In situ phytomanagement with *Brassica napus* and bio-stabilised municipal solid wastes is a suitable strategy for redevelopment of vacant urban land

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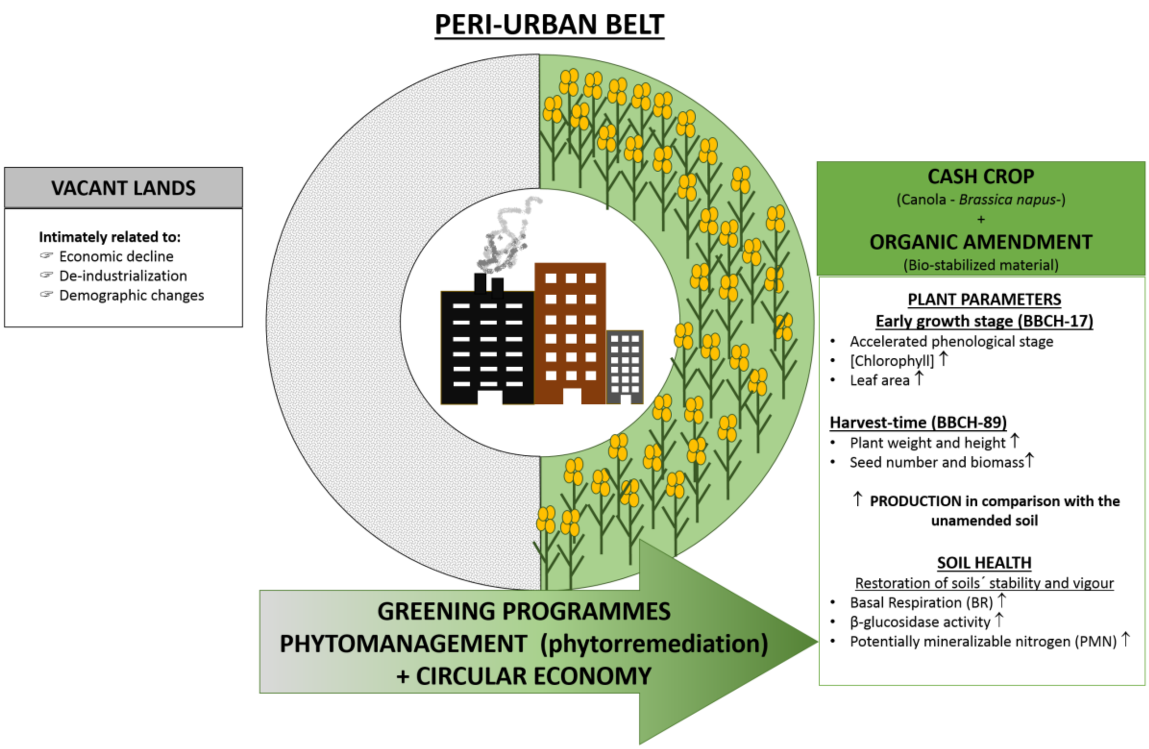
Graphical abstract



Highlights:

- Phytoremediation assisted by bio-stabilised material is an ideal soil-management strategy to increase the agro-economic potential of vacant urban soils in the short term.

- Bio-stabilised material proved to be a beneficial amendment for sustainable plant production, as it increased leaf area of *Brassica napus*.
- Application of bio-stabilised material increased microbial activity of peri-urban soils.
- The lower application rate of bio-stabilised material (50 t ha^{-1}) resulted in notable improvements in plant and soil parameters.
- It is possible to redevelop peri-urban vacant soils within the circular-economy model by using energy crops and properly treated urban solid wastes.

Key words: biofuels, microbial properties, organic amendment, peri-urban soil restoration, soil health

Abbreviations: AWCD: Average well colour development; BR: Basal respiration; BSM: Bio-stabilised material; Fv/Fm: Photochemical efficiency of photosystem II; FW; Fresh weight; MBC: Microbial biomass carbon; MSW: Municipal solid waste; NUS: Number of substrates used; PMN: Potentially mineralizable nitrogen; ROS: Reactive Oxygen species.

Abstract

The decline of industrial manufacturing left large areas of vacant land in the peri-urban belts of many European cities, becoming an economic, social and environmental concern. In the meantime, available fertile soils are being over-used to produce energy crops, and municipal organic wastes are accumulating in landfills, actions that hamper the development of wealth-creating and sustainable societies. Phytomanagement has emerged as a valuable *in-situ* strategy for the management of peri-urban vacant spaces, able to restore their fundamental ecosystem services. The field experiment described here was undertaken to study the potential of bio-stabilised material (BSM) obtained from commingled municipal solid wastes, both for *Brassica napus* (rapeseed) crop production and to improve the health/functioning of peri-urban vacant soil as a first step toward urban greening. Three months before sowing, soils were amended with 0, 50 and 100 t FW BSM ha^{-1}. Data were gathered on the physiology and growth of *B. napus* at the BBCH-16-17 (57 days) and BBCH-89 (260 days) phenological stages. The activity, biomass, and functional diversity of soil microbial communities were measured concomitantly. Overall, the results showed that the BSM-amended soils became more productive and functional than the unamended soils. At the plant level, the leaf area of *B. napus* plants was significantly increased at the BBCH-16-17 stage, which later, at BBCH-89 stage, translated to a higher yield. At the soil level, mainly microbial activities related to C and N turnover increased after BSM amendment. This was key in satisfying the oilseed nutritional requirements under our experimental conditions. This innovative study advocates for a circular economy and shows that the combination of BSM amendment and *B. napus* can be efficacious for the redevelopment of peri-urban vacant soils.

