Application of recycled slaughterhouse wastes as plant nutrients for vegetable crops cultivated in eastern India

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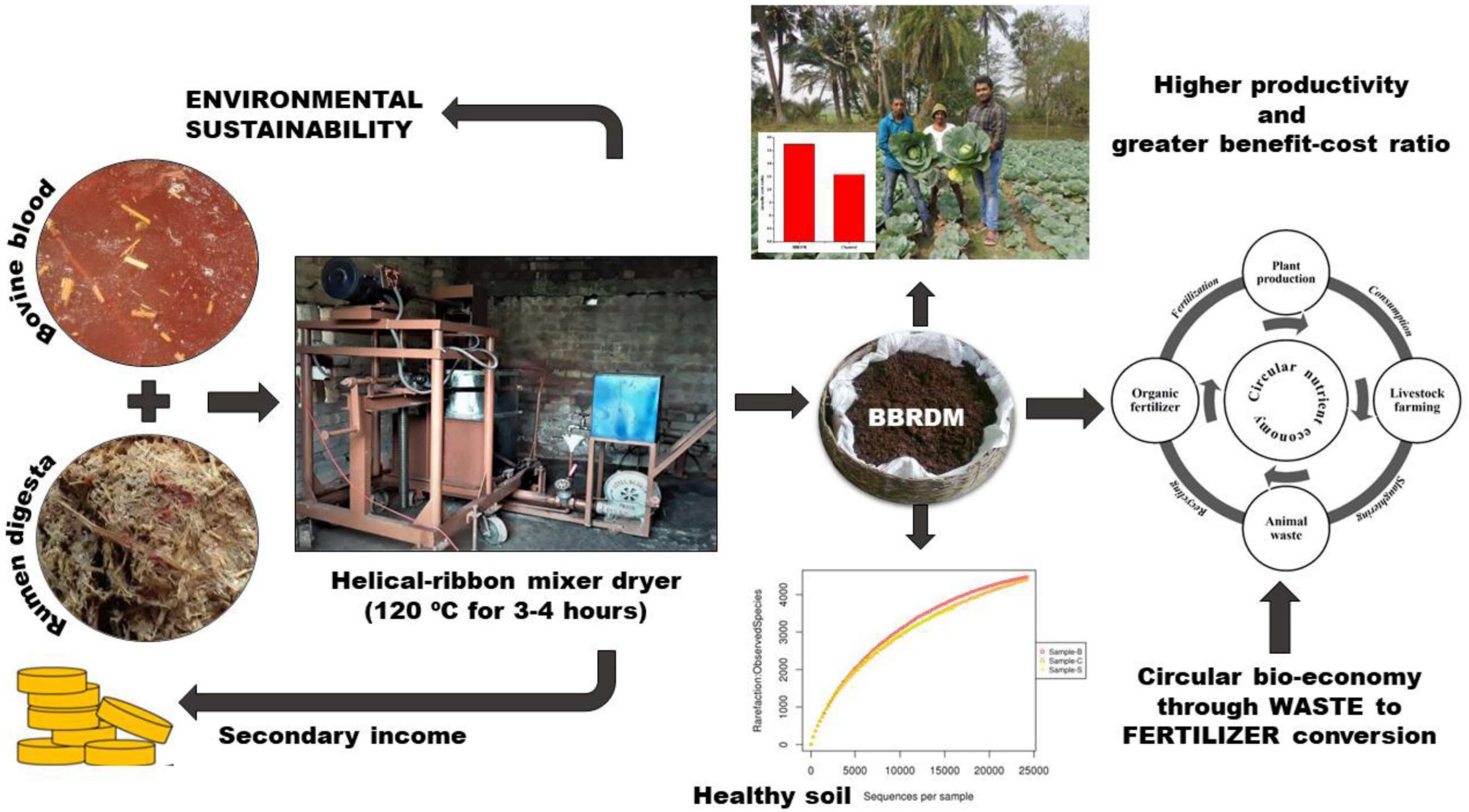
Abstract

The effects of 'bovine-blood-rumen-digesta-mixture' (BBRDM), an abattoir-derived organic fertilizer was studied on plant growth and soil health. Due to poor infrastructure and low waste generation in rural abattoirs, implementation of sophisticated waste management system is difficult resulting in environmental and public health hazards. Using a newly designed helical-ribbon mixer dryer, mixture of waste blood and rumen content (in 3:1 ratio) was converted at 90-110 °C for 2-3 hours to BBRDM having a C/N ratio of 4.68. The presence of essential microelements in BBRDM was revealed by scanning electron microscopy coupled energy dispersive spectroscopy (SEM-EDS). Compared to N/P/K=10:26:26+urea and vermicompost, the yield was significantly higher when BBRDM was amended at rates of 6 and 9 g kg^{-1} of soil. In contrast, plants died at the highest BBRDM rate (13 g kg^{-1} of soil) due to the presence of labile C percentage in animal waste. We evidenced almost double residual productivity when soil treatment was with 9 g BBRDM kg^{-1}. Judicious supply of BBRDM and proper N application allowed better soil organic carbon (SOC) accumulation, increased the percentage of soil macroaggregates, and encouraged copiotrophic abundance in soil which in turn impacted soil enzymes to convert organic matter into plant available form. Compared to chemical treatment, nitrate/ nitrite concentrations were lower with in fruits fertilized BBRDM. Air-soil methane flux (0.008 µg g^{-1} hr^{-1} in BBRDM-fertilized field) was approximately 1787 times lower than that emitted from the abattoir waste dumping sites (14.30 µg g^{-1} hr^{-1}). Interestingly, the average benefit-cost ratio for BBRDM treatment was 3.75 as opposed to 2.58 for NPK fertilization. Furthermore, circular bio-nutrient economy was also promoted by the waste to fertilizer conversion. Although, SWOT analysis showed lack of public awareness regarding the bio-based products could be a possible threat to circular economy of organic waste management.



Graphical overview

1. Introduction

Overuse of synthetic fertilizers and excessive nitrogen (N) addition to agricultural soils may result in soil acidification, deterioration of soil structure, biodiversity loss, and even disturbance of various ecosystem services, impeding sustainable agricultural development (Guo et al., 2018; Urra et al., 2020). On the other hand, careful application of well-prepared organic fertilizers rich in humus, organic matter, and beneficial microorganisms has a positive impact on agro-ecosystem health by promoting soil aggregate stability, soil organic matter (SOM) turnover, copiotrophic abundance, and native enzymatic activity as well as protects crops from soil-borne owing to development of synergistic consortia at the root-microbiome interface (De Corato, 2020).

