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Review

Composting of waste algae: A review

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A B S T R A C T

Although composting has been successfully used at pilot scale to manage waste algae removed from eutrophied water environments and the compost product applied as a fertiliser, clear guidelines are not available for full scale algae composting. The review reports on the application of composting to stabilize waste algae, which to date has mainly been macro-algae, and identifies the peculiarities of algae as a composting feedstock, these being: relatively low carbon to nitrogen (C/N) ratio, which can result in nitrogen loss as NH_3 and even N_2O; high moisture content and low porosity, which together make aeration challenging; potentially high salinity, which can have adverse consequence for composting; and potentially have high metals and toxin content, which can affect application of the product as a fertiliser. To overcome the challenges that these peculiarities impose co-compost materials can be employed.

Contents

1. Introduction

There is growing global interest in the role that algae can play in renewable fuel, food and materials generation. Algae are a diverse group of uni- and multicellular photoautotrophs. They are essentially biological solar panels that fix CO_2 for growth and the production of intracellular storage compounds (Chisti, 2007). They have a higher photosynthetic efficiency than other biomasses, and can be cultivated in simple open saline ponds so their production does not compete for arable land (Mata et al., 2010).

However uncontrolled growth of algae in natural and engineered environments can be a serious concern. The evidence includes some notable examples:

- *Qingdao, China (2008):* The world's largest "green-tide" event, caused by extensive aquaculture (Liu et al., 2009). Algal biomass, dominated by *Enteromorpha*, covered about 400 km^2 along the coast. The algal biomass blocked the port channel

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Fig. 1. Green-tide of Qingdao, China, in summer of 2008 (from Liu et al., 2009).

(Fig. 1). In June 2008 alone, more than 150,000 tonnes of wet algal biomass was collected from the region. More than 10,000 workers and 1000 boats were hired for the operation (Wang, 2008).

- *Albury-Wodonga, Australia (2009):* Blue green algae outbreak in Lake Hume, which is located east of Albury-Wodonga. The outbreak extended 600 kilometres, almost covering the whole main channel of the lake (Lauder, 2009).
- Venice, Italy (annual): In the Venice Lagoon, about 10 million tons (wet weight) of *Ulva rigida* biomass are produced annually. Harvesting has been carried out to reduce negative impacts of the algal biomass, however, due to the high costs of such effort, only 40,000 tons are collected every year (Cuomo et al., 1995).
- *Patagonia, Argentina (annual):* Large quantities of green seaweed, linked to eutrophication, are cast ashore every summer on the Puerto Madryn beaches (Eyras et al., 1998). This algal biomass interferes with recreational uses of the beach, and therefore must be periodically collected and disposed. It was estimated that about 8000 tons of seaweed are collected every year (Eyras and Rostagno, 1995).
- *Wuxi, China (annual):* Since 1981, cyanobacteria populations (Microcystis and Anabaena) have increased in Taihu Lake, Wuxi, China. Annual blue-green algae blooms in the lake have clogged intakes at municipal waterworks, interrupted domestic and industrial water supply, and caused losses in fish cultures (Pu and Yan, 1998).
- *The Mediterranean (annual):* The marine plant posidonia (*Posidonia oceanica*) beached in tourist zones represents a great environmental, economical, social and hygienic problem" (Cocozza et al., 2011). In many places the material is collected and disposed of in waste dumps (Castaldi and Melis, 2004).

Waste algae has been directly applied as soil conditioner and/or fertiliser in many coastal regions of the world (Castlehouse et al., 2003; Cocozza et al., 2011; Haslam and Hopkins, 1996). Here we review composting as a technology for waste algae stabilisation, which could potentially improve existing land application strategies. Composting is defined as the biological decomposition and stabilization of organic substrates under conditions which allow development of thermophilic temperatures as a result of biologically produced heat, with final products sufficiently stable for storage and application to land without adverse environmental effects (Polprasert, 1996). It is an aerobic process whereby organic carbon is oxidised to CO_2. Composting has been widely applied for managing household and food waste, but, while the opportunity to compost waste algae has certainly been recognised and the application of algae compost as a fertiliser for horticulture has been demonstrated (Eyras et al., 1998), reports on composting algae are relatively scarce.

