



Generation of highly potent organic fertilizer from pernicious aquatic weed *Salvinia molesta*

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Abstract

Utilization of *Salvinia molesta*, an aquatic weed which is notorious for its allelopathy and invasiveness, has been explored by its vermicomposting. Fourier transform infrared spectroscopy (FT-IR) and plant bioassay tests were conducted to analyze the composition and fertilizer value of *S. molesta* vermicompost. Germination and seedling growth tests were performed in soil supplemented with vermicompost at levels ranging from 0.75 to 40% by weight of the soil on three common food plants, ladies finger (*Abelmoschus esculentus*), cucumber (*Cucumis sativus*), and green gram (*Vigna radiata*). The influence of *S. molesta*'s vermicompost on some of the physicochemical and biological attributes of the soil was also studied. FT-IR analysis revealed that *S. molesta* loses its allelopathy, as the chemical compounds that are responsible for it are largely destroyed, in the course of its vermicomposting. There is also an indication that a portion of lignin content of *S. molesta* is degraded. Vermicompost enhanced the germination success and promoted the morphological growth and biochemical content of the plant species studied. It also bestowed plant friendly physicochemical and biological attributes to the soil. The findings raise the prospect that billions of tons of *S. molesta* biomass—which not only goes to waste at present but is also a cause of serious harm to the environment—may become utilizable in organic agriculture.

Keywords *Salvinia molesta* · Allelopathy · Organic fertilizer · Vermicomposting · Plant growth

Introduction

Giant salvinia (*Salvinia molesta*) is an aquatic fern native to southeastern Brazil and northern Argentina (Abbasi and Nipanay 1986, 1993). In its native habitat, it has been existing in competition with other species of plants and performing its share of ecosystem services in the manner normal of other species. During the latter half of the previous century, it was taken out of its native habitat to various other regions as an aquarium plant. There, partly due to the absence of natural enemies and partly due to the attributes of ease of reproduction, high rate of growth, and hardiness, *S. molesta* became an invasive species. The rapid anthropogenic deterioration of the wetlands that began occurring from 1950s onwards, and

which made it difficult for sensitive and delicate species of aquatic plants to survive, gave an opportunity for hardy species like *S. molesta* to aggressively invade new habitats and colonize them. *S. molesta* has proved to be a particularly dominant plant and has colonized wetlands of several regions to the exclusion of all but a very few other plant species.

S. molesta is capable of multiplying and growing faster than most other known botanical species (Mitchell and Tur 1975; Abbasi and Nipanay 1986; Room et al. 1981). It reproduces vegetatively; a tiny bit of *S. molesta* leaf can lead to daughter plants which then multiply so rapidly that a bank-to-bank coverage of a water body by the weed can occur in a matter of a few weeks (Mitchell and Tur 1975). Harley and Mitchell (1981) have recorded that at Lake Moondarra, Australia, *S. molesta* leaves doubled within 2.2 to 2.7 days in summer. Similarly rapid biomass doubling time was recorded at Lake Kariba, Zimbabwe, by Mitchell and Tur (1975). After spreading horizontally, *S. molesta* mats thicken vertically as the internodes become shorter and leaves longer. With it, the leaves are pushed upward and can get packed into mats up to 1 m thick (Bhat 2016). This enables *S. molesta* to attain biomass productivity of the order of 60 dry (ash free) tons per hectare

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per year (Abbasi and Nipanay 1993). This level of primary production puts *S. molesta* at par with water hyacinth—known to be the most productive of all plants (Abbasi and Nipanay 1993; Crites et al. 2006).

A typical *S. molesta* invasion of a water body soon leads to the coverage of its entire water surface, elbowing out most other free floating aquatic plants and cutting the sunlight off from the neuston and the benthos. This restricts the photosynthetic and aerial replenishment of oxygen in the water lying beneath the *S. molesta* carpet, seriously harming the water's chemical and biological quality. In turn, this devastates the biodiversity of the invaded wetland by letting none but a few very hardy species survive. Water quality beneath the mats is quickly degraded by decreases in dissolved oxygen and pH and increases in CO₂ and H₂S concentrations, as the weed's debris decays aerobically or anaerobically (Mitchell 1969). This has a cascading impact: low pH and DO help in the dissolution of metals from the underlying sediments into water (Abbasi and Abbasi 2011; Li et al. 2013). This, in turn, toxifies sensitive organisms.

As the plants die, their debris accumulates at the bottom and threatens the fisheries by creating a shallow-water environment that restricts fish breeding (Sculthorpe 1985). The decomposition of the organic matter further diminishes dissolved oxygen levels needed to support healthy populations of fish and other biota (Hattingh 1961; Coates 1982; Oliver 1993). The matters are made worse by the propensity of *S. molesta* mats to serve as breeding grounds for vectors of human diseases, notably encephalitis, dengue, and malaria (Oliver 1993); elephantiasis (Room et al. 1989); and schistosomiasis (Bennett 1975).

In the large number of wetlands now colonized by *S. molesta* across the tropical and sub-tropical world (Abbasi and Nipanay 1993; Bhat 2016), billions of tons of *S. molesta* biomass is generated every year. Since no means exist to utilize any significant portion of this biomass (Abbasi and Abbasi 2010; Ganeshkumar et al. 2014), it remains unharvested, leading to accelerated deterioration of the wetlands colonized by *S. molesta* (Abbasi and Nipanay 1986; Abbasi 1997). When *S. molesta* plants die, they decay aerobically and anaerobically—mostly latter—generating global warming gases carbon dioxide and methane (Abbasi et al. 2011a). As most of the degradation of dead plants occurs anaerobically in the anoxic epilimnion of the wetlands, it becomes a major contributor of methane emissions. Given that methane has, molecule to molecule, 34 times greater global warming potential than carbon dioxide (Shindell et al. 2009), the harm caused by *S. molesta* decay is immense.

There have been instances wherein rapidly growing spreads of *S. molesta* have been halted and repelled by the use of biological agents (Room et al. 1981), but such successes have been few and far between. Chemical and mechanical methods have seen even lesser success in controlling *S. molesta*. Attempts to find ways to utilize the weed have not been successful either, and no economically viable process has resulted from the

efforts to use *S. molesta* as compost, green manure or mulch (Raju and Gangwar 2004; Arthur et al. 2007; Dorahy et al. 2009), as fodder (King et al. 2004; Leterme et al. 2010), as a source of biogas (Abbasi and Nipanay 1984, 1985, 1991; Abbasi et al. 1990, 1992a, b; Ganesh et al. 2005; Tauseef et al. 2013a), or of drugs (Chantiratikul et al. 2009; Choudhary et al. 2008; Li et al. 2013a).

Recently, we have developed a process (Ganeshkumar et al. 2014) with which *S. molesta* can be directly and rapidly converted to vermicompost. The process is based on the concept of high-rate vermicomposting and associated technology developed by the authors (Abbasi et al. 2009, 2011b, 2015; Tauseef et al. 2013b, 2014) and is two to three times faster than the conventional vermicomposting. Nor does it require pre-composting or supplementation of animal manure which is essential if phytomass is to be vermicomposted by conventional technology (Abbasi et al. 2015). These attributes make the process potentially economical and open up the possibility of utilizing the enormous quantities of *S. molesta* that are generated across the world every year as a source of organic fertilizer.

