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ORIGINAL ARTICLE

The potential of *Ascophyllum nodosum* to accelerate green waste composting

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Abstract

Millions of tonnes of green waste are produced annually in the UK. Composting usually extends to more than two months as well as producing greenhouse gases that can affect the environment if not optimised. We proposed a potential approach to use the algal extract from *Ascophyllum nodosum* as a compost accelerator. Seaweed-based treatments offer an economical and effective biological solution that activates and stabilises organic matter decomposition, promoting better carbon sequestration. Reducing both the cost and time associated with widely used composting approaches. The seaweed was collected from the Scottish coastline, extracted, and formulated to enhance application. Its effects on the timeline of the composting process were systematically investigated through physical, biological, and observational quantification. The emission of gases, the pH, temperature, humidity, consistency, and microbial growth of the compost were studied. Interestingly, the results showed that the compost reached a stable state within six weeks, with lower ammonia and carbon dioxide production. The use of this formulation can minimise expense, reduce resources used, and also lower the levels of harmful volatile organics. This approach is economically beneficial and environmentally crucial in compost formation, controlling contamination, and carbon sequestration optimisation.

Keywords *Ascophyllum nodosum* · Compost acceleration · Alginate · Greenhouse gases · Carbon sequestration

Introduction

Daily consumption of food materials and agricultural industries produce large amounts of waste materials [1]. In 2018, around 179 certified compost makers distributed throughout the UK dealt with around 3.5–5 million metric tonnes of waste materials and produced approximately 1.86 million metric tonnes of compost. About 76% of these processes were carried out in England, 13% in Scotland, 7% in Wales, and 4% in Northern Ireland. Approximately 68% of all these processes were turned windrows in the open air, and more than 75% of the centres processed green waste [2]. These amounts of waste impose pressure on the environment and may cause water and air contamination. Gases like N_2O, CH_4, CO_2, sulphur compounds, and volatile organic compounds (VOCs) produced from the metabolism of these materials are additional challenges [3].

Composting the waste organic materials is one of the approaches used to convert the organic materials into useful biomass to achieve carbon sequestration [4]. The target of all recycling centres is to produce a safe compost free from or with undetectable levels of pathogenic microorganisms like *Bacillus anthraces* which causes anthrax and *Bacillus cereus* which causes gastroenteritis amongst others [5]. Usually immature compost is not suitable for plant fertilisation; it is also a source of nuisance odours [6].

Generally, the compost is produced by windrow and aerated pile techniques [7]. However, home-based composters who process a small amount of waste, is still of value in the composting of organic matter [8]. For the compost producer at the larger scale the control over the dynamics of the composting process is of great importance. At the municipal scale, aeration pumps can be used instead of the conventional pile turning process, even though it is more expensive. With a good control to the temperature and aeration of the pile, the aerated static pile can produce compost within a 3–4 month period [9]. Other studies show that the

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composting process can commonly take around 2–8 months depending on the type of waste, size of the pile, particle sizes of shredded waste, temperature, relative humidity, aeration mechanisms, and addition of compost accelerator [10].

The ideal temperature of composting is between 40 and 65 °C [11]. The stages of the composting process start by the sanitisation step, this step is usually accomplished within 3 days and some waste management companies run that process twice for 6 days. The pile in the vessel is activated using air current to blow the pile to destroy any anaerobic spots. The compost temperatures can reach up to 70 °C, ensuring that many pathogenic microorganisms are eradicated. However, higher temperatures also eliminate the microorganisms used in the compost formation [12]; thus relief of the pile's temperature is also recommended. Efforts to control the composting process are recorded like the adaptation of the routine composting techniques to increase the airflow through the pile by adding inert materials or "bulking agent" [13]. Addition of these bulking agents improve the aeration in the pile which ensures more aerobic microbiota activity, less odour, and a shorter time for compost formation. The chemistry of the molecules produced by the composting process is dependent on the types of the material metabolised by the microbiota of the waste mass, at the start of the composting process, simple organic molecules are metabolised and organic acids like; 3-hydroxypropionic acid, acetic acid, citric acid, gluconic acid, lactic acid, and succinic acid are produced [14].

During the thermophilic stage of the composting process, the temperature builds up and the microorganisms that thrive in the high temperatures resurge again. Complex molecules like polysaccharides and polyphenolic materials are metabolised into simpler entities [6]. In the final stage or mesophilic phase, the temperatures start to decline due to reduced microbial activities; this phase is called the maturation stage or mesophilic stage.

In addition to the addition of bulking agents to increase aeration of the compost pile, there is a constant effort to shorten the time required for compost formation and to reduce the release of harmful gases and volatile organic compounds (VOCs) to the environment. This can be achieved to some extent by adding organic or inorganic additives or microbial cultures [1, 6, 15]. The addition of microbial colonies containing Gram positive genera like *Bacillus*, *Clostridium*, *Enterococcus* and *Lactobacillus*, and Gram negative *Alcaligenes* lead to enhancing the composting process of the compost from cattle manure and decrease the ammonia and nitrate concentrations [16].