To date, most algal composting has been limited to stabilising macroalgae, particularly seaweed. The focus has been on composting material collected from green-tide events, like those listed above. *Ulva* sp. is the most important component of green-tide seaweed (Eyras et al., 2008) and so the stabilisation of that species has been most widely examined (Cuomo et al., 1995; Maze et al., 1993; Mendo et al., 2006).

In contrast to literature on the composting of macroalgae, there are few reports on composting microalgae. The degradation of *Chlorella* during composting has been reported (Kitano et al., 1998) and in recent years, a few studies on blue-algae composting have been carried out by Chinese researchers. Much of the blue-green algae that has been stabilised was collected from the aforementioned Taihu Lake (Jiang et al., 2012; Pu and Yan, 1998; Ren et al., 2012; Wang, 2008).

The aims of this review are to bring together literature on algal composting in order to (i) report the technologies for composting waste algae, (ii) assess the merits of composting for managing waste algae, and (ii) identify the peculiarities of algae as a composting feedstock. To the best of our knowledge, this is the first review on this topic.

2. Peculiarities of algae as a compost feedstock

Algae are characterised by a relatively low carbon to nitrogen (C/N) ratio. Additionally, algal biomass typically has high moisture content and, for algae grown in marine or brackish environments, high salinity (Cuomo et al., 1995; Jiang et al., 2012; Maze et al., 1993; Mendo et al., 2006). Algae can also have elevated metals content and blue-green algae can carry associated toxins. The physical and chemical characteristics of algal biomass to be stabilised by composting are summarized in Table 1. These characteristics and the role they play in the composting process as discussed below.

2.1. Carbon to nitrogen (C/N) ratio

The carbon to nitrogen ratio (C/N ratio) of the organic material to be composted is important as it affects the microbial compost

Table 1
Physical and chemical properties of algae or seaweed materials used for composting.

Materials	C[a] (%)	N[a] (%)	C/N ratio	Organic matter[a] (%)	Moisture (%)	EC (dS m^{-1})	Salinity[a] (%)	Ref.
Ulva sp.	5.78	0.68	8.5	13.7	39.4	–	1.4–4.7	Maze et al. (1993)
Ulva sp.	24.34	2.77	8.78	41.97	64.4	8.5–14.5	–	Mendo et al. (2006)
Green algae	26.3	3.6	7.3	53.3	75.2	–	–	de Guardia et al. (2010a)
Green algae	19.5	3.6	5.4	–	–	–	–	de Guardia et al. (2010b)
Blue-green algae	36.3	7.4	4.9	62.1	87.7	–	–	Jiang et al. (2012)
Blue-green algae	44.9	7.4	6.06	–	96.2	–	–	Wang et al. (2009)
Undaria pinnatifida	31.32	2.67	11.7	–	–	–	4.6	Tang et al. (2011)
Undaria pinnatifida	36.95	4.14	8.92	–	89	–	1.5–2.8	Tang et al. (2010)
Posidonia oceanica	36.0–46.2	0.6–1.0	36–81	–	55–65	12.5–15.8	–	Cocozza et al. (2011)

[a] Percentage by dry weight.

Table 2
Physical and chemical properties of co-composting material in algal composting.

Materials	C (%)[a]	N (%)[a]	C/N ratio	Organic matter (%)[a]	Moisture (%)	Ref.
Sawdust	50	0.24	208	–	–	Eyras et al. (1998)
Wood chips	46.3–50.3	0.07–0.1	463–719	98.0–99.8	5.5–61.2	de Guardia et al. (2010a)
Straw	47.02	1.26	37.32	81.04	41.5	Mendo et al. (2006)
Cow manure	39.88	2.43	16.1	68.76	54.6	
Rice hull	40.3	0.64			6.25	Wang et al. (2009)
Rice bran	51.5	1.59			8.27	

[a] Percentage by dry weight.

community, quality of product in terms of the degree of stabilization and the final available nutrients. The composting time and the cumulative CO_2 production have been shown to be linearly dependent on the initial C/N ratio (Chang and Hsu, 2008), which means a higher initial C/N ratio may result in a longer time to stabilize the compost material and shift the microbial community to include higher relative abundances of fungal biomass (Eiland et al., 2001). Nitrogen is limiting in materials with a too high C/N ratio (greater than about 100) (Leconte et al., 2009).