But before any initiative is taken for large-scale vermicomposting of *S. molesta*, it needs to be established whether *S. molesta* vermicompost is as much, or close to as much, soil friendly and plant friendly as manure-based vermicompost is reported to be (Edwards et al. 2011). This question is particularly relevant given the following three factors:

- i) Exceptionally high polyphenol concentrations in *S. molesta* (0.4–0.7% by mass) in contrast to most other plants that carry less than 0.1% of polyphenols (Chantiratikul et al. 2009). Given that >0.1% polyphenol concentration in a plant makes it allelopathic (Rizvi and Rizvi 1992), it becomes very important to check whether the polyphenols, hence the allelopathy, is retained in the vermicompost.
- ii) Exceptionally high lignin content of *S. molesta* leaves—13.7% by mass (Moozhiyil and Pallauf 1986; Leterme et al. 2010)—as against $4 \pm 1.5\%$ possessed by most other aquatic plants (Fileto-Perez et al. 2013) and $8 \pm 3\%$ possessed by most other terrestrial plants (Kumar et al. 2009; Kwabiah et al. 2011). This raises the prospect of the vermicompost being also high in lignin and not ideal for the soil.
- iii) The ability of *S. molesta* to propagate vegetatively (Mitchell 1974). This makes it necessary to check whether the vermicast of *S. molesta*-fed earthworms carry pieces of undigested *S. molesta* and entail the risk of its infestation through agricultural run-off in regions which are otherwise free from *S. molesta*.

In summary, (a) huge quantities of *S. molesta* biomass are generated in nature which not only go to waste at present but cause serious environmental damage; (b) none of the past

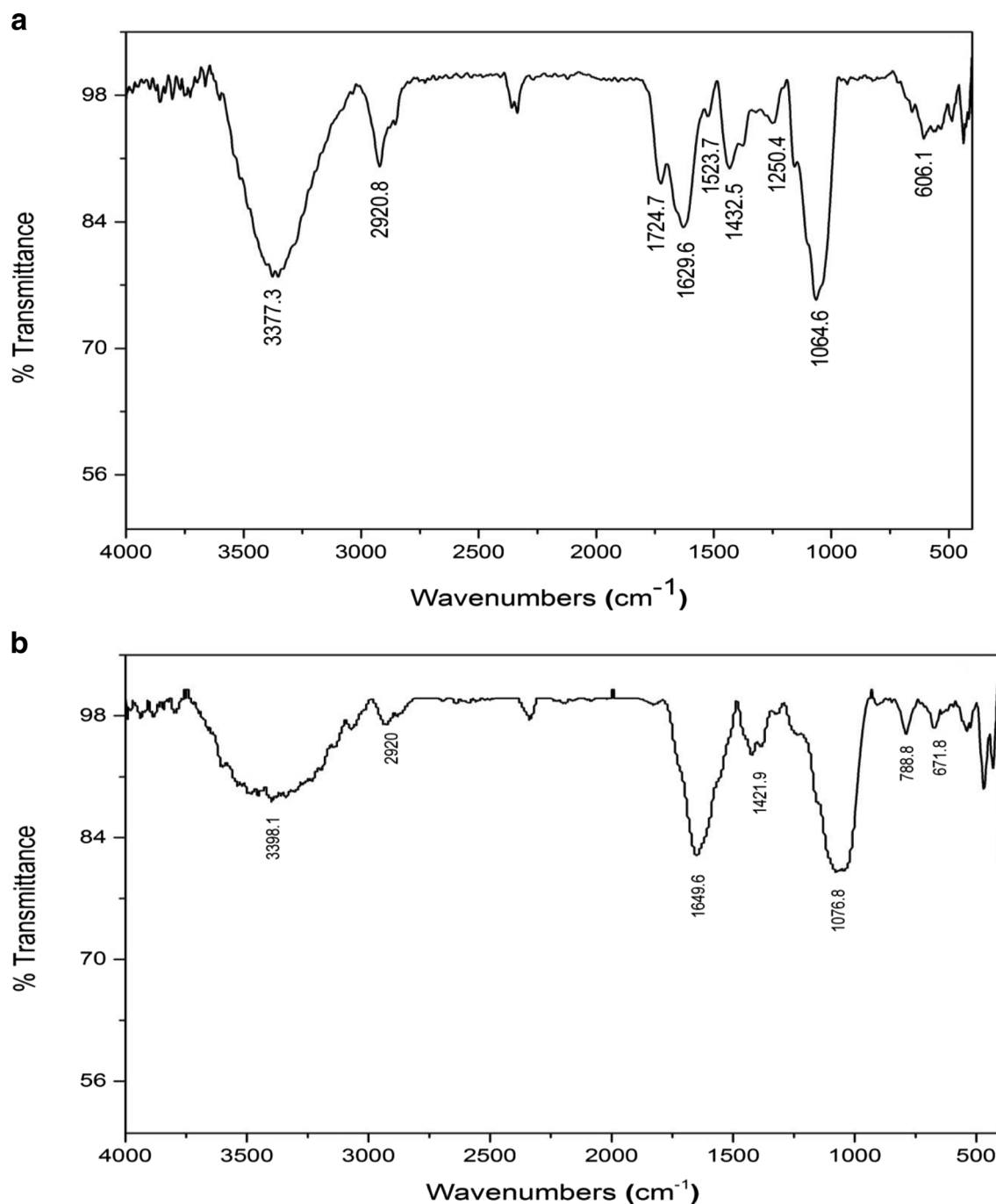


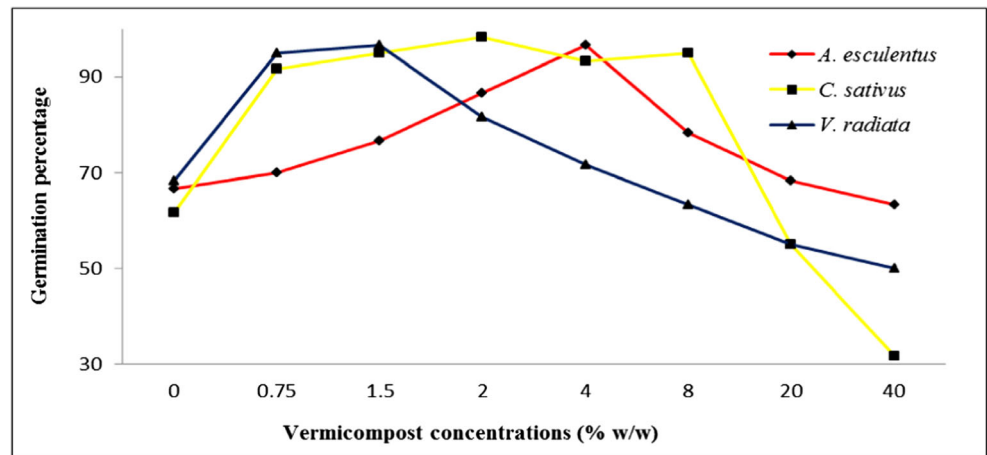
Fig. 1 Fourier transform infrared (FT-IR) spectra obtained from **a** *S. molesta* leaves and **b** vermicompost derived from *S. molesta*

attempts to utilize *S. molesta* have been economically viable; and (c) the “high-rate vermicomposting” process, which enables direct and rapid vermicomposting of *S. molesta*, has the promise to solve the *S. molesta* problem if it can be shown that the vermicompost of the weed is as plant-friendly and benign an organic fertilizer as the vermicomposts of animal manure are known to be.