The following fungi; *Plectosphaerella cucumerina*, *Fusarium oxysporum*, *Fusarium domesticum*, *Fusarium delphinoides*, and *Pyrenochaeta unguis-hominis* are able to metabolise all kinds of carbohydrates [17]. Hydrolysis of lignin is achieved by the *Streptomyces albus*, *Bacillus smithii*, and *Brevibacillus borstelensis*, and the fungus *Coniosycypha lignicola*. Lipase producer microorganisms such as the bacterial genera *Bacillus*, *Pseudomonas* and *Streptomyces* and the fungal genera *Fusarium*, *Alternaria*, *Penicillium*, *Scopulariopsis*, *Acremonium* and *Pyrenochaeta* are also of importance in compost formation [17, 18].

Investigation of the composting process of seaweed as a process has been carried out to limit their negative impact on tourism at beach locations and reduce their impact on trade traffic at seaports as excessive growth limited the movement of ships [19, 20] and to condition the soil treated by the compost that is produced by the aid of algae. The addition of oven-dried manually shredded sea lettuce (*Ulva sp.*) powder to the compost pile formed of green waste and manure produces higher temperature and a longer thermophilic stage. The composting process stabilised within 4 months [19]. Other studies revealed that the effect of the phosphorus and potassium provided by seaweed, the slightly alkaline effect of algae, and better aeration of the soil improved the production of tomato *Licopersicon esculentum* [20].

Having noted the potential of algal natural products to enhance composting and fortified soil, we report on the production of a seaweed extract-based formulation to enhance green waste composting and improve the quality of the compost produced. The effect of a natural extract from a Scottish source of *Ascophyllum nodosum* is investigated for the first time taking into account the influence of temperature, moisture, microbiota, O_2 and CO_2 levels and the release of VOCs on the composting process.

Materials and methods

Collection of algae

A. nodosum shown in Fig. 1 was collected manually from the intertidal zone of Irvine Rd, Ardrossan KA22 8PH, UK Lat: 55.669307794062966, Lng: -4.845159785066649 on the 11th of March 2019 and a voucher specimen code AN-Ardrossan01 was kept in natural products chemistry lab., Institute of Biomedical and Environmental Health Research (IBEHR), School of Computing Engineering & Physical Sciences, University of the West of Scotland, UK. The whole parts of the algae were completely dried by lyophilisation using Modulyo freeze dryer from Edwards.

Preparation & application of algal extract

The lyophilised material was pulverised using a mechanical mill and the powdered material was subjected to several steps of extraction leading to the final formulated algae extract concentrate product in one L of 3% Na_2CO_3 aq. sol. A one L sample of the extract was diluted to fifty L using

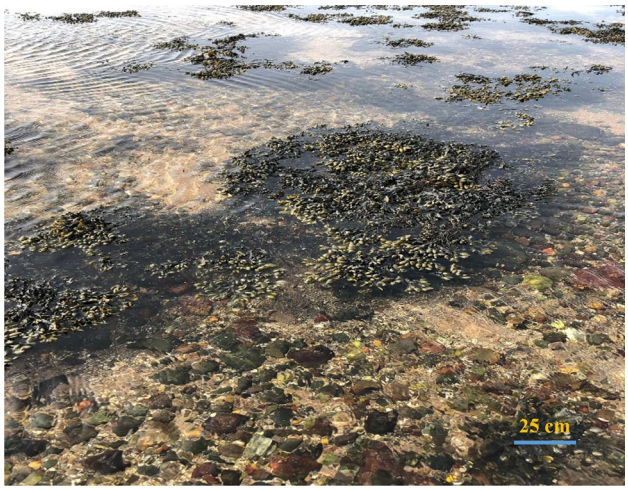

Fig. 1 *Ascophyllum nodosum* from the intertidal zone of Ardrossan, Scotland (Image scale 1:20)

tap water. A green garden waste was put through a sanitisation stage where temperatures must be held at > 60 °C for 48 h within a vessel at a local commercial waste recycling facility. The diluted algal mixture was dispensed and mixed with 5 metric tonnes of sanitised green garden waste and a similar quantity of the same sanitised waste patch is kept as a control sample. The study started on the 4th of February 2020 and ran for six weeks.

Monitoring temperature, moisture, $O_2$and CO_2 levels of the compost piles

The temperature, moisture %, O_2% *v/v* and CO_2% *v/v* were recorded using a generic monitoring device (Compost Manager, Freeland Scientific, Hextable, Kent, UK). This tool provides advisory information for optimising the aerobic composting process, with data logging over time. Using relative values of variables, the monitor provided guidance on turning, irrigation, or maintain compost piles. The balance between O_2 and CO_2 is important to avoid anaerobic digestion and production of airborne harmful gases like CO_2, ammonia, phenolic materials, and H_2S. The monitor recorded the O_2 and CO_2 from zero to 20% and 40% *v/v* respectively with ± 0.5% accuracy. Temperature can be recorded up to 90 °C with a ± 2 °C accuracy and moisture can be recorded at levels from 25 to 65% w/w with ± 10% accuracy [21].