Material with a low initial C/N ratio degrades quickly, but can result in nitrogen loss via ammonia NH_3 volatilisation, which means a waste of available nutrient and the generation of unwanted odours (Haug, 1993). With this in mind, it is recommended that compost feedstock have an initial C/N ratio of at least 30 (An et al., 2012; Haug, 1993; Zhu, 2007), which is the case for the seaweed *Posidonia oceanica*, (C/N of 36 (leaves) and 81 (fibres) (Cocozza et al., 2011)). The C/N ratio decreases as aerobic degradation of organic matter takes place, and a final C/N ratio around 15 is typical (Breidenbach, 1971; Haug, 1993; Iglesias Jiménez and Pérez García, 1991; Kumar et al., 2010; Rosen et al., 1993). The number can be an indication for compost stability and also a limiting value for nitrogen loss.

Generally, algae biomass has a relatively low C/N ratio, typically ranging from 8 to 11 (Cuomo et al., 1995; Maze et al., 1993; Mendo et al., 2006; Tang et al., 2010, 2011), although a C/N ratio of 23 has been reported for Ulva collected from Puerto Madryn beaches, Argentina (Eyras et al., 1998) but even this ‘high’ ratio is below the recommended C/N ratio. As far as the authors are aware, the lowest C/N ratio reported for algae is around 5 (de Guardia et al., 2010b; Jiang et al., 2012). It was suspected that the extremely low ratio caused additional nitrogen loss in the form of N_2O during composting of that material (Jiang et al., 2011; Xu et al., 2007).

An effective way to adjust the algal-based feedstock to have a suitable C/N ratio (around 30) is to mix with a high C/N ratio co-composting material. Sawdust, bark, straw and animal manure are commonly used as co-composting materials (Cuomo et al., 1995; Droffner and Brinton, 1995; Eyras et al., 1998; Mendo et al., 2006), but only materials with a relatively high content of readily biodegradable carbon should be considered in this context, else the co-composting material will simply modify the structure (e.g., porosity and moisture content) of the compost. Co-composting was conducted for the composting of green-tide seaweed in Brittany (France) and Venice Lagoon (Italy) (Maze et al., 1993; Vallini et al., 1993). The physical and chemical properties of some commonly used co-composting material for algae are summarized in Table 2.

2.2. Temperature

Temperature is one of the most important variables in the composting process. To enhance the removal of non-spore forming pathogens, for example *Salmonella* and *E. coli*, it is recommended that in a composting process temperature must exceed 55 °C for a period of at least two weeks (Droffner and Brinton, 1995). A temperature rise during composting is caused by exothermic oxidation of organic matter. The level of temperature rise depends on the rate of metabolic activity, the extent of oxidation and the rate of heat transfer from the composting material.

Temperature profiles of algae composting are widely reported. The profiles can be used to monitor the composting process (Cecchi et al., 1993; Eyras et al., 1998; Mendo et al., 2006). The theoretical basis for this is that there is a positive correlation between temperature rise and CO_2 production (de Guardia et al., 2010a; Tang et al., 2011). de Guardia et al. (2010a) studied the behaviour of five organic wastes during composting, where green macroalgae from a beach in Brittany was one. They observed that temperature rise was inversely related to aeration, because while higher air input can boost biological activity it also acts to cool the system to ambient conditions. Interestingly, the temperature profile of green macroalgae was more sensitive to aeration than was the case for some common composting materials (food wastes, household wastes, pig slurry and slaughterhouse sludge).