Animal manure application aids organic matter decomposing copiotrophs to soils whereas chemical fertilizations encourage the quantity of oligotrophs in rhizosphere. Oligotrophs are slow growing and *k*-strategist that thrive in nutrient-poor environments and are typically found abundant in soil microaggregates (<250 μm diameter aggregates) with reduced soil organic matter (SOM) (Lin et al., 2019). In contrast, long-term animal manure fertilization enhanced the percentage of stable macro-aggregates, having diameters >250 μm in soil and facilitated physical protection to soil organic carbon (SOC) ensuing a favorable environment for copiotrophic growth (Sheoran et al., 2019). Simultaneously, the activities of β-glucosidase, urease and alkaline phosphatase found higher in organically treated fields that have a crucial role in soil nutrient dynamics (Liang et al., 2014). According to Das and Varma (2011), soil enzyme levels can be altered because each soil type has a different organic matter profile, composition and activity of living organisms, and intensity of indigenous biological processes. Apart from their benefits, animal-derived organic amendments have certain disadvantages, such as presence of heavy metals, pathogens, antibiotic resistant genes, and emerging contaminants if the wastes are not perfectly processed (Urra et al., 2019).

In India, there are about 32,000 informal slaughterhouses, the bulk of which do not adhere to any scientific waste disposal procedures (Kennedy et al., 2018). According to Roy et al. (2016), an Indian rural abattoir kills 20 buffaloes (on average) per day which results in massive amount of animal excrement being dumped directly into municipal or local sewage systems without any treatment (Bhowmik et al., 2021a). Informal slaughterhouses in India and other underdeveloped countries like Kenya were unable to implement such advanced and expensive treatment techniques due to a lack of infrastructure and financial constraints, therefore rural abattoirs preferred landfilling and open dumping of waste as simplest option. Landfills release infectious pathogens, a variety of hazardous substances, and leachate into the environment. The burial and burning of slaughterhouse waste also carry similar environmental risks (Bhunia et al., 2022). On the other hand, release of toxic organic contaminants into the agro-ecosystem and increase of antibiotic-resistance in soil bacterial communities might be attributed through fertilizations with untreated animal waste (Urra et al., 2019). Therefore, to ensure biosecurity, waste recycling is necessary before reuse them in agriculture.

The present investigation may resolve two major socio-economic issues of the developing nations: (a) need for a cheap, good quality organic fertilizer for marginalized farmers and (b) hygienic waste management through reuse leading to development of a green business. In addition, BBRDM application could provide double benefits to farmers due to strong residual fertility of organic fertilizers as reported by Ragályi and Kádár (2012) earlier. To the best of our knowledge, no research on the agricultural applications of rural slaughterhouse waste has yet been published in which the application dose calculation, fertilization frequency determination, and impact analysis on plant and soil health taking farmer's economy into consideration were reported in a holistic manner. Therefore, pot and field-scale cultivations of seasonal vegetables were performed to address this gap as well as conducted social surveys in five districts of West Bengal (India) to study stockholder willingness for the product. Recycling organic waste in agriculture is the primary purpose of the study and objectives were threefold as; **(a)** characterization of recycled slaughterhouse waste as fertilizer, **(b)** dose calculation, application frequency determination, and effect analysis on agro-ecosystem health, and **(c)** stakeholder willingness assessment for the product, and development of bio-economy through waste to fertilizer conversion.

2. Materials and methods

2.1. Preparation of 'bovine-blood-rumen-digesta-mixture'

To prepare BBRDM, 60 L fresh blood and 20 kg rumen digesta were mixed (in 3:1 ratio) following Roy et al. (2013) and dried at 90-110 °C for 2-3 hours using a newly designed helical-ribbon mixer dryer to obtain 14 kg of BBRDM in one batch. The recycling unit comprises of three sub-units: (a) cylindrical drying vessel, (b) helical ribbon-shaped mixing spindle, and (c) a burner, and installed at Magrahat village for pilot-scale production of the fertilizer. Three batches were produced per day, and BBRDM was stored at room ambient during the study time. An Indian Patent was granted to us (Bhowmik et al., 2021b) in 2021 (number 370 569) on this equipment.

2.2. Characterization of BBRDM as fertilizer

A digital pH meter (LMPH - 10, Labman Scientific Instruments Ltd.) was used to measure pH of the final produce. Ammonical nitrogen (NH_4-N), total Kjeldahl nitrogen (TKN) and nitrate nitrogen (NO_3-N) were evaluated applying Kjeldahl method. Vanadomolybdophosphoric acid colorimetric and flame photometric methods were followed to determine total phosphorous (TP) and potassium (K) contents in BBRDM (Radojevic and Bashkin, 1999) respectively. Organic carbon (SOC) percentage was calculated according to the methodology of Walkley and Black (1934). Similar methodologies were applied to characterize commonly available vermicompost.

Spectral characterization was done using scanning electron microscopy (SEM) coupled with energy dispersive spectroscopy (EDS) and powder X-ray diffraction (XRD). Micrographs were recorded on ZEISS EVO 18 (Jena, Germany) SEM, and Bruker XFlash 6I30 (Billerica, United States) energy dispersive X-ray detector was applied for elemental identification of BBRDM. A Philips PAN analytical (Almelo, Netherlands) powder X-ray diffractometer was used to obtain XRD spectrum.

2.3. Assessment of BBRDM as fertilizer

2.3.1. Pot cultivation

A total eighteen tubs (18 cm diameter × 22 cm depth) were filled with (a) soil of Magrahat village as control (S), (b) soil + N/P/K=10:26:26+urea (as chemical fertilizer) generally applied for vegetable production in West Bengal (CF), (c) soil + vermicompost containing N/P/K=4:1:2 (VC), (d) soil + 6 g BBRDM kg^{-1} of soil (80 kg N ha^{-1}, low dose) (BL), (e) soil + 9 g BBRDM kg^{-1} of soil (120 kg N ha^{-1}, recommended dose of BBRDM which is similar to CF and VC) (BR), and (f) soil + 13 g BBRDM kg^{-1} of soil (180 kg N ha^{-1}, high dose) (BH) to perform successive cultivation of cabbage-spinach (during August to November, 2018) and bell pepper-amaranth (during November, 2018 to March, 2019). Before cultivation, soil was characterize using the techniques outlined in section 2.2. A completely randomized design (RBD) with three replications was followed for each six treatments. In order to keep nitrogen levels constant among treatments, the application dose of the CF treatment (N/P/K=10:26:26) was first calculated while accounting for the P and K contents of the fertilizer. Then, the required amount of N was subsequently given through urea (N/P/K=46:0:0) fertilization.