Statistical analysis

The results reported in this study were means of several replicates with standard deviation values. The temperature, moisture %, O_2% *v/v* and CO_2% *v/v* were recorded from eight different spots around the test and control piles, average values were calculated with the standard deviation of these values. Samples for pH studies were collected from three different spots around the pile.

Studying the microorganisms of the compost

Five g samples were collected as triplicate from three different points in the test and control piles in 50 mL sterile falcon tubes to culture the microorganisms and measure the pH. The sample was suspended in 20 mL of DW for 2 min and 100 µL was cultured in different growth agar plates for non-selective growth, selective bacterial growth, and selective fungal growth and incubated at 30 °C for several days to check the results. The sampling times were labelled as T0 (the day of application), T1 (7 Days), T2 (14 Days), T3 (21 Days), T4 (28 days), T5 (after 5 weeks) and T6 (after 6 weeks) of application. Ammonia levels were checked at different times during the composting process. Using the Dräger™ Short-Term Detector Tubes 2–30 ppm to adsorb ammonia molecules.

Elemental analysis

We used Thermo Scientific iCAP 6000 Series ICP-OES standard operating procedure, to 2 mL of the sample in a 50 mL Eppendorf 50 mL centrifuge tube we added 2 mL of H_2O_2 and 5 ml HNO_3. The tube has been placed in a hot block for 30 min. Made to 50 mL using UHP and filtered by 0.2 µm filter disk. We used a multi-element standard with stock concentration 100 mg/L and did serial dilutions for a working calibration, the dilutions were all made up to 50 mL with 10% nitric acid. 0.1 ppm–0.05 mL, 0.2 ppm–0.1 mL, 0.5 ppm–0.25 mL, 1 ppm–0.5 mL, 2 ppm–1 mL, and 10 ppm–5 mL. The standards to make 25 and 50 ppm were made from single element standards of 1000 mg/L stock concentration, again as before made to 50 mL with 10% nitric acid. Other parameters to note for the run are; plasma 8 L/ min, aux 0.2 L/ min, nebuliser 0.7 L/ min, power: 1500Watts, and sample flow rate 1.5 ml/ min.

Compost analysis

The compost samples were analysed by NRM, a division of Cawood Scientific Ltd. Coopers Bridge, Braziers Lane, Bracknell, Berkshire RG42 6NS. The results were supplied by Enva Organics Recycling Ltd, Glasgow, UK.

Results

The data was collected for two months from the date of application on the 4th Feb 2020 until 2nd of April 2020. The test pile and the control pile were turned on days 9,

16, 29, 34, and 56 of the test, as advised by the compost monitor. Graphical representation of the temperatures data recorded over the period of the test for the test and control piles is shown in Fig. 2. Descriptive analysis of the composting phases in the test pile is recorded as Fig. 3. Levels of carbon dioxide and oxygen in the test and control piles were recorded and plotted as Fig. 4, and Fig. 5 respectively. Figure 6 shows the comparison of the acidic-basic environments in these two pile recorded on a pH scale, and the moisture levels in them are shown in Fig. 7. After 6 weeks of the test

