A new method for converting foodwaste into pathogen free soil amendment for enhancing agricultural sustainability

Pramod Pandey \textsuperscript{a, b, *}, Mark Lejeune \textsuperscript{c}, Sagor Biswas \textsuperscript{a}, Daniel Morash \textsuperscript{c}, Bart Weimer \textsuperscript{a}, Glenn Young \textsuperscript{d}

\textsuperscript{a} Department of Population Health and Reproduction, Veterinary Medicine School, University of California, Davis, CA, 95616, USA
\textsuperscript{b} Division of Agriculture and Natural Resources (ANR), University of California, Davis, CA, USA
\textsuperscript{c} California Safe Soil, 1030 Riverside Parkway, West Sacramento, CA, 95606, USA
\textsuperscript{d} Department of Food Science and Technology, University of California, Davis, CA, USA

**ABSTRACT**

Increasing emphasis on controlling the uses of chemical fertilizers requires identifying safe Organic Soil Amendments (OSA) to use as alternatives. Converting organic waste, such as foodwaste into an OSA can be an option. Such approaches are also an attempt to make beneficial use of the enormous amount of foodwaste generated globally. In this study we conducted a pathogen challenge to determine the inactivation of three foodborne pathogens in an OSA derived from a complex foodwaste stream. Further, the physiochemical characteristics of the OSA were assessed at pilot-scale experiments. The inactivation of three most common foodborne pathogens (\textit{Escherichia coli} O157:H7, \textit{Salmonella enterica} subspecies enterica sv Typhimurium LT2, and \textit{Listeria monocytogenes}) was determined using bench-scale tests, simulating the process adopted at a pilot-scale facility. The pilot-scale facility uses three processes (enzyme digestion (55–57 °C), pasteurization (75–77 °C), and acidification treatments) for producing the OSA. In addition, the yields and nutrient characteristics of the OSA were analyzed using 16 pilot-scale batch tests. The results showed that the process adopted in this study for converting foodwaste to the OSA produced a soil amendment with non-detectable levels of \textit{E. coli} O157:H7, \textit{Salmonella} LT2, and \textit{L. monocytogenes}. The yield of the OSA was 84–96% of the initial foodwaste inputs, and organic matter and C: N ratio of the OSA were 20–25% and 12:1, respectively. We anticipate that the results presented here will help in enhancing agricultural sustainability.

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1. Introduction

Food production in the U.S. uses approximately 50% of its land, and utilizes 80% of the total fresh water consumed. About 40% of total food production, however, goes as waste (Gunders, 2012), which is equivalent of $165 billion each year. In contrast, currently more than a billion people are chronically malnourished (Foley et al., 2011). In theory, the total food waste produced in North America and Europe can potentially feed the world’s hungry three times over (Stuart, 2009). Alternatively, it can reduce the application of chemical fertilizers considerably if the use of soil amendment derived from food waste is adopted extensively.

Recycling foodwaste for producing products, such as OSA and bioenergy, has received a great level of interest recently. Organic waste treatment processes such as composting processes (i.e., windrow composting, vermicomposting, and powered composting) (VermiCo, 2013; Purkayastha, 2012; Munnoli et al., 2010; Shivakumar et al., 2009) and anaerobic digestion processes (Shin et al., 2010; Quiroga et al., 2014; Dai et al., 2013; Bernstad et al., 2013; Rouse fell et al., 2013) are promising technologies. Previous studies (Parthan et al., 2012; Broitman et al., 2012; Levis and Barlaz, 2011; Levis et al., 2010; Diggelman and Ham, 2006; Lundie and Peters, 2005; Ayalon et al., 2001) have assessed the waste treatment costs of the various treatment processes. Many factors including the application of the digestate (i.e., soil amendment), waste transport, gas collection and energy recovery, and the inclusion of environmental benefits are reported to influence the waste treatment costs. For example, Ayalon et al. (2001) suggested that the most cost-effective means to treat the degradable organic...
component for avoiding reducing CO₂ is aerobic composting. Another study by Levis and Barlaz (2011) assessed the various options of food waste treatment processes and estimated that anaerobic digestion was the most environmentally beneficial treatment option potentially because of avoided electricity generation and soil carbon storage from use of the resulting soil amendment. The authors also reported that a traditional landfill with energy recovery can have lower emissions than any of the composting alternatives when a fertilizer offset was used. Another study by Tsilemou and Panagiotakopoulos (2006) reported that anaerobic digestion and in-vessel composting are the most costly methods for solid waste treatment.