1. Introduction

In recent decades, cities across the globe have witnessed the proliferation of vacant lands around their urban belts. Through their close proximity to the population, these soils are extensively affected by human activities that result in overall soil degradation (Naylo et al., 2018). A host of interwoven factors, including economic globalization and decline, de-industrialization and a concomitant shift towards a service-oriented economy, and contemporary demographic changes such as shrinkage of neighbourhoods and out-migration from rural areas, lie behind the increase of long-term abandoned or unused spaces within city limits, also referred to as peri-urban vacant lands (Németh and Langhorst, 2014). In Central and Eastern Europe (Nilsson et al., 2013) as well in North America (Newman et al., 2016), the management of urban vacant lands has received close policy attention, particularly in post-industrial cities. However, land vacancy in Southern European urban areas still constitutes an under-addressed phenomenon.

"Dead spaces", "derelict landscapes" and/or "wastelands" (as they are frequently used as dumpsites) are common descriptors of urban vacant lands (Newman et al., 2016). Vacant lands symbolise urban disinvestment and decay, and consequently are very vulnerable to being used for marginal activities (Fu et al., 2018). As a result, urban vacant lands are viewed as a serious problem for local authorities and regulatory environmental agencies. Nevertheless, much of these derelict and non-cultivated lands or wastelands should be widely recognised as valuable ecological, social and economic resources (Anderson and Minor, 2017).

If properly managed, urban vacant lands can deliver fundamental ecosystem services with direct economic revenues and social benefits (Capotorti et al., 2019), such as, among others, primary production (provisioning); climate regulation, carbon sequestration and air-pollution removal (regulating); stormwater retention and mitigation of wildlife habitat destruction and biodiversity losses (supporting); and accommodation of different recreational and educational activities (cultural).

In order to improve the quantity, quality and/or resilience of these ecosystem services and circumvent any possible financial obstacle during the reclamation of urban vacant lands, low-cost and sustainable interventions with high rates of return, such as phytomanagement strategies, are required (Gómez-Sagasti et al., 2018). The term "sustainable intervention" is defined here as a spatial, ecological, and socio-economic action that allows balanced management of land resource and formation of essential natural capital, meeting a wide range of local needs, including those linked to food security and green areas increase. Although numerous cities worldwide have prioritised greening programs for urban vacant lands, mainly focused on landscape protection and provision of social amenities (Pallagst et al., 2017), less is known about the *in situ* implementation of gentle options for remediation of urban vacant lands, such as phytoremediation. Phytoremediation is defined as a non-destructive and cost-efficient remediation phytotechnology that uses the capacity of plants and their associated microorganisms to gradually mitigate contamination and restore ecosystem services. The term 'phytoremediation' is traditionally associated with contamination but can be used in those cases where plants are used to restore degraded areas. However, phytoremediation usually is not feasible within an economic time frame (i.e., < 10 years) because of technical concerns. In order to overcome such barriers, recently, phytomanagement has attracted considerable attention as an alternative management strategy. In phytomanagement, profitable crop production and soil amendments are combined to obtain concomitant environmental, economic and long-term social gains (Evangelou et al., 2014). Nonetheless, phytomanagement can be applied as part of an integrated site risk management (Mench et al., 2010; Cundy et al., 2016; Kidd et al., 2015).

The exceedingly rapid depletion of crude oil and natural gas reserves, in conjunction with recent energy policies that promote transport decarbonisation, have led to an escalation in biofuel consumption at the expense of food crops and agricultural and forest lands (Madejón et al., 2019). One of the main controversies surrounding biodiesels has been the diversion of large portions of arable lands to energy production, which has been accompanied by a rise in global food prices and social concerns (Thompson, 2012). This situation undermines the efforts towards sustainability that originally motivated biofuel production (Tomei and Helliwell, 2016).

The competition for soil and water resources between food crops and biofuel crops could be reduced by aligning biofuel production with the phytomanagement of urban vacant lands. Besides, this would avoid social problems such as a shortage of food crops and at the same time, would create new urban green spaces. However, soils of urban vacant lands have usually undergone severe degradation processes (e.g., pollution, compaction of physical structure and imbalance of biological activities via depletion of soil organic matter and biodiversity loss), and consequently are not suitable for safe food production (Carlet et al., 2017). An effective phytomanagement program must comprehensively address the physical, chemical and biological dimensions of soil. Incorporation into soil of organic wastes as amendments is imperative to improve bulk soil density, correct organic-matter content, and restore the quality/health of these urban soils prior to cropping (Lacalle et al., 2018; Gómez-Sagasti et al., 2018).

