may be attributed to nitrate exhaustion. Due to the laboratory closure, the effects of adding digestate at 4 ppm TAN on day 26 on nitrate could not be clearly observed. But it took 5 days for the TAN to reduce to 3 ppm. The preceding low pH values (below 5.8) may not have favoured nitrification, resulting in a low nitrification rate. Thereafter, the conversion of ammonia to nitrate proceeded well, as evidenced by a rapid, substantial increase in nitrate concentration to 160 ppm over 4 days. When the pH was around 6.5, the nitrification process was favoured again, but it decreased afterwards due to its high rate. The addition of digestate (ammonia), nitrification, and plant uptake of ammonia and nitrate all change pH and vice versa. Therefore, this symbiosis is an essential criterion for optimising RHS.

The following experiment aimed to control pH at a minimum of 5.8 to improve plant growth performance (Lind *et al*., 2021), while still within the pH range for nitrification. Soilless culture nutrient solutions should have a pH of 5 to 6 (usually 5.5) to maintain a pH of 6 to 6.5 in the root zone. This is the pH range where plants have the greatest access to nutrients (Maneejantra *et al.,* 2016). pH fluctuated between 5.8 and 6.6. Lower digestate addition ensured that pH did not rise too high, and the nitrification process did not result in sudden or too low pH. Although the aim was to control the pH at around 5.8, the addition of high-pH digestate, albeit in lower amounts, resulted in an average pH of 6.26 throughout the study. The RHS system using packed AC-coated Cosmoball® media showed a slight decrease in pH when digestate was added compared to the MBBR system using K1 media (Lind *et al*., 2021). Nitrate concentrations ranged from 80 ppm at the beginning of the study to 140 ppm. The average nitrate concentration was around 110 ppm, lower than that observed at pH 6.5 (maximum study). Less ammonia was available for nitrification, resulting in lower nitrate and affecting plant growth performance.

Plant Growth Performance in Pilot-scale Recirculation Hydroponic System

The plants' growth performance was evaluated by recording their weight, height, and leaf number at the beginning and at harvest. Table 1 presents the average weight, height, and number of leaves of the plants. Figure 8 shows the plant at 2 weeks after transplanting for all the treatments.

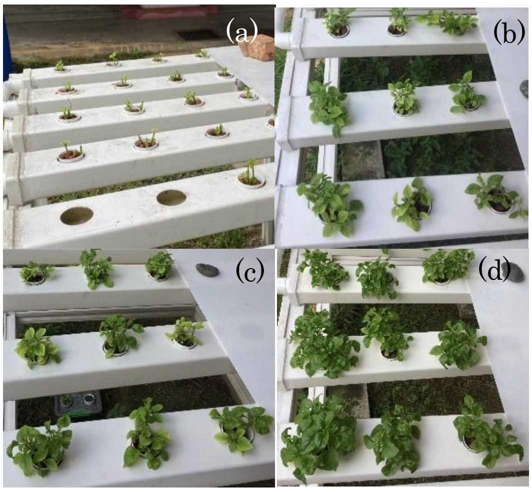

Fig. 8: Brazilian spinach plants (a) at transplanting, 2 weeks after transplanting for (b) Increasing TAN concentrations, (c) pH maximum at 6.5, and (d) pH minimum at 5.8 treatments

Table 1. Plant growth performance in the RHS at increasing TAN concentrations and controlled pH

	Increasing TAN Concentrations			**pH maximum at 6.5**			**pH minimum at 5.8**		
Data	**Fresh weight (g)**	**Height (cm)**	**No. of leaves**	**Fresh weight (g)**	**Height (cm)**	**No. of leaves**	**Fresh weight (g)**	**Height (cm)**	**No. of leaves**
Increment	21.6	15.24	60.9	27.66	14.68	64.94	32.94	6.72	35.11
Changes (%)	42.7	228.8	-	55.3	220.4	-	81.92	126.8	-
Increment/day	0.332	0.234	0.937	0.542	0.287	1.27	1.32	0.268	1.40

The 42.7% increase in weight indicates strong plant growth. A significant increase in height indicates that the plants have received a balanced distribution of sunlight. According to a previous study, the desired marketable size is around 20-50 g; therefore, the weight gain in this study is sufficient if marketed (Sun *et al.,* 2016). The final average number of leaves was relatively high, possibly due to excellent nutrient uptake, a suitable pH, and a high nitrate availability. The stem's weight correlates with the number of leaves. Previous studies have shown a correlation between the two parameters, but the increase in leaves ceases after a certain period of time (Sun *et al*., 2016).

Since nutrients are conserved as they flow from stems into leaves, the primary assumption arising from these studies and incorporated into the hypothesis is that the number of resources supplied by stems limits the resources available to leaves. Therefore, the isometric growth rates of stems and leaves should determine the trade-off between leaf mass and leaf number (Sun *et al.,* 2016). Furthermore, the addition of digestate with lower ammonia levels, along with increased nitrate uptake by the plants, led to improved plant growth performance in the study targeting a pH range of 5.8 to 6.5. A more stable pH may be the main reason for better weight gain. When comparing the two in terms of the days of the experimental run, the pH control attempt at a minimum pH of 5.8 is more than twice as heavy, slightly taller, and shows an increase in leaf number.

CONCLUSIONS

The use of activated carbon-coated media (Cosmoball®) to treat digestate from a food wastewater anaerobic digester successfully reduced NH_3-N concentrations and removed more than 90% of COD. The nitrate concentration reached 80 ppm after 21 days of treatment. However, a higher NH_3-N concentration in the digestate reduced COD removal to below 67% and delayed achieving the Standard A discharge limit compared to lower concentrations. A pilot-scale RHS system utilising AC-coated Cosmoball® as the biological media removed 62–66% of COD but maintained nitrate at an average of 116 ppm. After 40 days, the RHS's pH stabilised at around 6.8, the optimal pH for bacterial growth and plant nutrient uptake. However, adding 15 ppm ammonia disrupted pH stability, whereas better plant growth was observed when the RHS operated above pH 5.8 by adding 4 ppm TAN batches of the digestate. AC-coated Cosmoball® is suitable as the biological media in an RHS with a good pH control strategy.

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