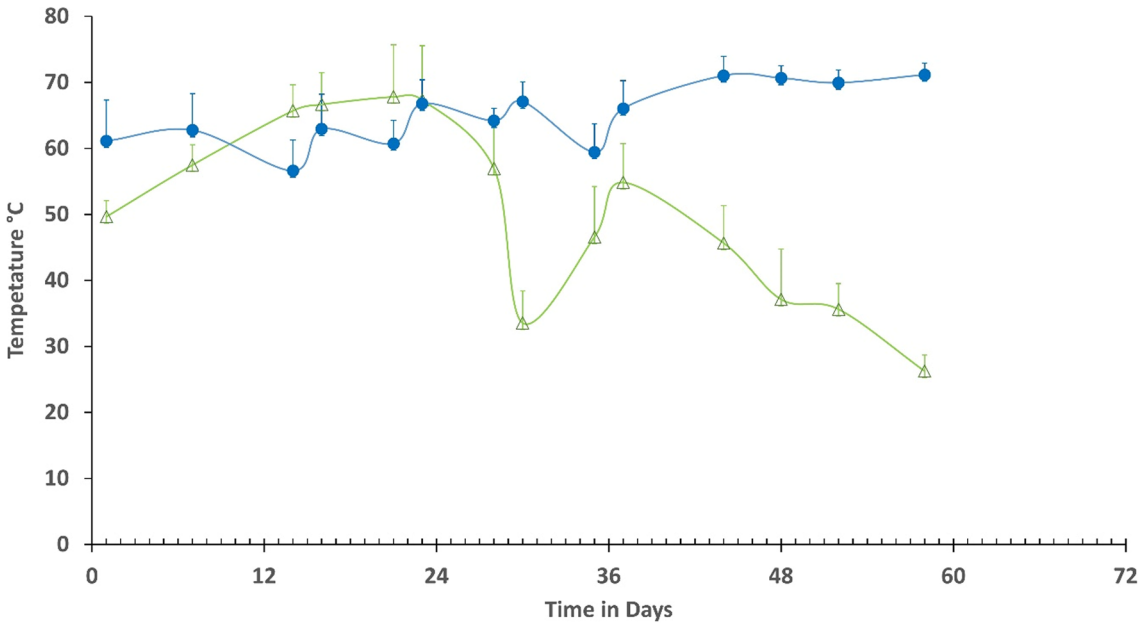

Fig. 2 Showing the temperatures against time as recorded in test Δ and control ● piles. Each point is the result of eight readings recorded at different points around the piles, and the error bars show the standard deviation of these readings

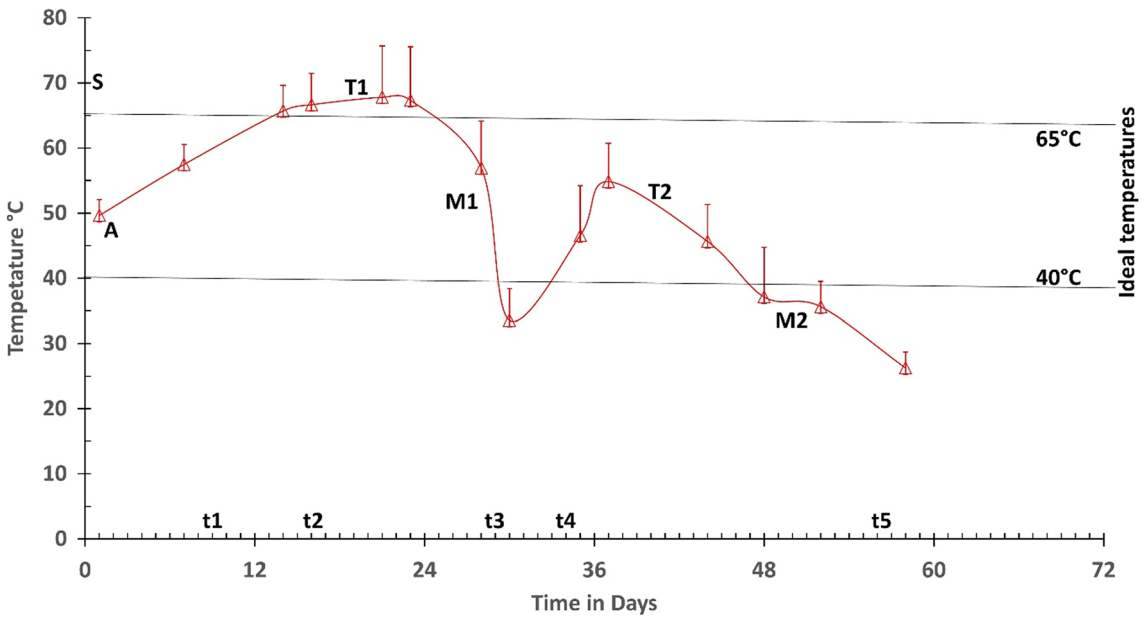

Fig. 3 The stages of the composting process at the test pile, point **A** represents the first temperature recorded after the sanitisation phase (**S**) which extended for 4 days. **T1** and **T2** are the first and second thermophilic phase, respectively. **M1** and **M2** are the first and mesophilic stages respectively. Each point is the result of eight readings recorded at different points around the piles, and the error bars show the standard deviation of these readings