In order to seek answers to the crucial question about the benignness and the plant-friendliness of *S. molesta* vermicompost, we have characterized the changes in

S. molesta vermicompost relative to the fresh weed by Fourier transform infrared spectrophotometry (FT-IR). On finding that the chemical compounds that are implicated in the allelopathy of *S. molesta* are largely eliminated in the process of the weed’s vermicomposting, we have studied the fertilizer value of its vermicompost. For it the effect of the *S. molesta* vermicompost has been assessed on the germination and the early seedling growth of three food plants: ladies finger (*Abelmoschus esculentus*), cucumber (*Cucumis sativus*), and green gram (*Vigna radiata*).

Fig. 2 Germination success of seeds as a function of the concentration of *S. molesta* vermicompost



Experimental

General

Healthy, adult, whole plants of *S. molesta*, of average tip-to-toe length 30 ± 5 cm, were collected from the ponds situated in the vicinity of Pondicherry University campus. *S. molesta* does not have true roots. When its leaves, which reproduce vegetatively, begin maturing, a fond develops in them under water

that is brown and highly divided. It has a fibrous ambience and it grows into a root-like structure which attains lengths equal to or greater than the above-water-level part of *S. molesta*.

The harvested plants, after the water adhering to them had been drained off, were utilized for vermicomposting without any pre-composting, animal manure supplementation, or any other kind of pretreatment. The vermicomposting was carried out using earthworm species *Eisenia fetida* in rectangular aluminum reactors of $2.5 \text{ m} \times 1 \text{ m}$ surface area and 0.25 m height

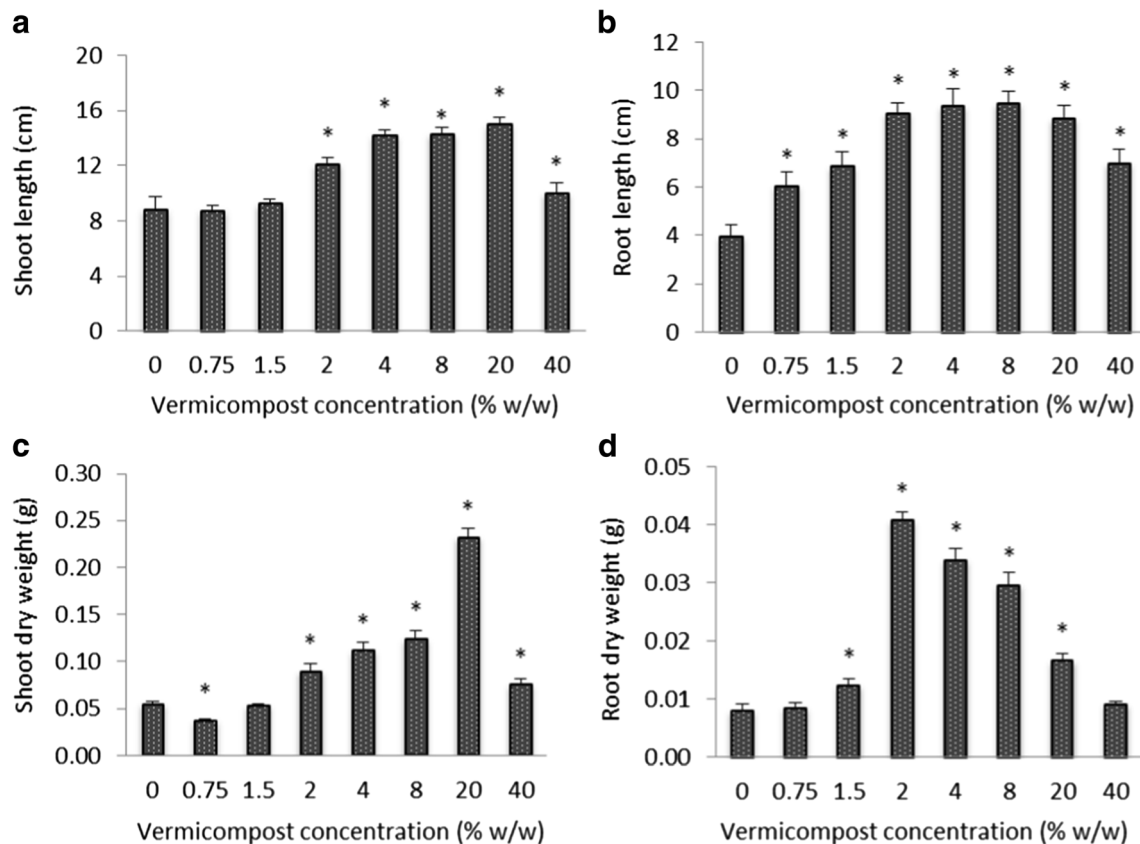


Fig. 3 Growth of *A. esculentus* as impacted with different doses of *S. molesta* vermicompost: **a** shoot length, **b** root length, **c** shoot dry weight, and **d** root dry weight. The results which differ from controls with a confidence level $\geq 95\%$ are marked by asterisk