Residual fertilizer effect was studied on the same soil after removing plant heads. On the previously fertilised pots, approximately same numbers of seeds were sown, and no fertilizer was added during the cultivation period.

2.3.2. Field study

The field cultivation of cabbage and spinach was carried out over two successive years in Magrahat village of South 24 Parganas district during August to November of 2019 as season 1 and in 2020 as season 2. Following Roy et al. (2016), the cultivation plot was divided into twelve sub-plots: six were fertilized with well-prepared BBRDM, and the remaining six were treated with N/P/K = 10:26:26+urea as a control. Fertilization was done manually (on dry matter basis) to supply 120 kg N ha^{-1} of soil as recommended for hybrid cabbage production. Half of the fertilizer was applied at the time of soil preparation as basal dose, while the remaining amount was delivered through side-dressing in two equal splits according to Tiwari et al. (2003), after 21 and 40 days of transplanting. However, after harvesting the cabbage heads soil samples from the cultivation fields were taken at 5-10 cm depth using a soil auger and then pooled them together to make two composite samples as described by Sengupta and Dick (2015) earlier: BBRDM-fertilized soil (BR) and chemically cultivated soil (CF). Elliott's (1986) wet sieving technique was followed to study the size distribution of the soil aggregates, and Walkley and Black's (1934) method was applied to calculate the SOC content. Activity of soil enzymes like β-glucosidase, urease, and alkaline phosphatase were measured according to Dick et al. (1997).

Residual fertilizer effect was investigated on the same soil cultivated spinach as test crop. The yield characteristics were recorded after 30 days of cultivation. Plant leaves from the main and residual plots were taken for nitrate and nitrite analysis, with the determination being made in accordance with ISO 6635: 1984 (Stachniuk et al., 2018). For comparison, cabbage and spinach leaves were also obtained from a local vegetable market.

2.4. Status of available soil N during the cultivation

The amount of available soil nitrogen (NH_4^+-N) was determined at the beginning of cultivation (day 1) and every two weeks throughout the cultivation period using Subbiah and Asija's (1956) alkaline permanganate method.

2.5. Microbiological analysis of soil under different treatments

Metagenomic DNA (from both pot and field soils as S, CF, BR) was extracted using Nucleospin Soil Kit (TaKaRa Bio Ltd, Japan). A ND-2000 UV-Vis spectrophotometer

(Thermo Scientific, Wilmington, USA) was used to quantify the extracted DNA. By synthesizing 16S rRNA Forward (5'-CCTACGGGNBGCASCAG-3') and 16S rRNA Reverse (5'-GACTACNVGGGTATCTAATCC-3') primers amplification of the hypervariable V3-V4 regions of the bacterial 16S rRNA gene was performed. The purified amplicons were then quantified using a Qubit fluorometer (Thermo Fischer Scientific, USA), sequenced (2 × 250 bp) on an Illumina platform (Illumina, San Diego, USA), and analyzed using Quantitative Insights Into Microbial Ecology (QIIME) bioinformatic pipeline following Caporaso et al. (2010). With the accession number PRJNA593705, raw sequences were submitted to NCBI Sequence Read Archive (SRA) database. In order to investigate the possible relationship between the relative abundance of bacterial phyla and soil characteristics under various field treatments, Principal Component Analysis (PCA) was performed using the R software.

2.6. Benefit-cost analysis from cabbage-spinach field

To perform benefit-cost analysis, land preparation, seedling purchase and transplantation, irrigation, fertilization, weed and pest control, harvesting and rental value of the land all were included as cultivation cost. BBRDM was purchased at INR 26 kg^{-1}, while the chemical fertilizer (N/P/K=10:26:26+urea) costed INR 34 kg^{-1}. Labors were provided with INR 350 per head per day during the field cultivation. An average market price of INR 30 kg^{-1} for cabbage and INR 20 kg^{-1} for spinach was considered for profit calculation. Then, in accordance with Tiwari et al. (2003), the benefit-cost ratio in terms of net return from cabbage-spinach rotation for both seasons over a hectare of soil was calculated.

2.7. Quantification of air-soil methane flux

Soil samples taken from the experimental site (both pot and field) and waste disposal site (WDS) were placed in 40 millilitre borosilicate screw cap vials, which were then kept in the dark for three days. With a Systronics GC-8205 (India) gas chromatograph linked with a flame ionization detector (GC-FID), methane concentrations (in 5 ml aerobic headspace) were measured. With some minor adjustments, the air-soil methane flow was computed in accordance with Khoiyangbam et al. (2004).

2.8. SWOT analysis for BBRDM commercialization

A multiple-choice questionnaire embedding twenty questions prepared in English was followed for data collection. A total 50 rural abattoirs from 7 districts of West Bengal namely Malda, Murshidabad, Howrah, Hooghly, Nadia, West Medinipur, and South 24 Parganas participated during the survey (between March and May, 2023), and both slaughterhouse owners (50 individuals) and local farmers (a total 500 individuals, 10 from each site) were interviewed to understand their mind-set. The recorded interviews were transcribed using grounded method, and barriers and enablers were shortlisted by Strength, Weakness, Opportunity, and Threat (SWOT) matrix following Paes et al. (2019) for wide-scale implementation of the model.