Although all above processes are applied for treatment the food waste and have numerous benefits, the fate of foodborne pathogens in these processes are not well understood. The presence of pathogens in an OSA can potentially recycle pathogens in agricultural systems (Holden and Treseder, 2013). Pathogens associated with growing plants have caused many foodborne outbreaks (Holden and Treseder, 2013; Hoffmann and Anekwe, 2013). The U.S. Department of Agriculture’s Economic Research Service (USDA-ERS) estimates that pathogens in food cause 6.5–33 million cases of human illnesses, and the cost of these illnesses is greater than $4 billion (Buzby et al., 1996). A relatively new study by Hoffmann and Anekwe (2013) reported cost of foodborne-illness in the USA ranging from $14.1 billion to $152 billion. Hoffman et al. (2012) estimated that 14 foodborne pathogens cause $14.0 billion in cost of illness. Approximately 90% of this loss is caused by five pathogens: Salmonella enterica, Campylobacter spp., Listeria monocytogenes, Toxoplasma gondii, and norovirus. Therefore, ensuring the destruction of these pathogens in the soil amendment, prior to application of soil amendment (derived from food waste) into crop land is crucial for protecting environment and mitigating human health risk.

Considering the enormous amount of food waste in global food supply chains (Papargyropoulou et al., 2014), additional research is needed to identify the processes capable of converting food waste into a safe and useful by-product such as OSA. Previous studies reported soil as an important source of pathogens such as Escherichia coli, which has been directly related to foodborne outbreaks (Perry et al., 2013; Bolton et al., 2011). In contrast to the OSA, ongoing excessive use of chemical fertilizers has lowered soil quality and leads to environmental degradation (Zhu et al., 2012). Since the global food production relies on soils (Lal, 2014; Blanco-Canqui and Lal, 2008), which are a finite resource, they require protection. Recently, the use of OSA has been seen as an alternative to chemical fertilizers, which enhance crop yield as well as promote the sustainable development of agricultural industry (Zhu et al., 2012).

The goal of this research is to assess the inactivation of human pathogens in the process of converting food waste into OSA. The objectives of this study are to: 1) understand the impacts of enzyme digestion (55–57 °C), pasteurization (75–77 °C) and acidification processes on the inactivation of foodborne pathogens (E coli O157:H7, S. enterica subspecies enterica sv Typhimurium LT2, and L. monocytogenes) in the OSA; and 2) assess the yields and nutrient levels of OSA derived from food waste.

2. Materials and methods

2.1. Conversion of food waste into OSA

The process described in this research (Fig. 1) uses hydrolysis, pasteurization, and stabilization processes for converting food waste into an OSA. The first step involves food waste (organic waste) collection from supermarkets located within 50 miles of the food waste processing center. Organic food waste (discarded food from produce, meat, bakery, & deli departments) is collected from super markets in double wall insulated containers suitable for perishable food storage and transported in refrigerated (temperature 5–8 °C) trucks within 2 days of being removed from the shelf at the supermarket. The second step involves an enzymatic digestion at 55–57 °C to digest the food waste. In a vessel digester, slurry is mixed with a cocktail of enzymes designed to digest the diverse food waste streams received from the supermarkets. The digestion process takes place for 3 h. In the third step, digested food waste is pasteurized in order to kill any remaining human pathogens. After pasteurization, the solution is screened with a sieve (74 μm) for separating the larger particles from the solutions. The fourth step involves stabilization i.e., decreasing the pH of pasteurized food waste to a pH of 2.8–3.0. In the stabilization process, the pH of the pasteurized emulsion is lowered by adding phosphoric acid to preserve the emulsion and prevent microbial activity in the emulsion. After 2.5 h of the stabilization process, the final product (i.e., OSA), Harvest-to-Harvest (H2H), is transferred to a storage tank, and then it is supplied as an OSA. The process of converting food waste into OSA has been tested at a pilot-scale plant, designed by California Safe Soil, LLC (CSS; West Sacramento, CA). CSS collects unsold food, such as produce, bakery, and delicatessen department waste materials, in insulated containers for use in this process.