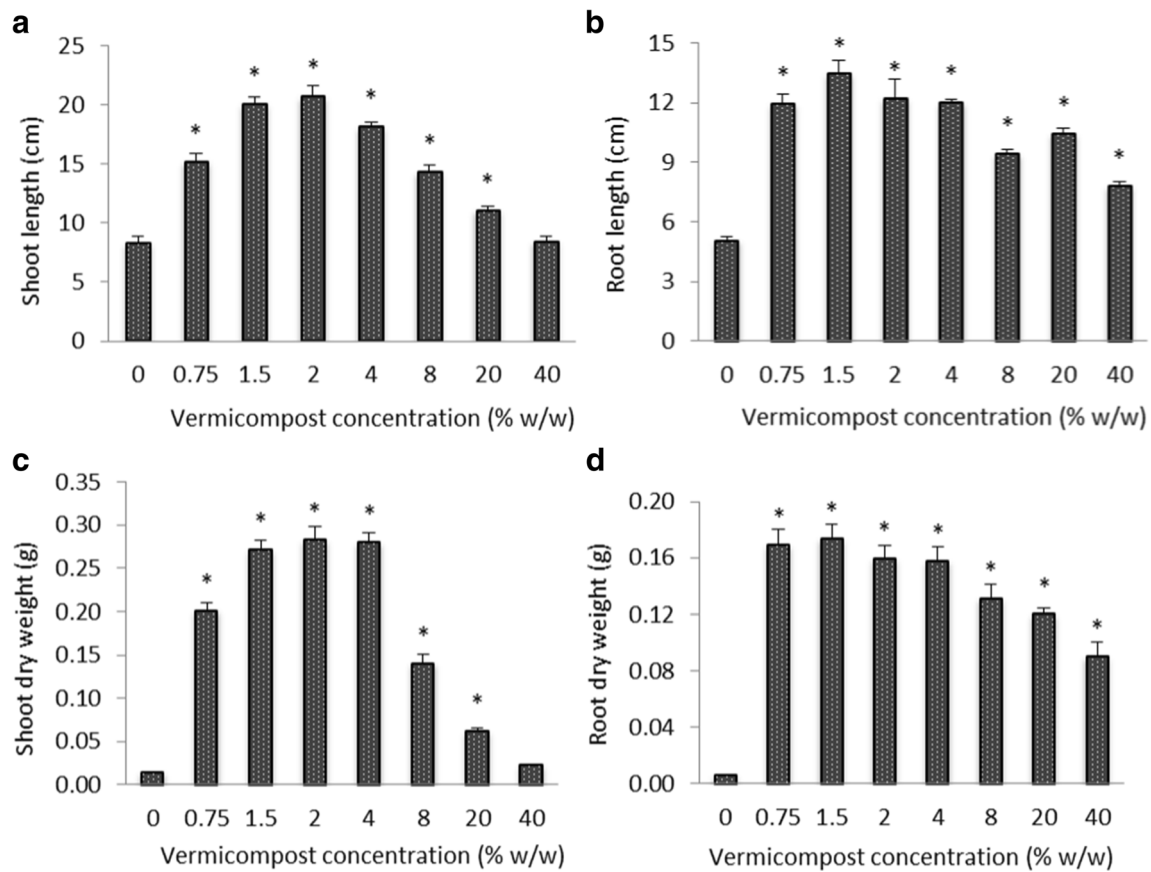


Fig. 4 Growth of *C. sativus* as impacted with different doses of *S. molesta* vermicompost: **a** shoot length; **b** root length; **c** shoot dry weight, and **d** root dry weight. The results which differ from controls with a confidence level $\geq 95\%$ are marked by asterisk

in a manner detailed earlier by us (Ganeshkumar et al. 2014). It was a semi-continuous, pulse-fed reactor operation as per the “high-rate vermicomposting paradigm” developed earlier by S. A. Abbasi and coworkers (Abbasi et al. 2015). As per its rationale, the granular, well-formed vermicast, which is generated in the *S. molesta*-fed reactors, was quantified as vermicompost. Whereas the average C:N ratio of fresh *S. molesta* was 42.8 ± 1.1 ; that of the vermicompost was only 14.4 ± 4 indicating that extensive mineralization had occurred in the course of conversion of *S. molesta* into its vermicompost.

Fourier transform infrared spectroscopic analysis

The FT-IR spectra of *S. molesta* and its vermicompost were obtained at the wavelength range of $4000\text{--}400\text{ cm}^{-1}$ at a frequency of 0.5 cm/s , using a Nicolet iS50 FT-IR spectrometer furnished with appropriate software. This was used for investigating the changes in the surface functional groups of the *S. molesta* vermicompost in comparison to its biomass (Ravindran et al. 2013). Samples were finely grounded and mixed separately with spectroscopic grade KBr in the proportion of 1:100 (sample: KBr). The mixture was then homogenized thoroughly in an agate mortar and pelletized at a

pressure of about 1 MPa. Their spectra were subjected to baseline correction and the bands were studied to quantify the changes that occur in *S. molesta* after it gets vermicomposted.

Plant bioassay

Soil which has not been subjected to any fertilizer application in the past was obtained from the Horticulture Wing of Pondicherry University. It was placed in $36 \times 42\text{ cm}$ enameled metallic trays up to 10 cm high and amended with 0 (control), 0.75, 1.5, 2, 4, 8, 20, and 40% (by weight) *S. molesta* vermicompost. These concentrations were chosen to achieve a fair representation of very low, medium, and high levels of the VC application. For each of the treatment, the trays were prepared in triplicate and in each tray randomly picked 60 seeds of *V. radiata* (Fabaceae) were sown. Similar experiments were set separately for *A. esculentus* (Malvaceae) and *C. sativus* (Cucurbitaceae). All trays were placed in identical ambient conditions of temperature ($32 \pm 3\text{ }^{\circ}\text{C}$ during the day and $27 \pm 2\text{ }^{\circ}\text{C}$ during the night) and relative humidity ($55 \pm 15\%$). In the region where authors work, and indeed in most of the developing world, nearly all the food crops are grown, from sowing to harvesting in the open, with very little use of

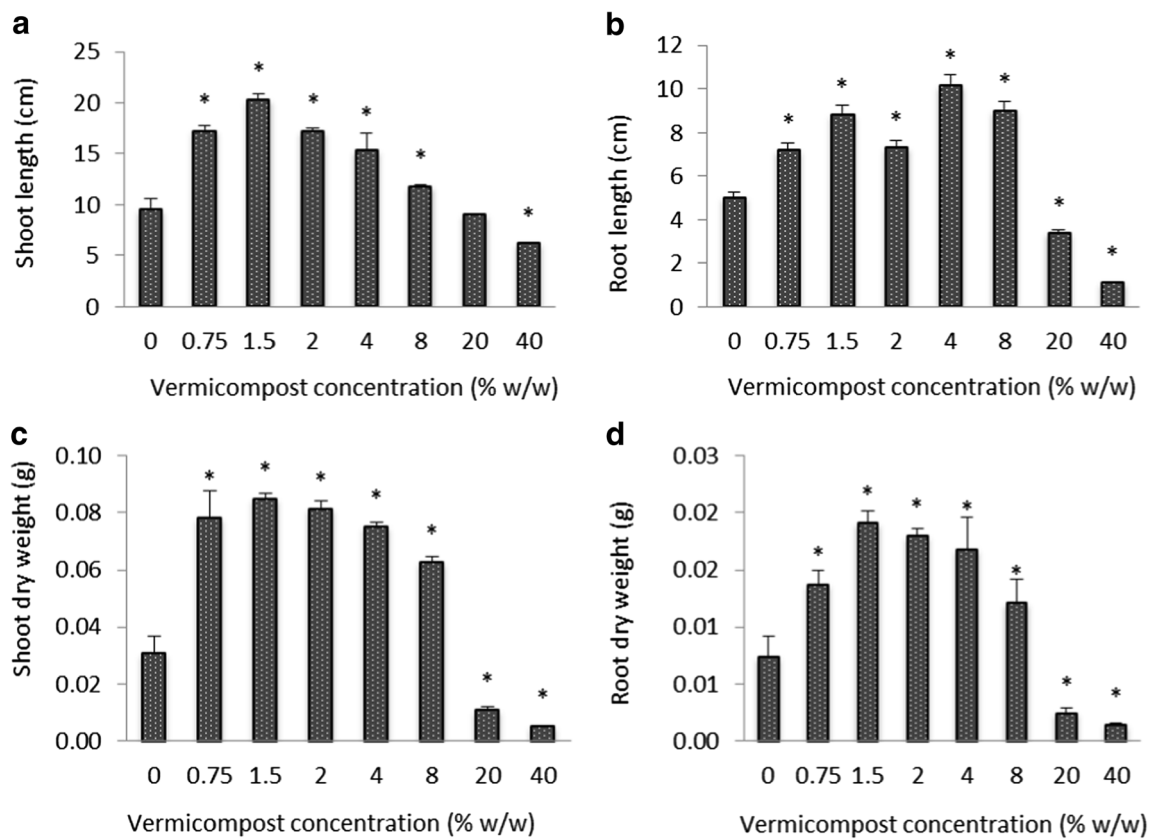


Fig. 5 Growth of *V. radiata* as impacted with different doses of *S. molesta* vermicompost: **a** shoot length, **b** root length, **c** shoot dry weight, and **d** root dry weight. The results which differ from controls with a confidence level $\geq 95\%$ are marked by asterisk