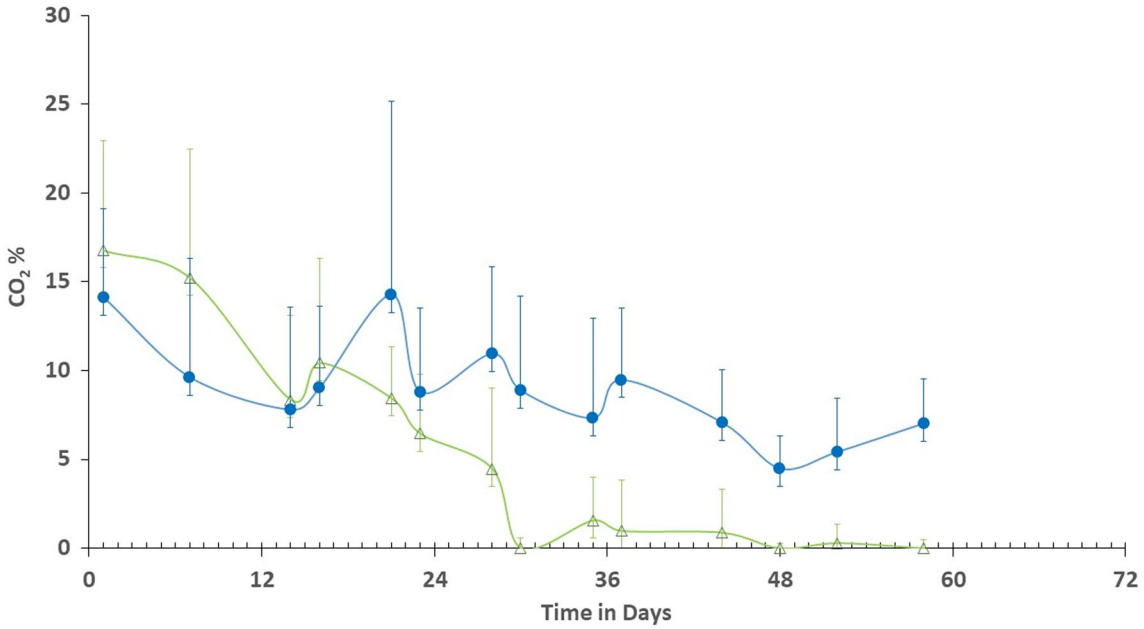

Fig. 4 CO_2% levels in test Δ and control ● piles. Each point is the result of eight readings recorded at different points around the piles, and the error bars show the standard deviation of these readings

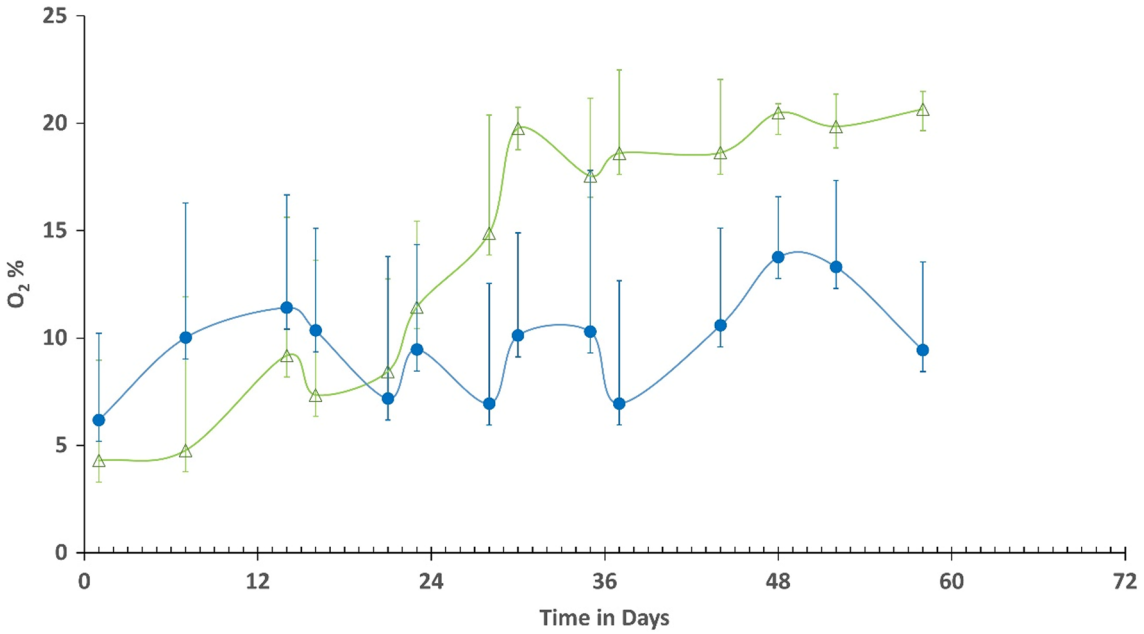

Fig. 5 O_2 levels in test Δ and control ● piles. Each point is the result of eight readings recorded at different points around the piles, and the error bars show the standard deviation of these readings

we recorded visually the difference between the test and control piles which is displayed as Fig. 8. Complete details of compost analysis are shown in Online Resources 1–7 in the supporting Information, and the elemental analysis results is tabulated in Table 1.