2.2. Pathogen challenge study

A batch-scale experiment was designed (Fig. 2) to test the pathogen inactivation and survival in the OSA at each stage (i.e., thermophilic digestion, pasteurization, and stabilization) of the process. The experiment was conducted inside a biosafety cabinet (level II) to minimize the pathogen risks to the personnel involved in the experiment as well as possible ambient contamination. The unstabilized OSA used in the pathogen challenge study was received from CSS immediately before starting batch-scale experiments. The experiment was performed in three stages: 1) enzyme digestion (55–57 °C for 150 min); 2) pasteurization (75–77 °C for 30 min); and 3) acidification (room temperature 22–25 °C for 120 min). To control the temperature of the OSA in a reactor used for digestion,
we regulated the temperature of the water jacket (Fig. 1) utilizing a heating plate (Thermolyne Corporation, Dubuque, IA, U.S.). The stirring of the OSA was performed using an overhead mixer (CAFRAMO Model BDC250U1) in all the three stages. During the thermophilic and pasteurization processes, stirring speed was 50 RPM, and during the acidification process, the stirring speed was 200 RPM, which creates uniformity in the OSA emulsion as well as helping to aerate the OSA.

2.3. Pathogen inoculation and enumeration

To test the pathogen inactivation, the OSA (i.e., H2H product) was inoculated with pathogens (E. coli O157:H7, Salmonella. Typhimurium LT2, and L. monocytogenes). To prepare inoculum, fresh pathogen culture of E. coli O157:H7 (ATCC #35150), S. Typhimurium LT2 (ATCC #700720), and L. monocytogenes (ATCC # BAA- 679D-5) was prepared in the lab prior to starting the experiment. Difco LB Broth Miller (Luria–Bertani) growth media was used for growing E. coli O157:H7 and S. Typhimurium LT2, and BBL Brain Heart Infusion was used to grow L. monocytogenes. A fresh culture of each pathogen was collected (4 ml) and pelleted using micro-centrifuge at 8000 RPM for 10 min. The cell pellets were mixed (i.e., dissolved) with the OSA, and stirred for 10 min at room temperature before use in the process treatments. Samples of E. coli O157:H7, S. Typhimurium LT2, and L. monocytogenes were streaked (i.e., plated) on MacConkey II Agar (Becton, Dickinson and Company, Sparks, MD, USA), Difco XLD Agar (Becton, Dickinson and Company, Sparks, MD, USA), and PALCAM Agar (with selective supplement) (HiMedia Laboratory Pvt Ltd, Mumbai, India) plates, respectively, for enumerating the pathogens. All the samples were tested in triplicates. A pH meter (Omega Engineering, INC., Stamford, CT, USA) equipped with a pH and temperature probe was used to measure the pH and temperature during the experiment.

2.4. Yield and nutrient characteristics of the OSA

In addition to the pathogen test, nutrient characteristics of the OSA were assessed. For nutrient characterization, the OSA samples, taken from a total of 16 independent pilot-scale batch tests, were analyzed (results are discussed later) using standard methods (APHA, 1999). Nutrient characteristics such as organic matter (OM), nitrogen (N), phosphorous (P), and potassium (K) were measured. The elements such as calcium (Ca), sulphur (S), magnesium (Mg), sodium (Na), iron (Fe), aluminum (Al), copper (Cu), zinc (Zn), crude protein, crude fat, and total carbohydrates were also measured.

3. Results and discussion

3.1. Pathogen challenge results

The analysis of the initial OSA (prior to inoculation) showed no detectable E. coli O157:H7, S. Typhimurium LT2, and L. monocytogenes. After the OSA inoculation with pathogens, the OSA samples were analyzed again, and pathogen levels in the OSA were greater than 6 orders of magnitude. Subsequently, pathogen levels in the OSA were tested at the end of each process and the results are discussed in the following subsections.

3.1.1. Inactivation of E. coli O157:H7

Fig. 3 shows E. coli O157:H7 inactivation in the enzyme digestion, pasteurization, and acidification steps of the process. The durations of each process step is shown by horizontal lines with both end arrows. The space between vertical dotted lines indicate time (approximately 10 min), which was required for phase change i.e., time for changing the temperatures from ambient to thermophilic and thermophilic to pasteurization. The results of the three experiments (Run 1, Run 2, and Run 3) are shown indicating inactivation of E. coli O157:H7 in the OSA.