greenhouse. Hence, to be as close to field conditions as possible, we did not use any greenhouse or incubator. They were adequately watered and the seeds were considered germinated when they exhibited radial extension of > 3 mm. Subsequently, the seedlings were exposed to sunlight for 9–10 h per day throughout the monitoring of early growth lasting 3 weeks. The plants were then sacrificed and their shoot length, root length, shoot fresh weight, and root fresh weight were determined. Samples of the pre-weighed plant material were also oven dried at 105°C to a constant weight, to obtain their dry weight. The estimation of chlorophyll, carotene, and tissue nitrogen was done by standard methods (AOAC 2012), employing an Elico SL 164 UV-VIS spectrophotometer, and have been reported on dry weight basis.

Soil analysis

After the plants had been removed, the samples of the soil (with or without vermicompost augmentation) were collected from each tray by a glass cylinder of known dimensions. After the volume of the samples had been measured, the samples were oven dried at 105°C to constant weight. Their bulk density, particle density, and total porosity were then determined by the methods reported by Carter and Gregorich (2006).

To measure the water-holding capacity of the soil, cylinders with perforated bases were filled with samples. Each cylinder was gently tapped to provide homogeneous spreading, capped, and immersed in water in a manner that the water level was lower than the sample surface. After the samples had got moistened up to the surface, the cylinders were taken out of the water. The excess water was drained off and the cylinders were weighed. They were then oven dried at 105°C and weighed again. The difference in the two weighings gave the measure of the water-holding capacity of the soil in each cylinder (Margesin and Schinner 2005).

Inorganic nitrogen in the form of NH_4^+ and NO_3^- was determined following the modified indophenol blue method and Devarda alloy method, respectively (Bashour and Sayegh 2007; Jones 2001). The microbial biomass carbon, which also indicates the microbial abundance in the soil, was measured using the chloroform fumigation method as detailed by Margesin and Schinner (2005). To minimize the probability of matrix effects influencing the accuracy of the analytical methods, calibration curves were drawn by standard addition (AOAC 2012). Precision was achieved by repeating all analysis till results agreeing to within a relative error of $\pm 2\%$ were obtained.

The data was statistically analyzed by multivariate analysis of variance (MANOVA), and least significant difference

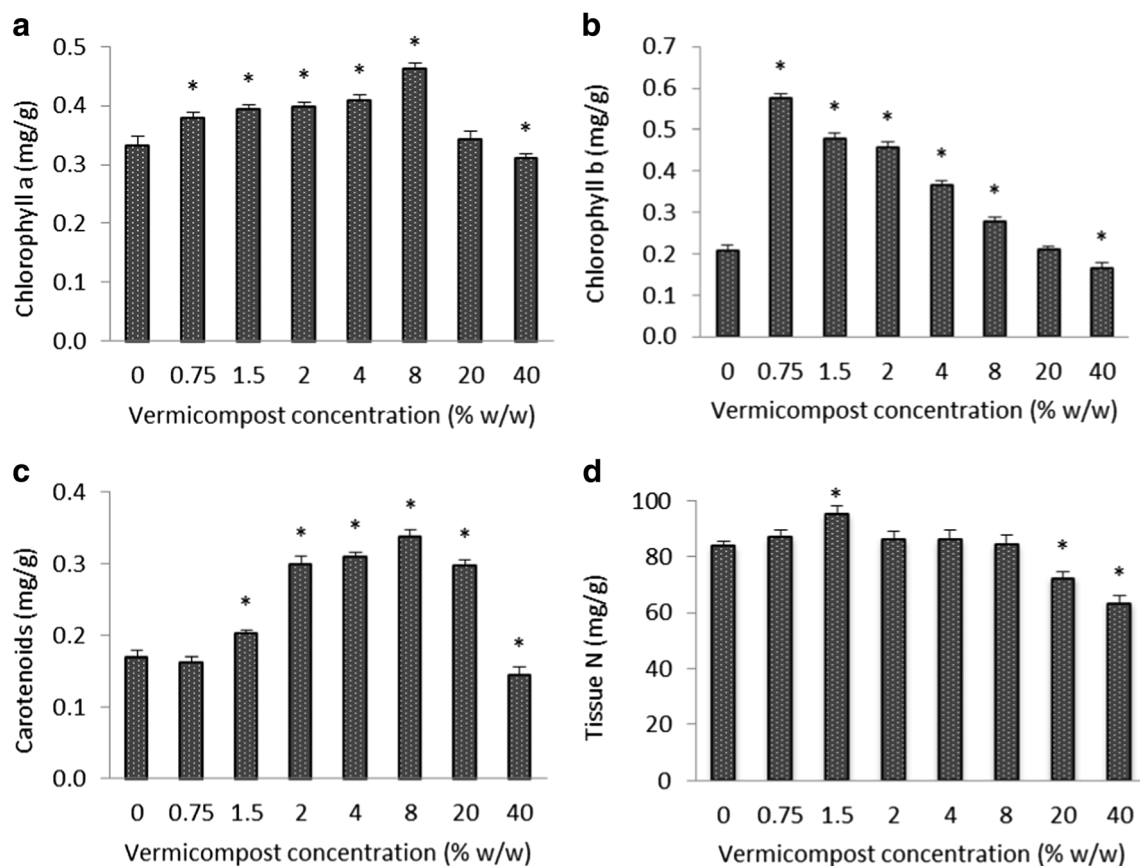


Fig. 6 Effect of *S. molesta* vermicompost on **a** chlorophyll “a”; **b** chlorophyll “b”; **c** carotenoids, and **d** tissue N content of *V. radiata* plants. The results which differ from controls with a confidence level $\geq 95\%$ are marked by asterisk

(LSD), to assess the impact of varied concentration of vermicompost on different variables (Clewer and Scarisbrick, 2001; Field 2009).

Results and discussion

The FT-IR analysis

Fourier transform infrared (FT-IR) spectra of *S. molesta* and its vermicompost are reproduced in Fig. 1. The spectra of *S. molesta* has a strong band at 3377 cm^{-1} which is attributable to the O–H stretching frequencies of phenols, alcohols, and alkaloids (Jouraiphy et al. 2005; Smidt and Meissl 2007; Ravindran et al. 2013; Hussain et al. 2015). There is another peak at 2920 cm^{-1} which corresponds to aliphatic C–H stretching vibrations of lipids and fatty acids and yet another at 1724 cm^{-1} which might have been caused by the C=O stretching vibration of lignin (Derkacheva and Sukhov 2008; Bykov 2008; Xu et al. 2012; Teh et al. 2014; Hussain et al. 2016).