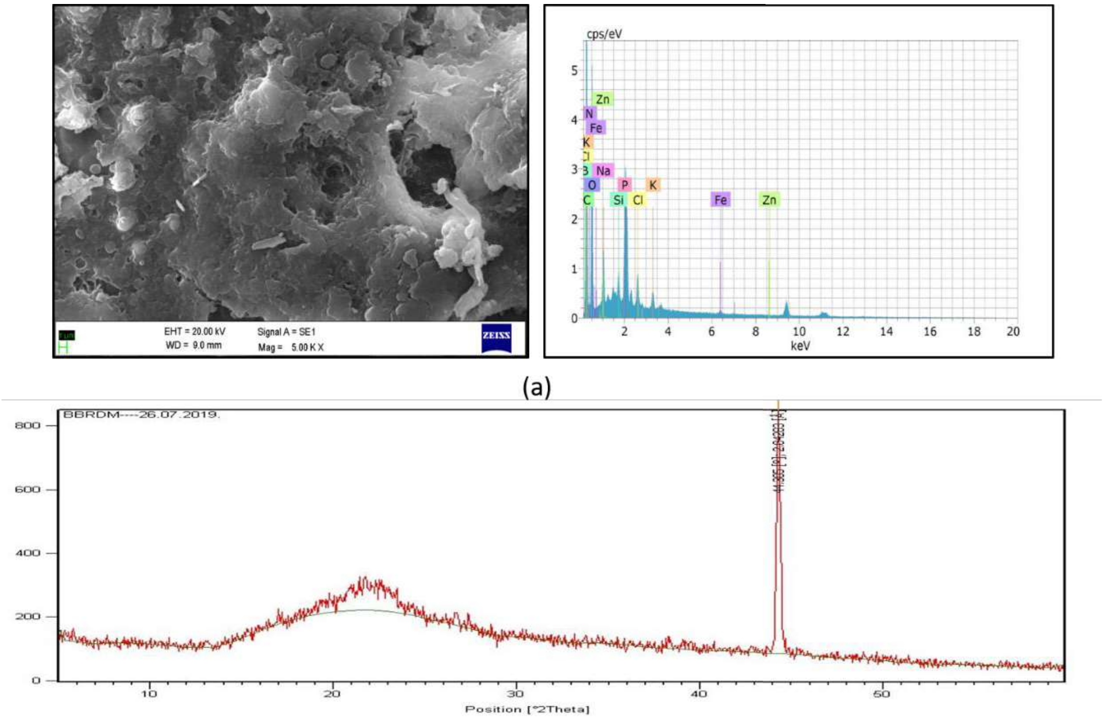
2.9. Statistical analyses

Statistics was established using SPSS software for Windows version 16.0 (SPSS Inc., Chicago IL, USA), and all experiments (except the metagenomic study, spectrum characterisation of BBRDM, and SWOT analysis) were performed in triplicates. Standard deviations are shown with mean values. While Student's *t*-test compared field applications, Tukey's *post hoc* analysis was applied to contrast pot treatments and nitrate/nitrite concentrations in cultivated vegetables. Differences made significant at 0.5% cut-off level.

3. Results and discussion

Table 1. Physico-chemical properties of the soil and organic fertilizers used

Treatments	pH	Moisture (%)	Nutritional status N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Org C (mg g^{-1})
Soil	6.5	17	1086.24	143.65	38.46	7.32
Vermicompost	6.0	39.54	2264.02	1016.57	454.36	14
BBRDM	7.5	16.95	5977.75	783.14	911.28	29.97



(a)

(b)

Figure 1. (a) Morphology and elemental composition of BBRDM was studied by SEM-EDS analysis, and (b) XRD confirmed the presence of ammonium-potassium nitrate complex in the final produce. See section 2.2 for details.

The NPK content of BBRDM was approximately 7.63:1:1.16. As shown in Figure 1a, the SEM-EDS analysis confirmed the presence of eleven different elements, namely carbon, oxygen, nitrogen, phosphorus, sodium, potassium, boron, zinc, iron, calcium, and silicon in

BBRDM. The carbon to nitrogen (C/N) ratio of BBRDM was measured around 4.68. It was determined by X-ray powder diffraction that ammonium-potassium nitrate complex salt was also present in BBRDM (Figure 1b). Table 1 summarizes the physico-chemical properties of soil and different organic fertilizers used during the cultivation.

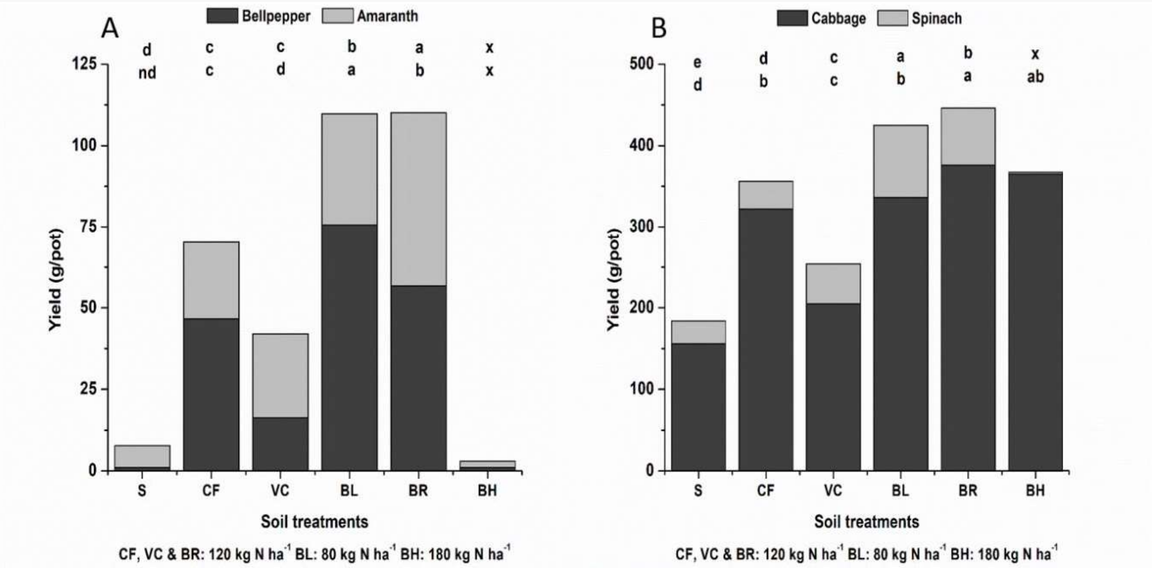


Figure 2. Crop yield from (a) bell pepper-amaranth and (b) cabbage-spinach rotation in pot. S: soil, CF: chemical fertilizer, VC: vermicompost, BL: low dose of BBRDM, BR: recommended dose of BBRDM, and BH: high dose of BBRDM. Pairwise comparison was performed by Tukey's *post hoc* analysis, and superscripts indicate significant differences among pot treatments at 5% cut-off level. X: plants died.