2.3. Moisture and porosity

The moisture content in material to be composted is a critical parameter. It affects microbial activity as well as the physical structure, and thus has a central influence on the biodegradation of organic materials (Ahn et al., 2008). It has been reported that microbial activity is inhibited when moisture content falls below 25%, and the aeration can be restricted when moisture content is higher than 70% (Rodriguez et al., 1995). Most materials are best composted in a moisture content from 50% to 70%, while some other materials can be effectively composted outside this range (about 25–80% on a wet basis) (Cronje et al., 2004; Haug, 1993; Richard et al., 2002; Willson, 1989).

Porosity, which is largely influenced by moisture content, is an important characteristic because it directly affects O_2 availability within compost piles. Air flows through a compost pile by the network formed by air filled pores, so it is important to distinguish air filled porosity (AFP) from total porosity (Ruggieri et al., 2009). Porosity (ε) is defined as the ratio of total void volume of the sample (Vv), comprised of air and water filled voidage, to total volume of the sample (Vs), as shown in Eq. (1).

$$\varepsilon = \mathrm{Vv}/\mathrm{Vs} \tag{1}$$

AFP is defined as the ratio of air volume (Vg) to total volume of the sample (Vs) (Haug, 1993), as shown in Eq. (2).

$$\mathrm{AFP} = \mathrm{Vg}/\mathrm{Vs} \tag{2}$$

The lowest viable AFP values in freshly placed organic material that will ensure aerobic microbial activity has been reported to be 30% (Haug, 1993; Jeris and Regan, 1973), while values over 60–70% seem to be excessive to achieve thermophilic temperatures in wastes with low biodegradable organic matter content. Currently there are no reports about the exact value of both porosity and AFP in algae feedstock for composting.

Algae, as they grow in aquatic environments, can have more than 90% moisture content even after harvesting and some dewatering (Table 1). As mentioned, such a high moisture content material will have low AFP, and so algal material should be mixed with drier co-composting material to improve air permeability and therefore enhance the composting process (Cuomo et al., 1995; de Guardia et al., 2010a,b; Eyras et al., 1998; Maze et al., 1993; Mendo et al., 2006), especially when composting microalgae (Kitano et al., 1998). Generally, moisture content in algal composting is adjusted to around 50% on a wet basis (Cuomo et al., 1995; de Guardia et al., 2010b; Maze et al., 1993).

2.4. Salinity

Considering macroalgae from marine environments is potentially a significant composting feedstock it is critical to understand the effect of salinity on composting processes. The ascension of salinity in compost material during the biodegradation of organic matter is common in composting processes (Canet et al., 2008; Huang et al., 2004). But sometimes this phenomenon can be problematic as high salt content can lyse microbial cells (Brock et al., 1994). Salinity above 8-dS m^{-1} has been shown to have negative impact on composting processes (Santamarıa-Romero and Ferrera-Cerrato, 2001). That said, there are actually very few studies on inhibition of composting processes due to salinity.

A high salt concentration or osmotic pressure could be a selective pressure for microorganisms (Haruta et al., 2004). Halo-tolerant microorganisms that are able to biodegrade petroleum hydrocarbons in high saline environment are characterised by an ability to keep an osmotic balance through the accumulation of intracellular salinity and salt adaptive enzymes that are insensitive to intracellular salinity (Margesin and Schinner, 2001).

However, composts produced from highly saline feedstocks such as algae will affect yields and germination processes for salt intolerant crops (Liu et al., 2000; Nelson and Ham, 2000). Some researchers have attempted to avoid salinity issues by washing algal feedstock prior to composting (Cuomo et al., 1995; de Guardia et al., 2010a; Eyras et al., 1998). However, some other researchers reported that final composts from washed and non-washed macroalgae had similar electrical conductivities, which indicates washing does not readily reduce the intracellular salinity of algae (Mendo et al., 2006).