The next prominent peak is at 1629 cm^{-1} caused by aromatic C=C vibrations (Mochochoko et al. 2013). Further down a peak at 1523 cm^{-1} is seen, which might have been caused by the aromatic skeletal vibrations of the

lignocellulosic content in the *S. molesta* (Smidt and Meissl 2007; Hussain et al. 2015). This was followed by peaks at 1432 and 1250 cm^{-1} , due to the stretching vibrations of guaiacyl rings and C–O stretching vibrations of lignin, respectively (Boeriu et al. 2004; Bykov 2008; Klein et al. 2010; Hu et al. 2014). The last prominent peak is at 1064 cm^{-1} attributable to C–O stretch of polysaccharides, cellulose, and hemicellulose (Ravindran et al. 2013; El Ouagoudi et al. 2014).

In comparison, the FT-IR spectra of vermicompost shows a pronounced flattening of the 3398 cm^{-1} peak indicating that a drastic reduction in the phenolic content has occurred in the course of the conversion of *S. molesta* to vermicompost. The peak at 2920 cm^{-1} is also much shallower. While the 1724 and 1523 cm^{-1} peaks are absent, the other peaks attributable to lignocelluloses and lignin—at 1432 and 1250 cm^{-1} —are much shallower. Evidently vermicomposting has caused degradation of lignocellulose, lignin, and carbohydrates contained in *S. molesta*.

Further down a sharp peak at 1421 cm^{-1} has also emerged, which is attributable to stretching vibration of CH–CH₂–, and CH₃ radicals in aliphatic structures (Ravindran et al. 2013). A new peak is seen at around 1380 cm^{-1} due to N–O stretching frequencies (Kumar et al. 2013) and at 788 cm^{-1} due to the N–H out-of-plane

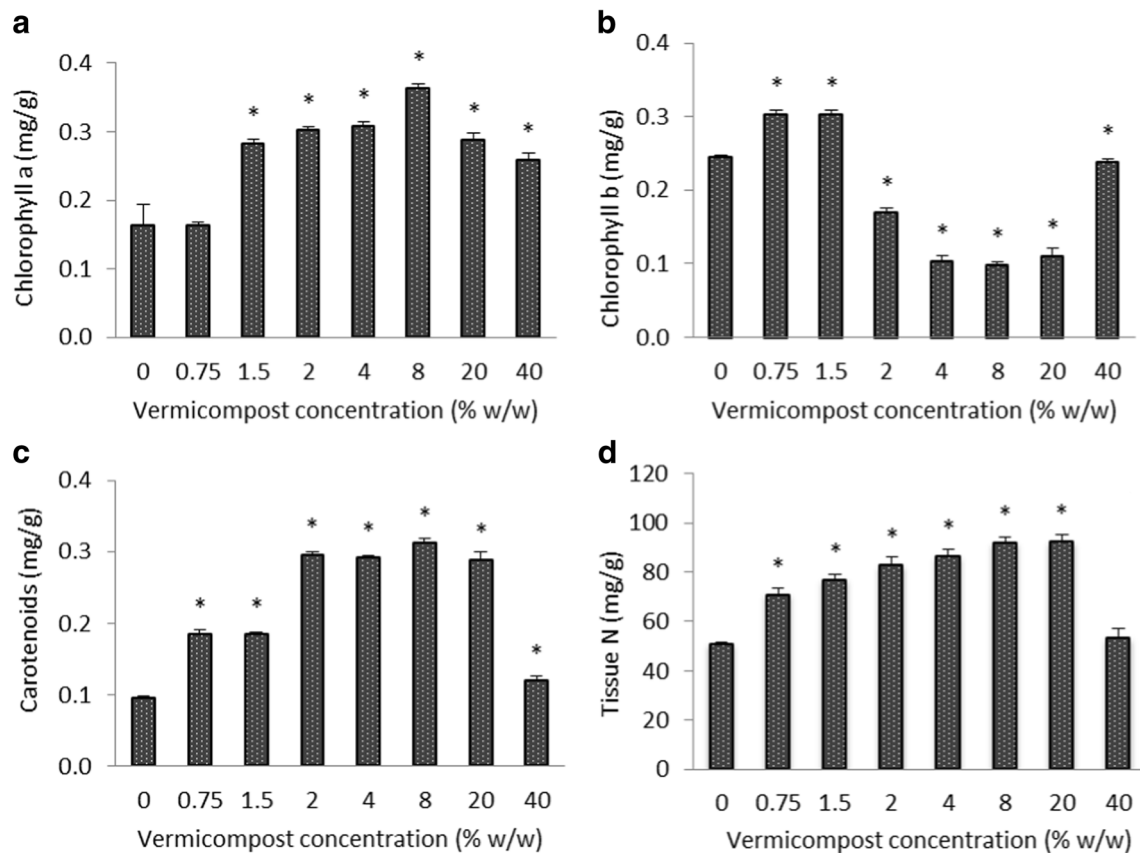


Fig. 7 Effect of *S. molesta* vermicompost on **a** chlorophyll “a”; **b** chlorophyll “b”; **c** carotenoids; and **d** tissue N content of *A. esculentus* plants. The results which differ from controls with a confidence level $\geq 95\%$ are marked by asterisk

bend of primary amine group (Pavia et al. 2001). The emergence of these peaks indicates that a rise in the concentration of nitrogenous compounds has occurred during the course of vermicomposting.

Effect of *S. molesta*'s vermicompost on seed germination

The findings are summarized in Fig. 2. The use of *S. molesta* vermicompost (VC) led to greater success in seed germination than control when used in the concentration range 0.75–20% in *A. esculentus*, 0.75–8% in *C. sativus*, and 0.75–4% in *V. radiata*. A 98% germination success occurred in *C. sativus* at 2% treatments. In *V. radiata* and *A. esculentus*, the highest germination success, 97%, was in soils treated with 1.5 and 4% vermicompost, respectively. At vermicompost concentrations above 4% in *V. radiata*, 8% in *C. sativus*, and 20% in *A. esculentus*, germination was inhibited compared to controls. This duality in the behavior of vermicompost, whereby it supports germination up to certain concentrations and then suppresses it, has been documented before with several plant species including *Solanum lycopersicum* and *Capsicum sp.* (Wilson and Carlile 1989), *Raphanus sativus* (Buckerfield et al. 1999; Atiyeh et al.