During this investigation, the crop yield was highest at a rate of 6 and 9 g BBRDM kg^{-1} of soil. In support of our work, an increase in okra production was demonstrated by Sankar et al. (2021) when soils fertilized with abattoir-derived organic briquettes. Outcome from Roy et al. (2016) established better yield of tomato applying dried abattoir waste instead of synthetic agro-chemicals. Concurrently, highest residual yield for amaranth and spinach was recorded at a rate of 9 g BBRDM kg^{-1} of soil comparing chemical treatment, as displayed in Figure 2 and 3. Although, plants fertilized with high dose of BBRDM (13 g kg^{-1} of soil) did not survive after second dose of fertilization due to the presence of huge labile carbon fractions in animal waste.as explained by Bonanomi et al. (2020).

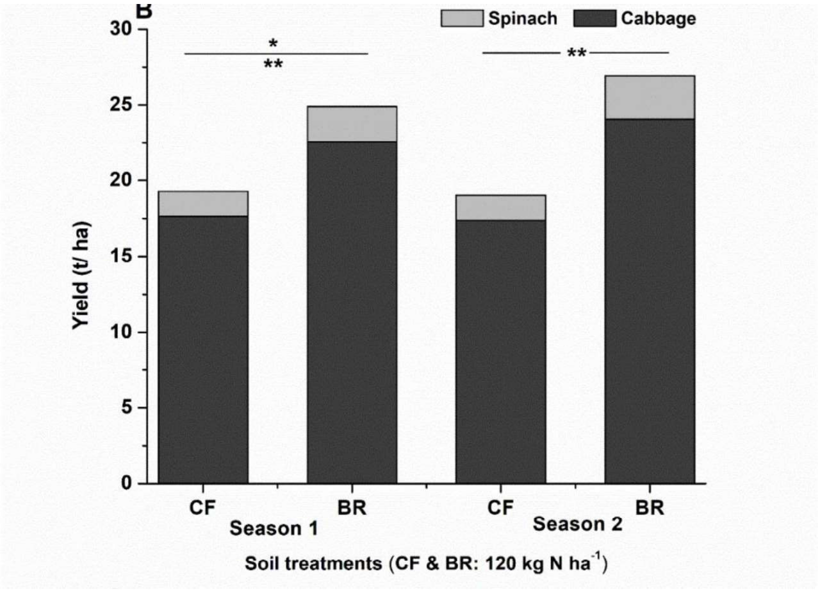
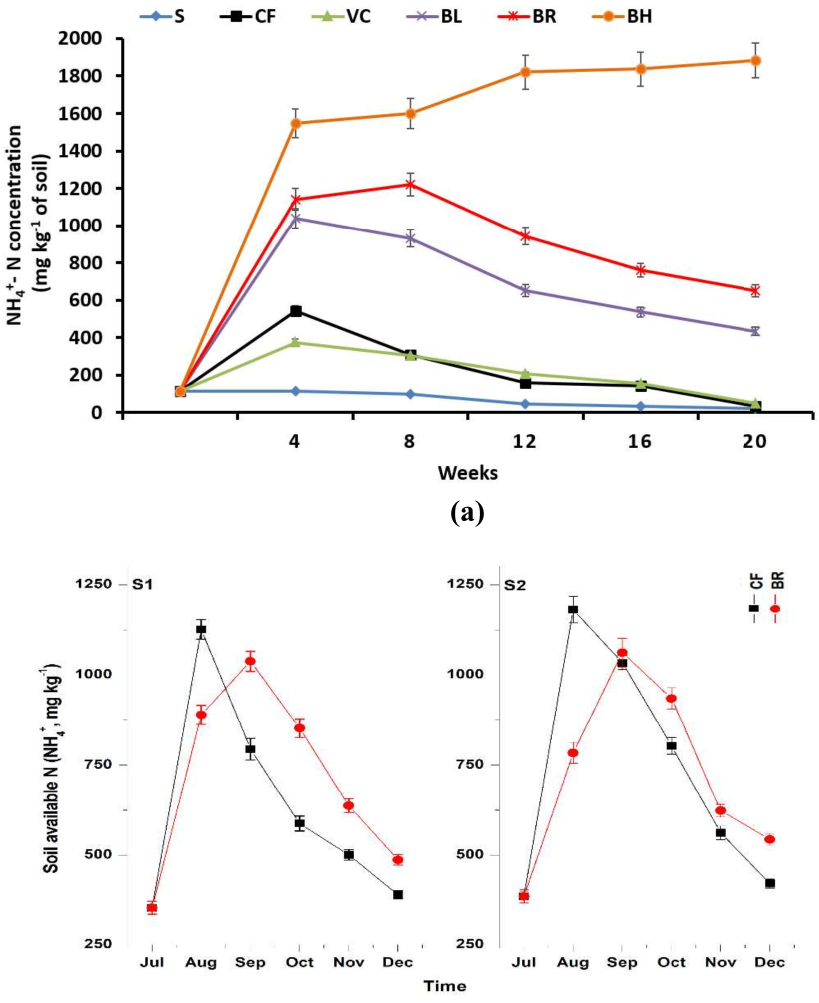


Figure 3. Cabbage-spinach yield in field. CF: chemical fertilizer and BR: recommended dose of BBRDM. Student's *t*-test compared the field treatments where ** represents $p < 0.01$ and * denotes $p < 0.05$. See section 2.3.2 for details.

The recycled slaughterhouse wastes supplied nitrogen as a major source of nutrient for the cultivation of seasonal vegetables. Considering NH_4^+ to be the first mineralized product of nitrogen, Takakai et al. (2017) quantified NH_4^+ as soil available N from soybean and paddy fields under various histories of manure application. Roy et al. (2013; 2016) also measured NH_4^+ during the pot as well as field cultivations of solanaceous vegetables in India. As shown in Figure 4, with the progression of time, NH_4-N was found to be more readily available in BBRDM fertilised soils than the chemical. This finding may be explained by an increase in organic matter decomposition (Takakai et al., 2017) brought on by copiotrophic abundance and higher enzymatic activity (Dong et al., 2014), which was also a sign of health agro-ecosystem. Although, due to plant mortality concentration of NH_4^+ in BH treated pots increased over the time (Figure 4a). To expedite soil nutrient availability and to avoid phytotoxicity events, Ozdemir et al. (2021) suggested farmers to adopt side-dressing method for vegetable cultivation.