Tang et al. (2010) studied the effects of salinity on the composting of the seaweed *Undaria* sp. The material containing various levels of NaCl (15.2–28.2 mg/g, dry basis) was composted with *Bacillus* sp. HR6 as an inoculum. The results indicated that peak composting temperatures were reached faster in piles of *Undaria* sp. with lower salinity (Fig. 2). As a high content of alginate is a main characteristic of *Undaria* sp., salt tolerant alginate-degrading bacteria were added to the composting system in a following study by the same authors. The results showed that the degradation rate of *Undaria* sp. can be very effectively enhanced by *Halomonas* sp. AW4 and *Gracilibacillus* sp. A7 (Tang et al., 2011).

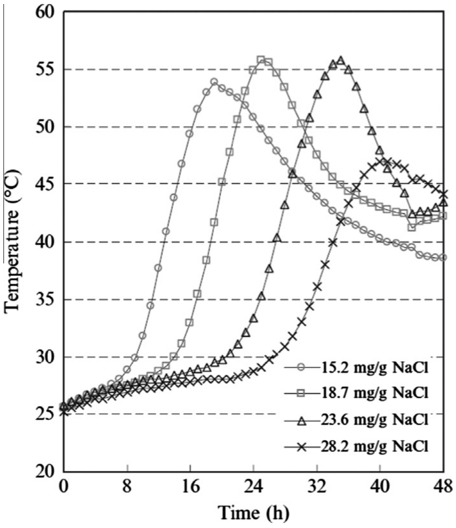

Fig. 2. Effect of salinity on the temperature changes during wakame (*Undaria* sp.) composting (from Tang et al., 2010).

2.5. Heavy metals

Algae have the ability to accumulate heavy metals (Muñoz and Guieysse, 2006) and it has been reported that these heavy metals or metalloids are a potential risk when seaweeds or seaweed composts are used as fertiliser in agriculture (Castaldi et al., 2004; Castlehouse et al., 2003), with cadmium (Cd) being potentially particularly problematic. Greger et al. (2007) identified the Cd content of some seaweed compost to be higher than the limit levels suggested by a few countries (Cuomo et al., 1995) and that the Cd content in plants cultivated using seaweed compost exceeded EU limits for lettuce and oats, although the Cd content in the edible portions of root vegetables and leguminous plants was below EU limits (Greger et al., 2007).

Most studies, however, show that algal compost has low heavy metal and metalloid content (Castaldi and Melis, 2002; Cocozza et al., 2011; Cuomo et al., 1995; Illera-Vives et al., 2013; Orquin et al., 2001) – in some cases owing to the introduction of co-compost materials. Castaldi and Melis (2004), who studied the effect composted and beached *Posidonia oceanica* (a seaweed that is deposited on beaches in the Mediterranean), concluded that most metals strongly interact with the organic matter of compost, limiting the vegetal absorption.

2.6. Microcystins

Microcystins are a family of cyclic peptides that are produced by cyanobacteria (blue-green algae). They can be toxic and chemically stable in the environment (Carmichael, 1992; Dawson, 1998; van Apeldoorn et al., 2007), but they can be degraded efficiently during the composting process. Wang et al. (2009) showed that, within 35 days, more than 95% of the total microcystins were degraded in all of their blue-green algae compost piles mixed with different bulking agents (sawdust, rice hull, wheat bran and rice bran). Jiang et al. (2012) studied the dynamic profile of microcystins in blue-green algae composting: more than 90% of both microcystin-RR and microcystin-LR were degraded by day 48. Efficient degradation of microcystins during composting may be due to the wide variety of microorganisms present in compost systems (Dawson, 1998; Kormas and Lymperopoulou, 2013).

3. Application of composting technologies for algal stabilisation

Of the two major options for large scale composting: windrow and aerated static pile, windrow appears to be most appropriate for low cost waste algae stabilisation. The two options, along with in-vessel composting, which is appropriate for studying algal composting at lab or pilot scale, are shown in Fig. 3. A summary of the application of various composting technologies for algae stabilisation and analysis of algae stabilisation is shown in Table 3.