Initial E. coli O157:H7 levels in the OSA (before inoculation) was non-detectable. The levels of E. coli O157:H7 in the inoculum (i.e., pure culture) were 2.8 × 10^9, 1.7 × 10^9, and 1 × 10^9 CFU/mL in Run1, Run 2, and Run 3, respectively (shown as red (in the web version) circles in Fig. 3). The pellets of E. coli O157:H7 were dissolved in the OSA, which resulted in enhanced E. coli O157:H7 levels in the OSA. After inoculation, increased E. coli O157:H7 levels in the OSA were 6.1 × 10^6, 1.7 × 10^6, and 8.0 × 10^5 CFU/mL in Run1, Run 2, and Run 3, respectively (shown as green (in the web version) triangles in Fig. 3).

After 150 min of digestion (at the end of thermophilic process (55–57 °C for 150 min)), E. coli O157:H7 levels in Run 1 were non-detectable (shown as ND in Fig. 3). Subsequently, the OSA was pasteurized (at 75–77 °C for 30 min), which also showed ND levels of E. coli O157:H7. After pasteurization, acidification process was carried out (pH was decreased to 2.8–3.0). During the acidification process, continuous mixing of the OSA (200 rpm for 150 min) was provided, and the samples collected after the acidification process also showed ND levels of E. coli O157:H7 in the OSA.

3.1.2. Inactivation of S. Typhimurium LT2

Fig. 4 shows S. Typhimurium LT2 inactivation in digestion, pasteurization, and acidification processes. The levels of S. Typhimurium LT2 in inoculum were 4.3 × 10^8, 3.1 × 10^8, and 5.2 × 10^7 CFU/mL in Run 1, Run 2, and Run 3, respectively (shown as red (in the web version) circles in Fig. 4). During Run 1, Run 2, and Run 3, initial S. Typhimurium LT2 levels were 7.4 × 10^6, 1.1 × 10^6, and 2.8 × 10^5 CFU/mL, respectively. Similar to E. coli O157:H7 inactivation, S. Typhimurium LT2 inactivation in digestion, pasteurization, and acidification processes are shown in Fig. 4. In Run 1, S. Typhimurium LT2 levels were reduced from 7.4 × 10^6 CFU/mL to ND after the thermophilic process. In Run 2, S. Typhimurium
LT2 levels were reduced from $1.1 \times 10^8$ CFU/mL to ND. Similarly, S. Typhimurium LT2 levels in Run 3 were reduced from $2.8 \times 10^7$ CFU/mL to ND, indicating no survival. The results of acidifications are also shown in Fig. 4. The OSA samples testing after the acidification process also showed ND levels of S. Typhimurium LT2 indicating no survival of S. Typhimurium LT2 in the OSA.

### 3.1.3. Inactivation of L. monocytogenes

Fig. 5 shows the inactivation of L. monocytogenes in the OSA. In Run 1, the level of L. monocytogenes in inoculum was $6.0 \times 10^8$ CFU/mL. In Run 2, the level of L. monocytogenes in inoculum was $2.1 \times 10^9$ CFU/mL, while in Run 3, L. monocytogenes level in inoculum was $1.2 \times 10^9$ CFU/mL (shown as red (in the web version) circles in Fig. 5).

After inoculum mixing in the OSA, the levels of L. monocytogenes in the OSA were $5.0 \times 10^6$, $4.3 \times 10^6$, and $3.0 \times 10^6$ CFU/mL in Run 1, Run 2, and Run 3, respectively (shown as green triangles in Fig. 5). Subsequently, thermophilic digestion in all three runs resulted ND levels of L. monocytogenes in the OSA. In all the three runs (Run 1, Run 2, and Run 3), the levels of L. monocytogenes at the end of

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pasteurization and acidification were also ND. Enzyme digestion, pasteurization and acidification results are shown in Fig. 5.