(a)

(b)

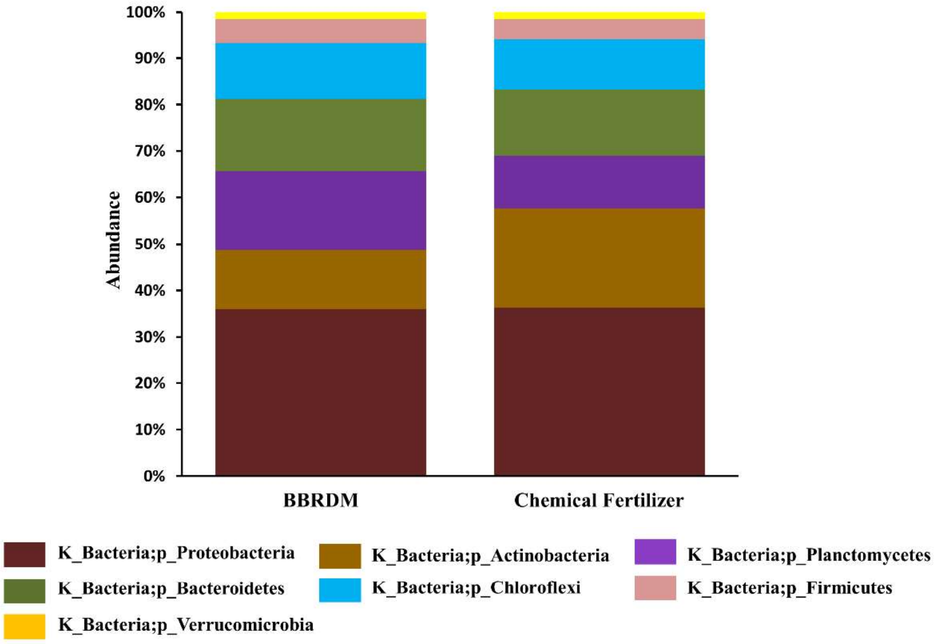
Figure 4. N dynamics in (a) pot and (b) field. Subbiah and Asija's (1956) method was followed to determine available soil N. See section 2.4 for details. S: soil, CF: chemical fertilizer, VC: vermicompost, BL: low dose of BBRDM, BR: recommended dose of BBRDM, and BH: high dose of BBRDM.

Table 2. Nitrate/nitrite concentration (mg kg^{-1} fresh weight) in vegetables after final harvest

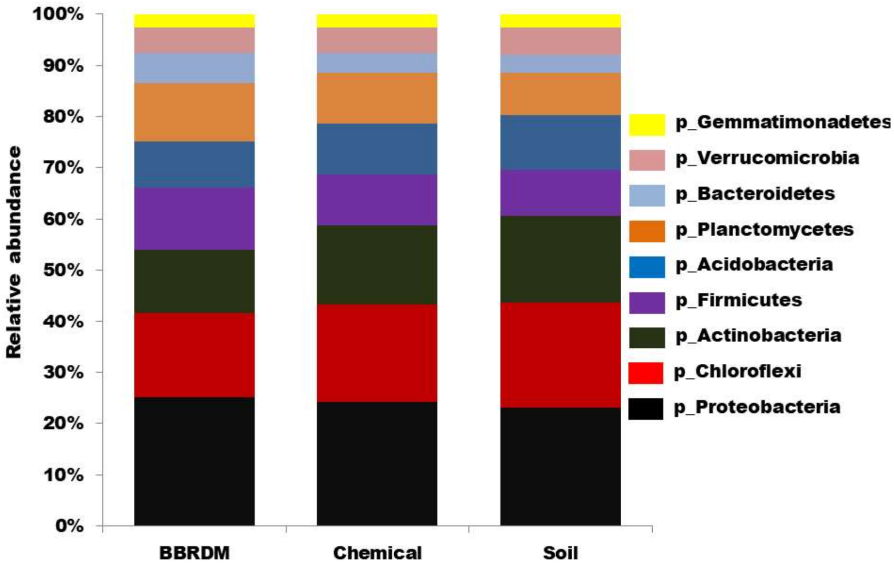
Cultivar		NO_3^-			NO_2^-		
		Organic	Chemical	Market	Organic	Chemical	Market
Cabbage	S_1	586.04 ± 27.51 ^{a}	742.66 ± 31.08 ^{b}	1019.41 ± 38.04 ^{c}	3.40 ± 0.13 ^{a}	5.17 ± 0.34 ^{b}	5.56 ± 0.66 ^{b}
	S_2	617.55 ± 18.63 ^{a}	694.19 ± 16.54 ^{a}	1228.72 ± 46.19 ^{b}	4.61 ± 0.50 ^{a}	4.83 ± 0.19 ^{a}	5.72 ± 0.51 ^{b}
Spinach	S_1	162.66 ± 12.43 ^{a}	119.84 ± 22.31 ^{a}	452.06 ± 24.8 ^{b}	0.08 ± 0.06 ^{b}	0.03 ± 0.01 ^{a}	0.23 ± 0.07 ^{c}
	S_2	156.51 ± 06.19 ^{b}	104.56 ±18.06 ^{a}	477.23 ± 27.55 ^{c}	0.09 ± 0.03 ^{ab}	0.06 ± 0.04 ^{a}	0.17 ± 0.08 ^{b}

Tukey’s *post hoc* analysis was performed to compare the treatments. With standard deviations, values represented as mean of replicates for each treatment. Significant differences between the treatments at 0.05 level are indicated by the superscripts. chemical: N/P/K=10:26:26+urea, organic: recommended dose of BBRDM, and market: samples obtained from local vegetable market; S_1: season 1 and S_2: season 2.

Soil health and food security are the principal components of Organic Agriculture 3.0. As shown in Table 2, in comparison with vegetables purchased from the local market, concentration of nitrate/ nitrite was lower in cultivated products which indicated indiscriminate use of synthetic agro-chemicals by the farmers during cultivation. BBRDM treated vegetables accumulated considerably lower amount of nitrate/ nitrite even after providing same amount of N to the experimental plots which is consistent with the findings of Roy et al (2016). Lower concentration of nitrate/ nitrite in BBRDM-treated vegetables may be due to the delayed mineralization of the organic N present in BBRDM and slow nutrient release, as visualized in Figure 4. According to Gupta et al. (2017), a higher nitrate and nitrite concentration in food is linked to a higher risk of gastrointestinal cancer and methemoglobinemia in young infants. Therefore, proper fertilization and judicious N supply is recommended for safe and quality food production.



(a)



(b)

Figure 5. Abundance of bacterial phyla in (a) pot soil and (b) field, *Proteobacteria*, *Actinobacteria*, *Planctomycetes*, *Bacteroidetes*, *Chloroflexi*, *Firmicutes* and *Verrucomicrobia* under N/P/K=10:26:26+urea and organic BBRDM treatment was studied on Illumina platform. Quantitative Insights into Microbial Ecology (QIIME) was applied to analyze the sequences. Color code (read L to R) indicates their abundance. See section 2.5 for details.