Windrow composting, which is the most common method to produce compost from organic wastes (Avnimelech et al., 2004), has already been demonstrated to be effective for algae stabilisation (see Table 3). In windrow composting, aeration is achieved by mechanical turning and natural convection. Owing to simple operation and minimal inputs, windrow composting is relatively

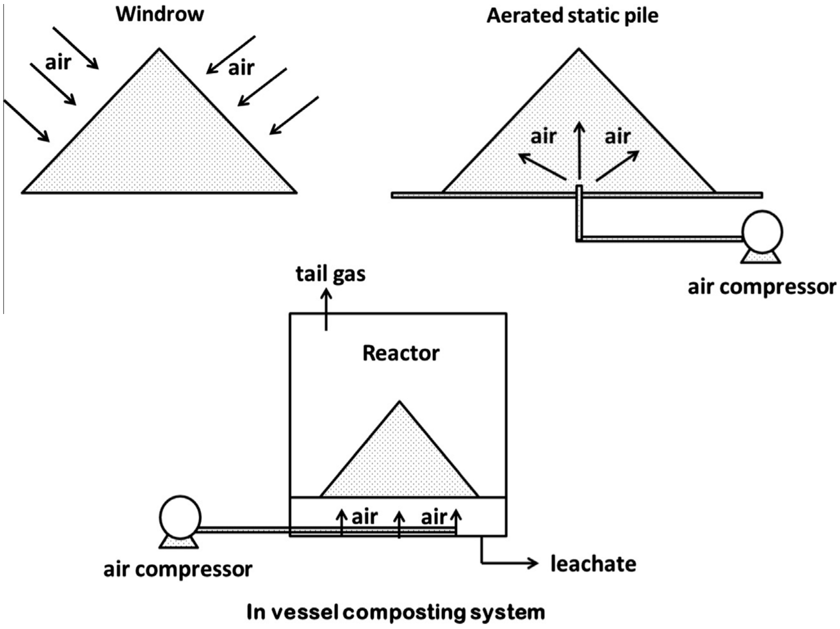

Fig. 3. Typical composting systems (from Kumar, 2011).

Table 3
Design parameters for reported algal composting systems.

System	Algae	Source	Size	Scale	Operating for aeration	Ref.
Windrow	*Ulva* sp.	Brittany, France	25 tonne pile	Pilot	The piles were turned 1 time in 3 months	Maze et al. (1993)
Windrow	*Ulva* sp.	Paracas Bay, Peru	1 m^3 pile	Pilot	The piles were turned 3 times per month	Mendo et al. (2006)
Windrow	Mixed seaweed	Patagonia, Argentina	Length 5 m, width 1.2 m, height 0.5 m	Pilot	The pile was turned when anaerobic conditions were detected inside the pile	Eyras et al. (1998)
Aerated static pile + windrow	*Ulva rigida*	Venice Lagoon, Italy	10 kg and 20 tons piles	Bench and pilot	Forced aeration for in the first 3 weeks and pile turning for 8 weeks	Cuomo et al. (1995)
In vessel system	Green algae (seaweed)	Brittany, France	300 L reactor, 270 L algal mass	Pilot	Continuous forced aeration	de Guardia et al. (2010a, b)
In vessel system	*Undaria* sp.	Amagazaki Port, Japan	5 L reactor, 1.5 kg *Undaria* sp.	Bench	Continuous forced aeration at a flow rate of 0.5 L min^{-1}	Tang et al. (2010), Tang et al. (2011)
In vessel system	Blue-green algae	Taihu lake, China	600 mL container in incubator	Bench	Composts were exposed to air every 2 days	Wang et al. (2009)
In vessel system	Blue-green algae	Taihu lake, China	60 L reactor	Bench	Composts were forced aeration for 30 min every 6 h and turned every 4 days	Ren et al. (2012)

low in cost and suitable for large scale operation, and as such, is highly suited for waste algae stabilisation. Pilot scale windrow composting trials have been performed on green-tide seaweeds harvested from Brittany (France), Paracas Bay (Peru), and Patagonia (Argentina) (de Guardia et al., 2010a; Margesin and Schinner, 2001; Santamaría-Romero and Ferrera-Cerrato, 2001). All the algal windrow piles in these trials had volumes of at least 1 m^3 (Table 3). A study in France considered static 25 t algae piles (Maze et al., 1993) These piles were large enough to generate thermophilic conditions without insulation facilities.