2000; Zaller 2007), *Medicago sativa* (Zhang et al. 2009), *Phaseolus vulgaris* (Rodriguez-Quiroz et al. 2011; Gutiérrez-Miceli et al. 2012), *Brassica oleracea* (Ievinish 2011), and *Arachis hypogaea* (Mathivanan et al. 2012). The possible reasons are as follows:

- Vermicompost is known to contain diverse biochemicals including phenols, hydroxyquinoline, alcohols, acetone, and ethyl ether (Arancon et al. 2003, 2008; Ievinish 2011; Martinez-Balmori et al. 2013). These chemicals have been identified as breakers of seed dormancy, thereby enhancing germination success (Jones and Stoddert 1977).
- Increased germination success in soils fortified with *S. molesta* VC might also have been due to the involvement of NH_4^+ and NO_3^- in the germination process. Both NH_4^+ and NO_3^- are known for breaking the seed dormancy, thereby stimulating germination (Bewley and Black 1982; Hilhorst and Karssen 2000; Bradford and Nonogaki 2006).
- All the chemicals which are known to break the seed dormancy up to certain concentrations inhibit it when provided above a threshold level (Reigosa et al. 1999; Atiyeh et al. 2002; Guitierrez-Miceli et al. 2012; Hussain et al. 2015).

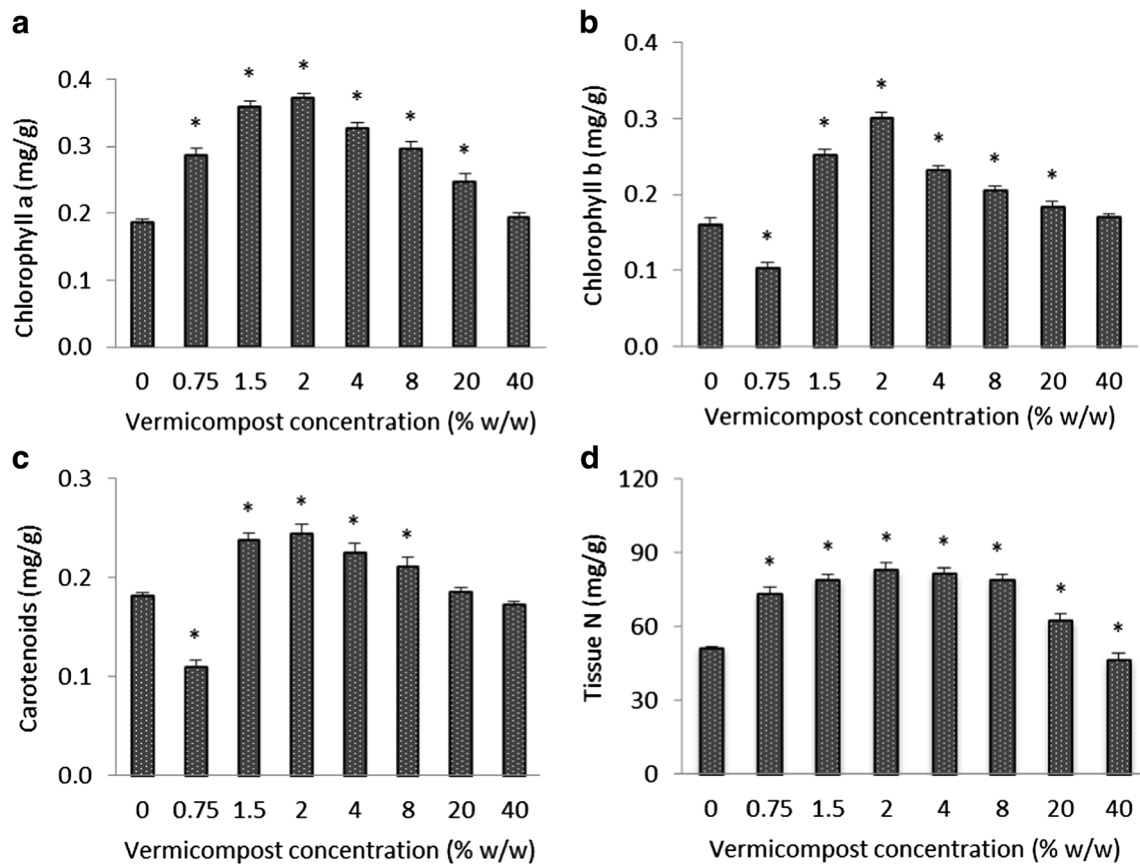


Fig. 8 Effect of *S. molesta* vermicompost on **a** chlorophyll “a”; **b** chlorophyll “b”; **c** carotenoids; and **d** tissue N content of *C. sativus* plants. The results which differ from controls with a confidence level $\geq 95\%$ are marked by asterisk

The novelty and utility value of the present study arises from the findings that *S. molesta* vermicompost does not manifest any of the hostility towards inhibition in the germination and growth of other plant species that *S. molesta* does.

Effect of *S. molesta*'s vermicompost on morphological and biochemical aspects

In the case of *A. esculentus* (Fig. 3) and *C. sativus* (Fig. 4), VC treatments at all the attempted levels stimulated the plant growth, compared to the controls. The highest growth in terms of shoot length and shoot dry weight in *A. esculentus* was recorded in 20% VC treatment, while the root length and root dry weight were the highest in 8 and 4% treatments, respectively. In case of *C. sativus*, 1.5–2% VC in soil elevated growth better than higher VC levels did.

The maximum growth of *V. radiata* plants from the stand-points of shoot length, shoot dry weight, and root dry weight was witnessed in the soil containing 1.5% VC, and the next best in the soil with 2% VC (Fig. 5a, c, d). The root length was highest in 4% VC (Fig. 5b) and second highest in 8% VC.

Except for the tissue nitrogen concentration in *V. radiata*, the total chlorophyll, chlorophyll-a, chlorophyll-b,

carotenoids, and nitrogen levels of all the experimental plants in the 1.5–20% VC range were higher than that in the control (Figs. 6, 7, and 8). In most cases, the highest values occurred within the 2–8% VC range.

As observed in the case of seed germination, the early growth of the plants is also adversely affected if grown in media supplemented with excess chemical fertilizers (Lammatina and Polacco 2007; Jones 2012). This phenomenon has been witnessed earlier with numerous botanical species as well, which were grown in media fortified with high quantities of vermicompost (Lazcano et al. 2010; Ivenish 2011; Hussain et al. 2015).

All the observations reveal that upon vermicomposting, the *S. molesta* biomass becomes an excellent biofertilizer. Studies reported in “The FT-IR analysis” section corroborate these findings.