During this investigation, found that BBRDM-fertilized soil had increased copiotrophic abundance both in pot and field (Figure 5) which accelerated OM decomposition and facilitated appropriate nutrient circulation, making the majority of nutrients more accessible in the rhizosphere. In a recent study by Ozdemir et al. (2021), it was shown that addition of poultry abattoir waste was more favourable for chickpeas growth than the experimental soil. Our study demonstrated that, in contrast to CF treatment, BBRDM fertilizer soils attained more macroaggregate percentage, while microaggregates formation was promoted by the CF treatment in soils having lower SOC (Figure 6) which is consistent with the earlier findings of Guo et al. (2018) and Lin et al. (2019). As found, better soil aggregation in BBRDM treatment which in turn, accelerated copiotrophic communities for faster proliferation (see Figure 5), may be due to higher SOC content. A positive correlation between the soil aggregation stability and associated binding agents (SOC) was established earlier by Guo et al. (2018) as noticed during our study (Figure 11).

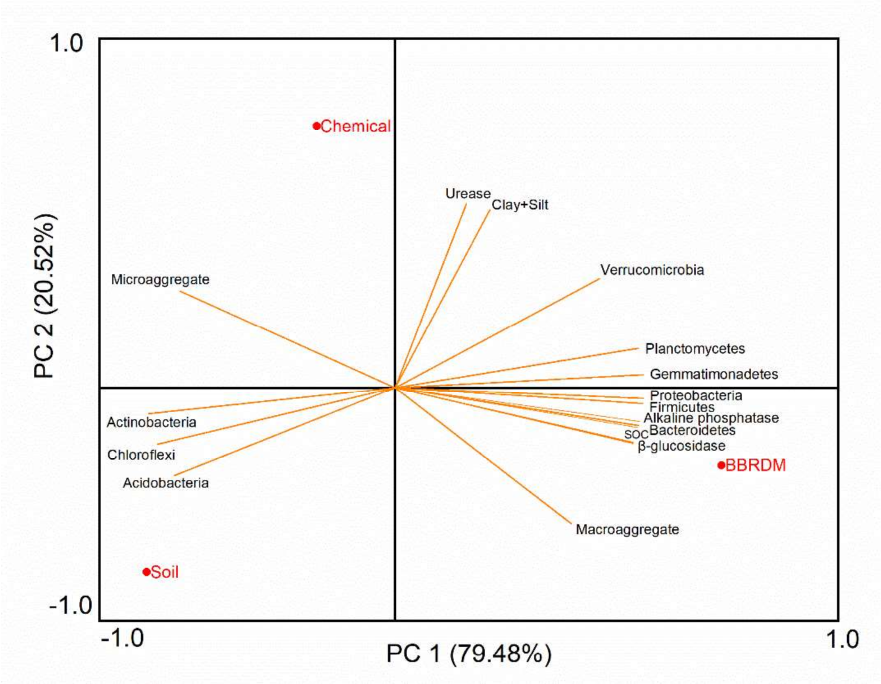


Figure 6. Biplot of the multivariate principal component analysis (PCA) carried out on soil physico-chemical changes and respective microbial abundance under various fertilizer treatments. Arrows indicate correlation coefficient.

An inverse correlation between the abundance of oligotrophs (especially *Acidobacteria* and *Actinobacteria*) and organic substitution ratio was reported by Ji et al. (2018), where we found two major phyla *Bacteroidetes* and *Proteobacteria* showed strong positive correlation with the increased C/N ratio as displayed in Figure 6. According to Wang et al. (2018), phyla *Chloroflexi* and *Acidobacteria* contained many acidogenic bacteria and their presence indicated intense soil acidification. In the current study, increased copiotrophic activity in response to BBRDM addition helped to neutralize soil acidity via supply of alkaline matter (Figure 5). Corroborative to the research of Urra et al. (2020), upon the application of well-prepared BBRDM, increased β-glucosidase and alkaline phosphatase activity was evidenced, while urease activity was profound in soils directly fertilize with N/P/K=10:26:26+urea (Figure 6) which was already mentioned by Sun et al., (2019) in his study few years back. There was an inverse relationship between the soil urease activity and N release from fertilizer. However, a strong positive correlation between β-glucosidase activity and SOC content (as shown in Figure 6) was established.

After appropriate heat treatment of abattoir waste, a significant decrease in the air-soil methane flux was noticed, which was around 150 times lower in pot and 1787 times in filed. According to Majumdar et al. (2006), due to lack of appropriate moisture in recycled waste CH_4 emission decreased significantly. Earlier, Salminen et al. (2003) claimed that because metabolism of long-chain fatty acids is quickly in animal waste therefore they showed higher methane yield potential which might be lowered applying proper treatment. However, according to Student's *t*-test, CF and BR treatment do not differ statistically at $p < 0.05$ in terms of air-soil methane flux (0.008 $\mu g\ g^{-1}\ hr^{-1}$ in BR and 0.005 $\mu g\ g^{-1}\ hr^{-1}$ in CF), where during the pot study CH_4 emission was found to be higher in BH and VC treatments (0.04 $\mu g\ g^{-1}\ hr^{-1}$ in VC and 0.136 $\mu g\ g^{-1}\ hr^{-1}$ in BH). However, application of BBRDM as an organic fertilizer seems to be preferable than landfilling/ open dumping in terms of emitted methane.

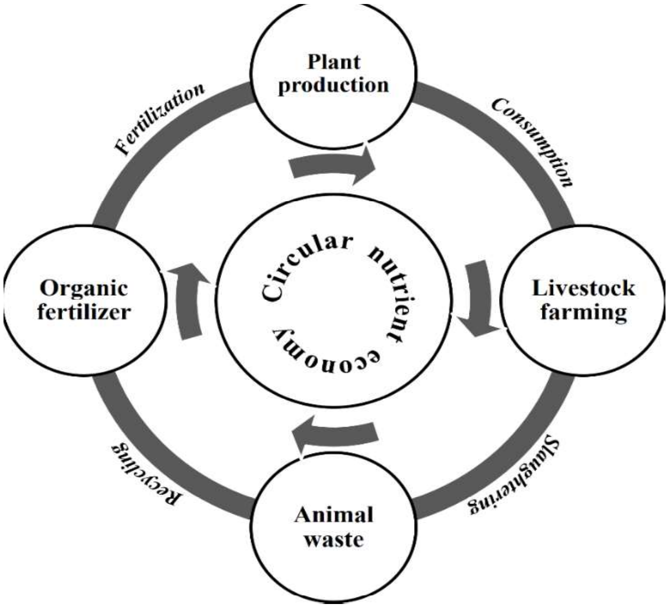


Figure 7. Recirculation of nutrients along with economy in a circular bio-nutrient economy system.