An alternative to windrow composting is the aerated static pile, whereby aeration is provided and controlled by air blowers or air diffusers (Fig. 3). Aerated static piles have been applied in conjunction with windrow composting to stabilise algae. *Ulva rigida* harvested from the Venice Lagoon (Italy) was first set in a static pile under forced aeration for thermopihic aerobic stabilisation (Cuomo et al., 1995). The temperature of the pile was monitored and when it was stabilised the compost was put to windrow for maturation. The major drawback for the aerated static pile is the blower costs (capital and operation), which would be prohibitive for infrequent/seasonal large scale waste algae stabilisation.*In vessel* composting systems are designed to make operating conditions more readily controllable. Also, with the aid of relevant instruments, the key operating conditions and rates (temperature, oxygen uptake rate (OUR), respiratory quotient (RQ), NH_3 and N_2O emissions) can be monitored continuously. However, as the price of *in vessel* systems is much higher than windrow or aerated static pile, such systems are generally only appropriate at bench or pilot-scale, where they can be used for detailed investigation of the composting process (Mason and Milke, 2005). For example, de Guardia et al. (2010a, b) examined carbon and nitrogen dynamics during composting of green seaweeds in a closed reactor (300 L); Tang et al. (2011) used *in vessel* system to assess the potential to accelerate the composting of wakame (*Undaria* sp.) adding salt tolerant alginate-degrading bacterium; Wang et al. (2009) and Ren et al. (2012) used an *in-vessel* system to examine blue-green algae composting.

4. Algal compost quality

The terms stability and maturity are often used interchangeably, but they are technically different with stability being a measure of the biological activity of the compost and maturity being defined as the extent to which biodegradable material, including phytotoxins, has decomposed (Wu et al., 2000). It has been shown that algae compost can be both mature and highly stable.

Trials have shown the organic content of composted seaweed is less than 25% (dry mass), compared with typical organic content of above 80% (dry mass) for home waste and food waste compost (de Guardia et al., 2010a). Accordingly, the oxygen uptake rates (OUR) of composted seaweed is low, with OUR rates far lower than 500 mg O_2/kg OM/h (Gea et al., 2004; Scaglia et al., 2000; Tambone et al., 2004). To put this into context, the European Commission (European Commission, 2001) suggests that dynamic oxygen uptake rates (OUR) of less than 1 g O_2/kg OM/h can characterise stable composts, while various researchers consider dynamic OUR of lower than 500 mg O_2/kg OM/h as a criterion for highly stable compost (Gea et al., 2004; Scaglia et al., 2000; Tambone et al., 2004). Such stability is important if the objective is to avoid accumulation of putrescible waste.

Beyond being stable, algal compost is mature. The Australian standard states that compost maturity is a combined determination of compost characteristics relevant to both biological stability and plant growth response (COMMITTEE CS-037, 2011). In some earlier reports, the concept "maturity" was not even mentioned (Cuomo et al., 1995; Maze et al., 1993). Researchers have previously evaluated the quality of seaweed compost by examining the organic and heavy metal content of their final compost; phytotoxicity was not taken into account. But some latter reports provide a more comprehensive evaluation for seaweed compost quality by introducing an examination of aerial plant biomass production cultivated on different proportions of the composts (Eyras et al., 1998; Mendo et al., 2006). In their studies, the seaweed compost increased the aerial plant biomass production showing a good compost quality and maturity. Also, the Germination Index (GI), which is defined as the product of relative seed germination and relative root growth (Tiquia and Tam, 1998), is high when using algal compost. Orquin et al. (2001), Castaldi and Melis (2002), and Cocozza et al. (2011) conducted germination trials using composted macroalgae and found most of the tested GI values were higher than 100, which indicated the compost can stimulate plant growth.