Effect of *S. molesta*'s vermicompost on soil

Addition of *S. molesta* vermicompost to the soil cropped with *A. esculentus*, *V. radiata*, and *C. sativus* caused a decrease in the density of the soil with concomitant increase in the soil's porosity and water-holding capacity. The effect was

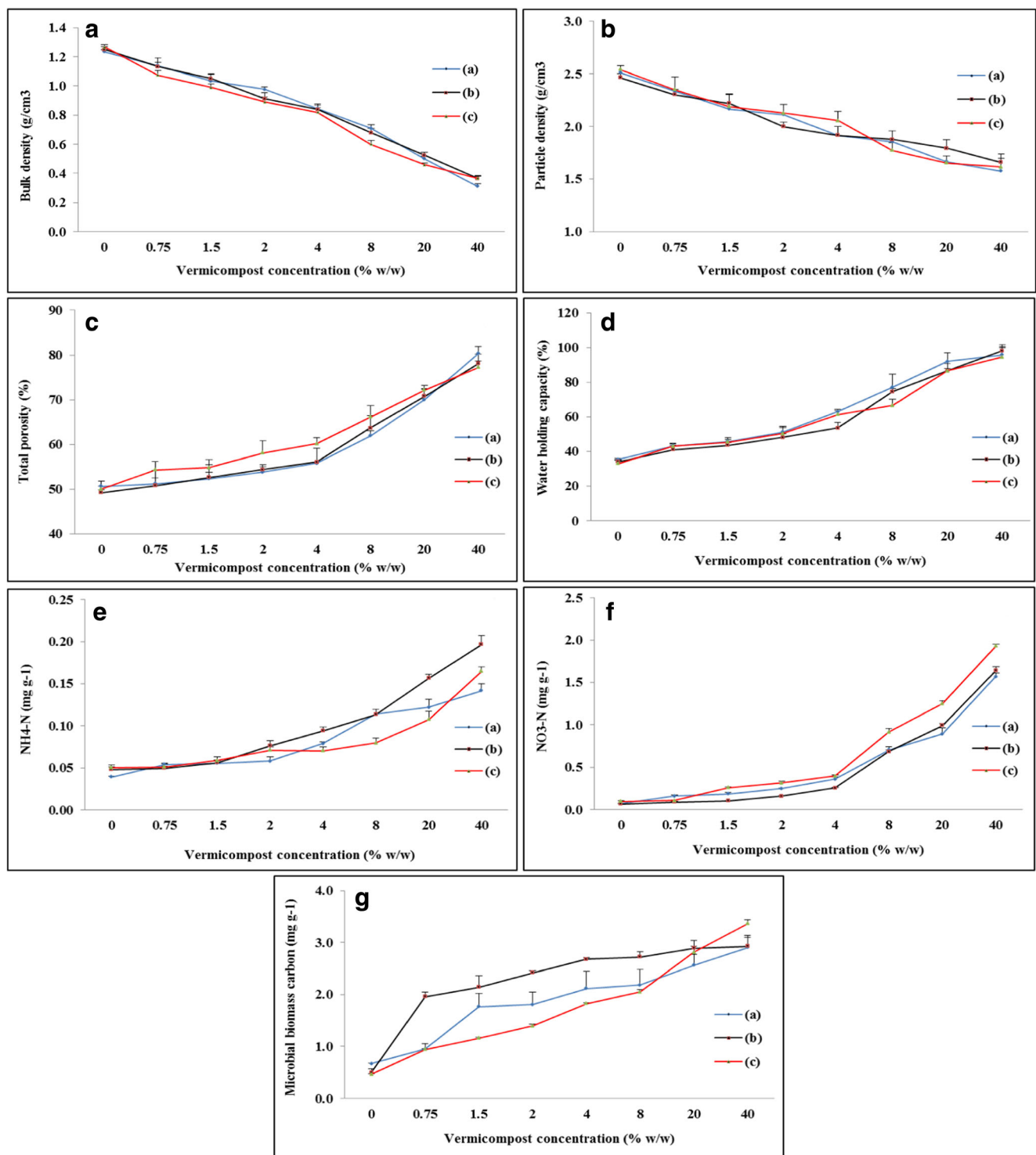


Fig. 9 Impact of *S. molesta* vermicompost on **a** bulk density, **b** particle density, **c** total porosity, **d** water-holding capacity, **e** ammonium concentration, **f** nitrate concentration, and **g** microbial biomass carbon of the soil

cropped with *a* *A. esculentus*, *b* *C. sativus*, and *c* *V. radiata* plants. The standard deviation is indicated on the chart

concentration dependent; the higher the vermicompost concentration applied to the soil, the stronger the effect (Fig. 9a–d). Vermicompost is rich in organic matter, which is apparently the reason why its addition to the soil resulted in an increase in the porosity and water-holding capacity of the soil

with a proportionate decrease in the soil's density (Lazcano and Dominguez 2010; Akhzari et al. 2015; Aksakal et al. 2015; Hussain et al. 2015, 2016). The density of a soil is an indicator of the organic matter content of the soil which influences its fertility. Low bulk density increases the ventilatory

capacity of the soil, leading to efficient growth of roots, eventually enhancing crop productivity.

An increase in the NO_3^- and NH_4^+ concentrations in the soil was observed with the increasing concentration of *S. molesta* vermicompost (Fig. 9e, f). Of these, the proportion of NO_3^- in the soil was significantly higher than that of NH_4^+ . This is evidently due to the higher concentration of the former in the vermicompost (Atiyeh et al. 2001, 2002; Edwards 2004; Dass et al. 2008). In the course of vermicompost formation, earthworms increase the numbers of ammonia-oxidizing bacteria and archaea in the biodegrading substrate, which significantly enhances the nitrification process (Wang et al. 2011; Yang et al. 2014). The dominant bacterial species which have been identified to stimulate nitrification are *Nitrosomonas* sp. and *Nitrosospira* sp. (Wang et al. 2013). It is apparently due to the action of these microorganisms that the nitrate concentration in *S. molesta* is much larger than the ammonium concentration.

With increasing concentration of *S. molesta* vermicompost, a proportionate increase in the microbial biomass carbon in the soil was observed (Fig. 9g). Vermicomposts, being rich in organic matter content, are known to harbor diverse microbial populations in it and their augmentation to the soils may have increased the microorganism populations in the soil (Edwards 2004; Tejada et al. 2010; Xu et al. 2010). This was apparently reflected in the soil fortified with *S. molesta* vermicompost.

Summary and conclusion

Vermicompost, which had been derived solely by the action of the epigeic earthworm *Eisenia fetida* on aquatic weed *Salvinia molesta*, using a recently developed high-rate process, was tested for its chemical composition by FT-IR spectrometry. It revealed that the phenols and other chemicals that are responsible for the negative allelopathic impact of *S. molesta* are largely destroyed in the course of vermicomposting. The lignin content of *S. molesta* is also significantly reduced. To check whether the *S. molesta* vermicompost has acquired plant-friendly and soil-friendly attributes, its effect was assessed on the germination and early growth of three common food plants ladies finger (*Abelmoschus esculentus*), cucumber (*Cucumis sativus*), and green gram (*Vigna radiata*). The vermicompost was seen to significantly enhance germination success, impart plant-friendly physical features to the soil, increase the biomass carbon content of the soil, and promote early growth as reflected in several morphological and biochemical characteristics in plants which had received the *S. molesta* vermicompost in comparison to those which had not. The findings show that *S. molesta* vermicompost possesses most of the soil-friendly and plant-friendly attributes that make it a fertilizer ideal for organic farming. The studies also make it possible that the billions of tons of *S. molesta* phytomass that is generated annually—and which not only

goes to waste but harms the environment—can be gainfully utilized in producing high-quality organic fertilizer via vermicomposting. When it is sought to use *S. molesta* growing in metal-contaminated waters, the metal levels in its VC should be checked for compliance with relevant standards before the VC application. Longer-term studies on the impact of *S. molesta* vermicomposts on various species of food plants are also required.

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