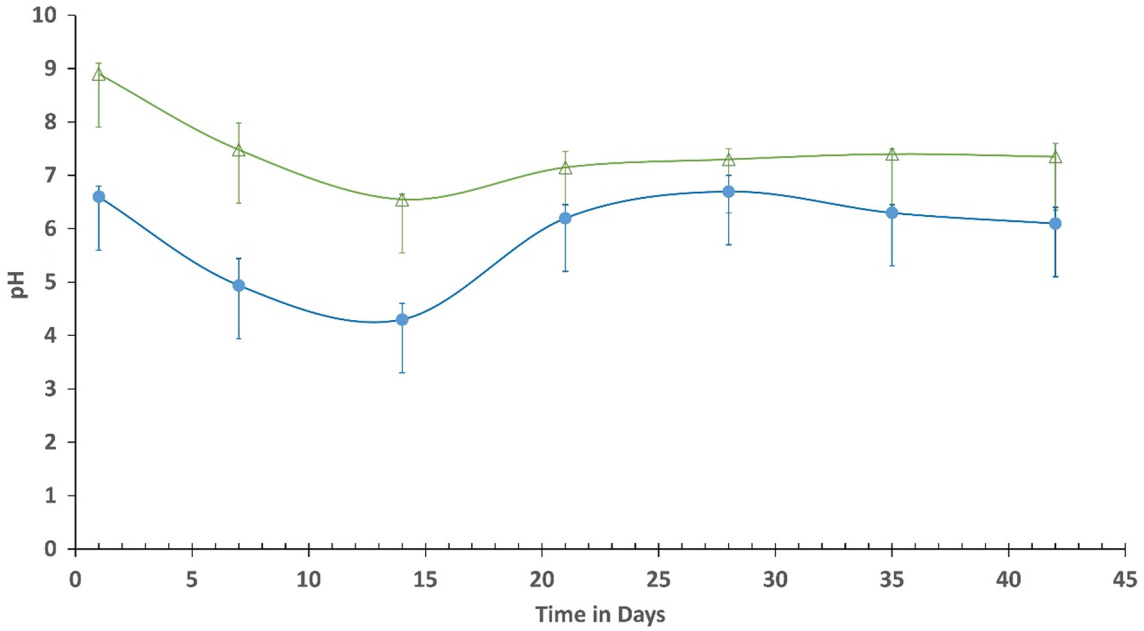

Fig. 6 The pH levels in test Δ and control ● piles. Each point is the result of three readings recorded from samples collected from three different points around the piles, and the error bars show the standard deviation of these readings

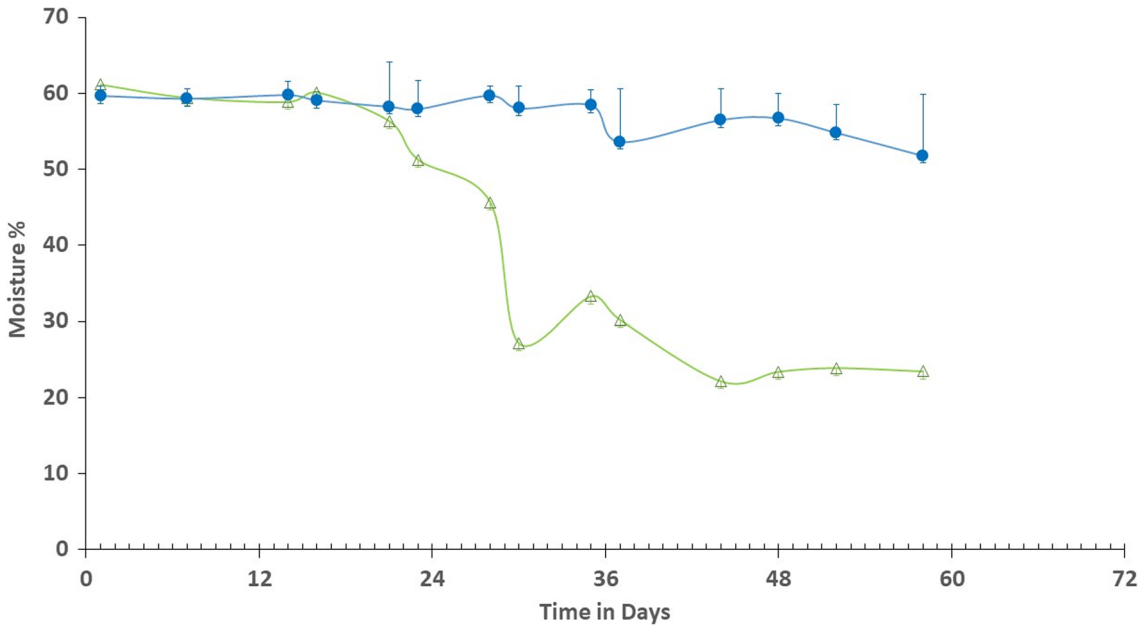

Fig. 7 The moisture levels in test Δ and control ● piles. Each point is the result of eight readings recorded at different points around the piles, and the error bars show the standard deviation of these readings

Discussion

Analysis of the phases of the composting process

The waste mass was subjected to a sanitisation process which was expected to kill the pathogenic microorganisms as temperatures between 50 and70 °C eliminate all the enteric bacteria [11, 22]. Other researchers stated that temperatures above 55 °C for three days was enough to meet the Class A, alternative 5 requirements under 40 CFR Part 503 regulations [9]. This indicates the necessity of a