5. Carbon footprint of algal composting process

Carbon footprint is a measure of the total amount of CO_2 equivalents that are directly and indirectly emitted by an activity or over the life stages of a product (Wiedmann and Minx, 2007). CO_2, CH_4, and N_2O are the relevant greenhouse gasses in composting processes. But the main product, CO_2, should not be considered as a contributor to carbon footprint as it is biogenic and therefore, according to the IPCC, carbon neutral (IPCC, 2001), On the other hand, CH_4 and N_2O, which have significant global warming potential (Lashof and Ahuja, 1990), should be considered when determining carbon footprints of composting processes. These potent greenhouse gases are products of poorly operated composting processes (Amlinger et al., 2008; Amon et al., 2001; Leytem et al., 2010; Meijide et al., 2007; Szanto et al., 2007). There is a strong correlation between N_2O emission and accumulation of nitrite in the composting process (He et al., 2001).

Algal composting might have a high emission of N_2O compared to composting other organic wastes. A study on nitrogen dynamics during composting of five different types of waste showed that N_2O can comprise between 8.0% and 17.3% of total nitrogen loss in green algal composting, while there were almost no N_2O emission in the composting of household waste or food waste (de Guardia et al., 2010b). The phenomenon was probably due to the low C/N ratio in algal biomass (Amlinger et al., 2008).

Generally, a relatively higher C/N ratio will help to reduce N_2O emissions, while a sufficient oxygen supply and a long term thermophilic stage (>40–55/60 °C) will also help to reduce CH_4 and convert nitrite into nitrate to prevent N_2O emission. Bulking material will help to provide the necessary air-filled pore space throughout the composting process to maintain good oxygen supply throughout a compost pile. A moisture range from 50% to 60% (w/w) is ideal to maintain adequate AFP in most compost piles (Amlinger et al., 2008).

Additional to operating conditions, the activity of ammonia oxidation bacteria (AOB), nitrite-oxidising bacteria (NOB), and methanotrophic bacteria (MB) can have significant bearing on emission of CH_4 and N_2O. As such, these organisms could play important roles in determining the carbon footprint of algal composting. Fukumoto et al. (2006) added NOB to a pig manure composting process and found total N_2O–N loss was strongly reduced compared to control trials without NOB supplementation, and that the ratio of AOB/NOB was also positively correlated with the amount of N_2O emission. NOB were added after the thermophilic phase of the composting process to avoid adverse effect of high temperature on the organisms (Jakel et al., 2005).

6. Conclusion and future perspectives

Uncontrolled growth of algae in natural and engineered water environments leads to the generation of large quantities of biomass that must be both harvested and managed or it will accumulate as piles of unsightly and often odorous decaying material. Composting is a simple and practical method to manage the waste algae biomass removed from such environments, and it is likely for this purpose that algae composting will most widely be applied into the future, with the compost product being suitable as a fertiliser. It is expected that low cost windrow based technologies will be generally used as the irregularity and often remote location of bloom events will prohibit the installation of well vented aerated static piles. That said, there is reason to suspect that the performance of some windrow systems will be poor, due to insufficient aeration if bulking agents are properly used, particularly for low porosity microalgal sludges; the few reports to date on large scale algal composting refer to well managed systems. There is the risk that poorly managed systems end up as piles of unsightly and odorous decaying material – the very outcome which composting is employed to avoid.

Algal biomass usually has a low C/N ratio and high moisture content. The effects of such peculiarities on the composting of this feedstock have been addressed by some researchers. The emission of N_2O is a potential issue in algal composting, as compared to normal organic wastes, because of the low C/N and AFP typically associated with algae; algae biomass has consequently been mixed with other organic wastes to render a blend more suitable for composting. All aerobic stabilisation technologies have substantial carbon footprint, which is exacerbated when CO_2 emission is accompanied by N_2O emission. But anaerobic alternatives are likely not feasible due to irregular and often remote production of algae waste.

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