3.2. Yield and nutrient characteristics of the OSA

3.2.1. OSA yield

In addition to the pathogen challenge study (discussed in section 3), the OSA was analyzed to estimate the process yield, which is shown in Fig. 6. The figure shows the average values of 16 batch tests. The input weights of produce, meat, fine screen overs, and total foodwaste are shown in Fig. 6. The OSA yield (OSA weight (kg)/total waste input (produce, meat, fine screen overs)) is also shown in the figure. The input of produce weight varied from 494.8 to 1057.6 kg (average = 736.8 kg; stdev = ± 174 kg). The weight of meat changed from 100.2 to 319.7 kg (average = 170.0 kg; stdev = ± 59.0 kg). The fine screen overs weight varied from 72.6 to 408.2 kg (average = 143.3 kg; stdev = ± 98.1 kg). The total foodwaste input weight varied from 800 kg to 1449.8 kg (average = 1050 kg;
stdev = 237.5 kg), which produced the average OSA of 970.6 kg (variation from 680 kg to 1271 kg with stdev of 191.4 kg) resulting in the OSA yield of 89%. The OSA yield varied from 86% to 96% (stdev = 3%).

3.2.2. OSA nutrient characteristics

Fig. 7A and B showed the nutrient characteristics (i.e., crude protein, crude fat, total carbohydrate, N, P, K) of the OSA. The descriptive statistics of the micro and macro nutrients including metals are shown in Table 1. The proportion of crude protein and crude fat in the OSA were 5.82% and 7.97%, respectively. The proportion of total carbohydrates was 8.18% (Fig. 7A). Fig. 7B shows the average of total N, P, K contents of the OSA. Total N varied from 0.81% to 1.16%, and total P varied from 0.38% to 0.92% (Table 1). The average of total N was 0.93% (±0.1), while the average P was 0.56% (±0.1). The total K varied from 0.25 to 0.42%, with average of 0.36 (±0.04).

The moisture content and organic matter content of the OSA varied from 72 to 75% and 15.9–26.7%, respectively. The average C: 

Fig. 5. Listeria monocytogenes inactivation in thermophilic, pasteurization, and acidification processes (ND = not detected) (detection limit was ≥1 colony at 10^6 dilution).
N ratio was 12:1. The ranges of secondary nutrients and micro-nutrients such as Ca, Mg, and S in the OSA were 0.1–0.15%, 0.02–0.04, and 0.05–0.25%, respectively. The Fe, Al, Cu, and Zn varied from 34 to 790, 9–602, 2–35, 5–106, respectively.

Field trial data of strawberry plant growth using the OSA are shown in Fig. 8. When the OSA (i.e., H2H) was mixed with Grower Standard (GS) (chemical fertilizers typically used by farmers), the weight of the whole plant was increased by 25%. The root and shoot weights were increased by 69 and 4% (Fig. 8A), respectively. The increase in fresh weight is shown in Fig. 8B. The fresh weight of strawberry was increased by 32% when the OSA was mixed with GS compared to only GS. The fresh weight of strawberry was increased by 40% when the OSA was applied alone compared to the GS alone. Further, the H2H can be particularly useful for orchard crops. Once the orchard crops are planted, it is challenging to incorporate solid composts into the soil without disturbing the root structure. In contrast, the H2H can be applied with the irrigation water through the existing drip system. The use of H2H is likely to reduce nitrate runoff into the ground water because it is applied right to the root zone, and hence increased nutrient availability to the plants. Field trial data showed that the use of H2H resulted in reduced nitrate fertilizer applications and increased on strawberry yields.

Considering the benefits of the OSA in plant growth, the nutrient characteristics of the OSA, and non-detectable pathogens in the OSA, the approach described here for the OSA production can be a potential method for converting the food waste into a soil amendment. In the past, many human pathogen infections were related to food products (Akhtar et al., 2014; Tauxe et al., 2010), and the disposal of contaminated food waste into the environment can

Fig. 6. Input of food waste and organic soil amendment yield.

Fig. 7. Organic soil amendment characteristics: A) protein, fat, and carbohydrate contents; and B) total N, P, and K values of the OSA.

Fig. 8. Strawberry plant growth under with soil amendment application and without soil amendment application: A) whole plant, root, and soot growth; B) fresh weight growth.

Table 1

<table>
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<tr>
<th>Characteristics</th>
<th>Average</th>
<th>Min</th>
<th>Max</th>
<th>STD</th>
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<tr>
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</tbody>
</table>

Note: n = number of samples.
potentially disseminate the foodborne pathogens in soil and water and subsequently in food crops. As an example, Scallan et al. (2011) reported Salmonella as the leading cause of food borne illnesses in the USA, and many of these illnesses were linked with agriculture farms.