Compared to N/P/K=10:26:26+urea treatment, a larger net return from BBRDM application was recorded during the multi-season field trials. Such a higher return and considerably lower fertilization budget should be alluring to farmers' economy. For owners of rural abattoirs, simultaneously, BBRDM manufacture concurrent with the meat trade was found to be more profitable which also encourage them to recycle instead of open-dumping or landfilling of waste. To shift the economy from linear to circular track and to encourage hygienic waste disposal in rural abattoirs, adoption of strategies like waste to fertilizer conversion might be helpful as suggested by the recent investigation of Bhowmik et al. (2021a). Through recycling organic waste in agriculture, our research evidenced development of circular bio-nutrient economy where recirculation of nutrients occurred along with economy in each step of a loop providing socio-environmental benefits, as shown in Figure 7, although SWOT analysis (see Figure 8) showed that lack of public awareness regarding the bio-based products was the main threat to circular economy of abattoir waste management. Biomass availability and huge dependency on chemical ferming were the considerable weaknesses. Low fertilizer cost, secondary income to rural abattoirs, generation of alternative employment opportunities, and stakeholder willingness to pay for the waste-derived product were identified as major strength and opportunities of the model as earlier demonstrated by Paes et al. (2019). Bhunia et al. (2022) also suggested the bio-based circular economy model for biorefinery systems. Under the framework of circular bio-economy, commercial application of BBRDM was taken under consideration for the first time for sustainable agricultural development.

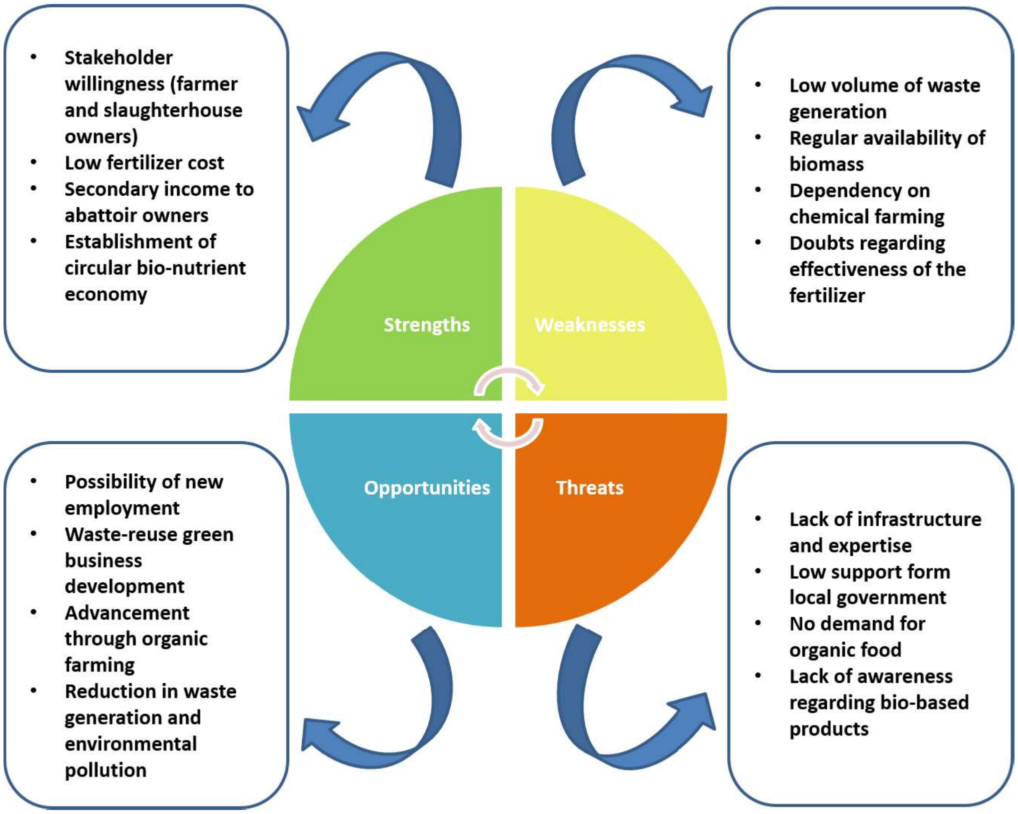


Figure 8. Strengths, weaknesses, opportunities, and threats examination of the concept “circular bio-nutrient economy” for sustainable management of rural abattoir wastes in agriculture.

4. Conclusion and future scope

Recycling organic waste in agriculture could make safe disposal of livestock waste without harming the environment. Through this investigation, it has been established that judicious use of recycled abattoir waste increased crop productivity, improved soil fertility, provided high-quality food, and preserved farmers' income. Reusing slaughterhouse wastes could curtail the habit of openly discarding solid organic wastes, minimize nutrient loss in the form of waste, and lesser the need for chemical fertilizers. More importantly, farmers could gain double benefit applying BBRDM as fertilizer due to its strong residual effect on crop yield. Concurrently, this strategy significantly reduced the footprint of GHGs from dumping sites. Furthermore, waste to fertilizer conversion is a low-energy requiring process that promoted circular bio-economy. Thus, considering the promotion of soil fertility, microbial abundance, disease protection and economic considerations application of animal-waste-derived organic fertilizer should be the mainstay for sustainable agriculture. Adoption of this methodology may be advantageous in other developing countries having scattered, unorganized rural abattoirs for transition towards circular bio-economy.

Future directions: Development of (a) farmers' producer company, (b) scaling up of field trials with diverse crop varieties, and (c) effect analysis on fruit quality need to be taken under consideration for future research. Author also suggested to explore (d) the possible mechanism of defending soil-borne phytopathogens by BBRDM as lesser disease infestation upon BBRDM application was noticed during multi-season field cultivation of cabbage and spinach, and to evaluate (e) the abundance of antibiotic resistance gene in BBRDM fertilized soils if present as livestock husbandry nowadays received huge antibiotic supply. These findings could be helpful in converting other organic wastes as fertilizer.

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