Fig. 8 This figure shows more white filamentous materials in the test pile (marked by the yellow arrows) compared with the control one (Image scale 1:20), indicating the achievement of stabilisation stage in the test pile after six weeks of the test

Table 1 Shows the concentration of the elements in mg detected in 1 L of formulation

Wave length in nm	Al 396.153 nm	As 188.979 nm	B 249.677 nm	Ca 317.933 nm	Fe 238.204 nm	K 766.490 nm	Mg 285.213 nm	Na 589.592 nm	Sr 407.771 nm
Average con	10.5	0.8	5.06	396.1	9.9	2422	178.7	8946	16.4
SD (n = 2)	± 0.04	± 0.18	± 0.04	± 3.47	± 0.18	± 21.72	± 1.69	± 358.21	± 0.07

sanitisation step before commencing the test to decrease the concentrations of harmful or pathogenic microorganisms. Literature review showed that the best temperature for the microbiota responsible for composting process to thrive within compost has been reported to be between 40 and 65 °C [11] and higher temperatures of the compost for a longer time decreased the microbiota activity responsible for composting the organic matter [9] which come to support that data collected during our test as recorded in Fig. 2 which showed that the temperatures of the control at all stages of the composting process were almost above 60 °C, indicated weaker composting process compared to the one at the test pile. During the course of composting, the declined temperatures indicated a depletion in the organic matter that worked as a food source for the microorganisms that dwell in the compost and the development of unfavourable conditions for the microorganisms.

The temperatures in the test compost pile continued to increase until day 23 of the test to record 67.35 °C as the first thermophilic phase then declined to record 33.5 °C on day 30 of the test. That revealed a six-day first mesophilic phase, then increased again reaching the maximum temperature at 58 °C on day 37 of the test as a second thermophilic phase. It then decreased again after that indicating the initiation of the maturation stage or the second mesophilic phase. The compost stabilised at 26.3 °C. The composting profile was comparable with the data recorded in several research articles [23, 24].

This composting profile revealed two building stages with one concave point as shown in Fig. 3. The temperatures range between 26 and 45 °C is the ideal environmental temperature to nourish the *Actinomycetes* and other thermophilic microbiota [25]. This explained what happened in the test pile where this ideal temperature range led to the rejuvenation of the microbial activities which increased the temperature again. We noticed that turning of the test pile (t3) led to increasing the temperature from 33 °C on day 29 of the test to 50 °C on day 34 of the test (t4), the fourth turning point of the test pile. The maximum temperature 58 °C of the second thermophilic phase has been reached on day 38 of the test. This indicated that turning the test pile led to activation of the aerobic digestion as shown in Fig. 3.

The profile of composting using the algal extract formulation agreed with the results of composting using other means of compost accelerator like GORE ® cover membrane and a ventilation system [26]. Figure 3 illustrates the stages of the composting process at the test pile. The figure showed that the two thermophilic phases were identified at the ideal temperature composting temperature range 40–65 °C.

Studying the aerobic vs. anaerobic metabolism conditions in the compost piles

The levels of CO_2 and O_2 shown in Fig. 4 and Fig. 5 respectively. The CO_2 production decreased with time for both the test and control piles. However, the control pile produced more CO_2 compared with the test pile as shown in Fig. 4. The reduction of release of CO_2 may be attributed to the effect of the algal extract which contains high concentrations of sodium alginate. Sodium alginate restricted the release of CO_2 after formation of a nitrogen coated surface due to reaction with ammonia molecules.

This assumption is supported by the results of other studies that the molecules of sodium alginate contain many hydroxyls and carboxylic acid moieties which upon treatment with ammonia produced by the composting process

accelerated the interaction with CO_2 due to the formation of the basic environment [27, 28]. The composting process in the test pile appeared to occur under aerobic conditions compared with relatively anaerobic conditions at the control pile as shown in Fig. 5 which is the unfavourable scenario in the composting process.

Analysis of the pH levels and effects of pH on the production of greenhouse gases

The pH results for the test and control piles are shown in Fig. 6. The pH of the compost decreased from 8.9 to 6.5 during the first 13 days of the composting process due to the production of small organic acid like acetic and butyric acids that were produced due to the microbial activities [29]. Then the pH started to increase to reach a neutral pH value of around 7.2. The buffering capacity of the composting media is important to the final quality of the compost produced.