In North-America and Europe, food waste per capita is 95–115 kg/year, while in sub-Saharan Africa and South/Southeast Asia food waste is 6–11 kg/year, amounting to global food loss more than 1.3 billion tons each year (Gustavsson et al., 2011). Approximately 33% of the food produced for human consumption is lost or discarded globally (FAO, 2011). The results of this study showed the OSA yield greater than 80% while converting the foodwaste into soil amendment. Further, the proposed food waste conversion is not energy intensive. The digestion and pasteurization require heat, which was produced using a natural gas boiler. The modest amount of electric power is used to run the pumps, grinders, and agitators, which are not energy intensive devices. The capital requirements are quite modest, compared with the alternative technologies such as anaerobic digestion and composting, with a far smaller environmental footprint, and a more valuable finished product.

Taking 80% yield as an example, there is a potential of producing more than 1 billion tons of soil amendment each year from food waste alone. The remaining solids screened from OSA production may be used as feed for pork or chicken production, or pet food, increasing the potential beneficial use of food waste. In the past 50 years, global fertilizer use has increased by 500% (Tilman et al., 2001; Foley et al., 2011) for enhancing crop production, which has impacted the ecosystem adversely. If the ongoing chemical fertilizer uses need to be continued, then this trend will most likely degrade freshwater and marine ecosystems further.

Current food waste production is huge; however, it can be trapped for soil amendment production at a large scale in cost-effective manner. As an example, supermarkets already optimize the distribution of goods offered for sale at their stores through networked food distribution centers (DC). Co-locating the food waste conversion plants with the DCs can be an option. In the proposed system, double wall insulated food waste storage containers will be provided by CSS to supermarkets to collect food waste inside the back of their stores. These containers filled with food waste will be back hauled to the DCs in otherwise empty truck (a “free backhaul”). Subsequently, the containers will be shuttled to the food waste conversion plants located in the vicinity of the DCs. In this manner, every major supermarket in every major city can be linked with food waste conversion plants. Since the process has no significant air emission, liquid effluent, solid waste, or nuisance odors, it is possible to obtain all necessary operating permits in urban areas.

Developing the capability of converting food waste produced globally (greater than a billion tons annually) into OSA can help in controlling adverse impacts of chemical fertilizers on ecosystems. Therefore, identifying suitable methods capable of converting food waste into OSA, which are relatively safe to the environment, can be a viable option. Previous researchers have studied various food waste recycling processes, such as anaerobic digestion (Shin et al., 2010; Zhang et al., 2007; Kim et al., 2011), however the effect of the digestion process on pathogen inactivation (such as S. Typhimurium LT2, L. monocytogenes, and E. coli O157:H7) was not verified well. Currently, there is little research focusing on understanding food system that include the chain of activities connecting food production, distribution, consumption, and waste management are available (Pothukuchi and Kaufman, 2000; Lundqvist et al., 2008; Parfitt et al., 2010; Parizeau et al., 2015), which are crucial for improving the agricultural sustainability and waste utilization. In summary, the pathogen challenge study presented here showed inactivation of pathogens in OSA derived from food waste. Pathogen levels (S. Typhimurium LT2, L. monocytogenes, and E. coli O157:H7) in the OSA were reduced from 7 to 8 orders of magnitude to ND level indicating the reduced microbial risk to the environment and public health. Further, a nutrient analysis of the OSA and a preliminary field trial showed enhanced plant growth when the OSA was mixed with the GS. We anticipate that the results and analysis provided in this research will help in improving the existing food waste treatment processes as well as deriving new methods for producing microbiologically safe OSAs, hence, will improve waste recycling.

4. Conclusions

The results showed that the processes adopted in this study for converting food waste into organic soil amendment (OSA) reduced the pathogen levels from 7 to 8 orders of magnitude to non-detectable levels indicating that the final OSA product has minimal risk of pathogens. The food waste recycling approach presented in this research produced OSA with organic matter and C:N ratio of 21% and 12:1, respectively. Field trials of strawberry plant growth showed that the plant growth was increased by 25% when the OSA was added with grower standard chemical fertilizer. We anticipate that the results presented here will help in improving the understanding of pathogen inactivation in food waste as well as improving the existing food waste recycling processes.

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