The large amount of ammonia that leaves the compost leads to the production of compost with poor agricultural value and more noxious odour during the composting process. The evaporation of ammonia played a critical role in reduction of the pH [30]. This clearly indicated that the algal formulation saves a considerable amount of nitrogen and increase the pH in the compost compared with the control pile. The ordinary composting process wasted up to 70% of the total nitrogen contents [31]. Sodium alginate in the formulation adsorbs a significant part of the ammonia produced by the composting process. This revealed by Dräger sampling tubes which detected lower ammonia levels around 50% in the vicinity of the test pile compared with higher levels of ammonia that reached around 20 ppm in the vicinity of the control pile. Sodium alginate could efficiently immobilise the ammonia-oxidising bacteria that have an essential function in the transformation of ammonia to nitrite [32]; a property that would facilitate the use of our extract in further applications like the remediation of the waste water as well as in agriculture as a soil bioremediation product.

Effect of moisture levels on the production of methane

Methane usually produced due to the effect of high moisture and lower oxygen contents of the compost [33] these conditions were apparently noted in the control pile. Figure 7 shows the moisture levels in the test and control piles. Lower levels of moisture were recorded from the test pile after 4 weeks of the experiment compared to the moisture levels of the control pile. This could be attributed either to more microbial activities and metabolism, or the drying effect of the wind affecting the test pile at the windrow. Considering that more moisture and less oxygen in the pile produced more methane [33], we proposed that algal extract reduced methane levels released by the composting process. However, the concentration of the methane produced by the composting process needs to be checked and analysed thoroughly.

Several approaches have been used to decrease the production of greenhouse gases like CO_2, CH_4, N_2O, and NH_3 using a semipermeable cover [34] or by the addition of methanotophic microorganisms to consume the methane produced in their oxidation metabolism [35]. Aeration of the pile by adding bulk materials like spent mushroom and mulch decrease the anaerobic spots in the pile and reduce the methane ultimately produced [36]. Absorption of the gas produced was also used as an adaptive measurement to decrease the release of methane to the environment, and the surface area was also crucial in the absorption process as more surface area absorb more methane. Example of this is the use of small particles of biochar to adsorb more methane [37].

The microbiota in the test and control piles

Clear difference between the control and the compost piles was recognised during the test, comparison of these piles revealed that the algal extract altered the physical appearance of the compost pile markedly. The fungus-like bacterium, Actinomycetes or fungal populations were distributed more throughout the test pile while the control pile showed less white filaments, as shown in Fig. 8. This indicates more decomposition of complex fibrous tissues in the test pile [38]. Isolation and cultivation of the compost microbiota on T1 revealed that the microorganisms were more abundant in the test pile compared with the control. This tread generally continued until week 6 (T6) of the experiment where the microbiota in the test pile was found to be more abundant than that in the control pile. Several endophytes were isolated from *A. nodosum*, around 800 bacterial isolates isolated from this seaweed some of them have polysaccharides hydrolytic activities [39]. This indicated that the bacterial cells present in *A. nodosum* might play a positive role in the digestion of the waste material and enhance or accelerate the composting process.

Stabilisation of the compost

Algae have relatively low C/N contents so the ideal composting process can be achieved by mixing material with high carbon content like trees, shrubs, etc. to reach the required 30 C/N mixture and to kick off the composting process. Aerobic metabolism consumes the carbon of the biomass, the stabilisation stage of the compost is achieved at 15 C/N mixture. Higher carbon contents in the waste biomass extends the time of composting. Hence the stabilisation process and achievement of higher fungal contents in the compost takes

longer time [40]. This means the high fungal contents of the compost is one of the signs indicating compost stabilisation. The oxygen levels in the test piles were almost 20% and carbon dioxide approached zero levels suggesting the achievement of maximum aeration and aerobic metabolism led to complete decomposition of the organic materials. The pH of the test pile was just above 7 in contrast to the acidic pH of the control pile, which is further evidence that the algal extract accelerated the composting process toward the formation of favourable neutral compost. Further details of compost analysis are shown in Online Resources 1–7.

Elemental analysis

Table 1 shows the concentration of the elements detected in the formulation in mg per 1 L of the formulation using ICP-OES. Mainly the alkali group I & II metals were of high concentrations, but as expected sodium concentration was the highest concentration compared to other elements.

Conclusion

In conclusion, the algal extract formulation has shown to influence the composting process of green waste leading to shorter time to attain a final stable compost. The results indicated that this formulation accelerated the compost production by 25% and altered the classical course of this process. The effects of *A. nodosum* extract were clear through a reduction in the normal time line of 8 weeks for the composting process to around 6 weeks and diminished the release of harmful gases to the environment. This formulation is environmentally friendly as it is composed ultimately of phytochemicals extracted from *A. nodosum*, and the endophytes naturally available in this alga. This algal extract produced higher class compost, almost neutral which is of higher value in agricultural applications. The aerobic metabolism facilitated by the algal extract led to the retention of nitrogen in the compost instead of loss it in the form of ammonia. Lower moisture of the test pile which was mixed with this formulation with more oxygen in the pile promoted the lower production of methane and released into the environment.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10163-023-01746-0.

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Declarations

Conflict of interest The authors declare that they have no competing interests.

Ethical approval and consent to participate Not applicable.

Consent for publication Not applicable.

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