Currently, municipalities must deal with the massive generation of solid wastes that compromises sustainable urban environmental planning. On account of this reality, European legislation increasingly aims at promoting safe and integrated waste-management strategies, which, in turn, match with the main objectives of the Circular-Economy paradigm (Gómez-Sagasti et al., 2018). Particularly, the bio-stabilised organic fraction/material (BSM) obtained from commingled municipal solid wastes (MSW) originating from a non-separated bin collection system could be a promising soil conditioner, due to its high nutrient content. Unlike the classic composts resulting from source-separated solid wastes, before it is loaded into soils, BSM requires an extra mechanical treatment to reduce the quantity of inert materials (especially plastics and glasses) in order to obtain more-structured material (Boen and Haraldsen, 2011). The valorization of an organic residue such as BSM is inevitably advantageous, as it involves the reduction of residue disposal in landfills as well as the improvement of degraded soils. Consequently, this environmentally friendly action reduces negative impacts on ecosystems and allows reaping economic benefits from residues with potential value that nowadays are mostly discarded.

The main objective of this study pursues the green redevelopment of a peri-urban vacant land, using the biofuel crop *Brassica napus* and BSM as an alternative amendment. This aim encompasses the use of phytoremediation as an effective phytomanagement strategy. Hence, the benefits of this study can have influence at (i) the environmental level, through the increase of soil health in terms of biomass, activity and functional diversity of microbial communities (supporting service); (ii) economic level, through obtaining economic benefits from the BSM revalorization and crop production (provision service);

and (iii) social level, thanks to the increase of green areas that may even benefit human health (Brindley et al., 2019).

2. Materials and methods

2.1. Experimental site

The field experiment was established in a vacant plot of land in the peri-urban belt of Vitoria-Gasteiz (42°50’N; 2°40’W, northern Spain, altitude: 508 m asl). The climate is Mediterranean temperate, with dry summers, cold winters, and mean annual rainfall of 700–800 mm. Prior to any action, the soil surface was cleared by removing some construction and demolition wastes, plastics and other inert residues derived from uncontrolled anthropic activities. The physico-chemical properties of the soil were measured (Table 1). The soil is loam with low topsoil organic-matter (1.0%) and high carbonate (54.7%) contents. In addition to the low contents of some essential plant nutrients (N, P, K, Ca and Mg), the slightly alkaline condition (pH = 8.55) of this peri-urban soil can restrict even more their solubility and phytoavailability (Table 1). The concentrations of potential toxic trace elements in this soil did not exceed the critical reference values for agricultural settings (IHOBE, 1998).

2.2. Organic amendment

The BSM used here was acquired from “BIOCOMPOST de Álava U.T.E.”, a municipal solid-waste treatment plant near the study area. As mentioned above, the BSM was obtained from non-source-separated solid wastes (referred to as commingled MSW). After an extra mechanical separation of inert materials, the BSM was sieved twice (40 and 25 mm) to reduce the content of rocks, gravel and impurities (e.g., metal, plastic and glass). Subsequently, the content of inert heterogeneous materials larger than 2 mm in diameter was reduced to a final concentration of 2.4% (mainly rock fragments, metals, plastics and glass), thus achieving a homogeneous product. Then, the material was stored to allow it to partially compost through spontaneous bio-oxidation processes. The measured chemical composition of the sieved BSM fraction is detailed in Table 1. In order to apply this BSM as a soil amendment, we followed the recommendations of the Spanish legislation for organic fertilisers such as compost, regarding water content, organic-matter content, C:N ratio and metal content.

2.3. Layout of field experiment

In June 2015, the vacant land was divided into nine randomised experimental plots (25 × 25 m) separated by unplanted buffer zones 1 m wide. Three increasing doses of BSM were used: (i) 0 t ha^{-1}, 0BSM; (ii) 50 t ha^{-1} (9017 kg organic C ha^{-1}), 50BSM; and (iii) 100 t ha^{-1} (18034 kg Organic C ha^{-1}), 100BSM. Each treatment had three replicates. The BSM was applied uniformly as a top-dressing, and both the amended and unamended soils were ploughed with a rotary tiller to a depth of 30 cm. Three months later (September 2015), once the BSM was integrated into the soil, *Brassica napus* cv. Expower was sowed at 5.7 kg ha^{-1} in rows spaced 30 cm. Plant and topsoil samples were collected at 57 (November 2015) and 260 days (July 2016) after sowing, for analysis. During the experimental period, the plots were not supplemented with mineral fertilisers.

2.4. Soil physico-chemical characterization

For the determination of soil physico-chemical properties, soil samples were oven-dried at 35 °C for 48 h. Soil pH was determined (1:2.5 w/v soil:water) using 10 g of 2-mm sieved dried soil and 25 mL of deionised water. Physico-chemical parameters, i.e., soil texture, % organic matter, total organic carbon (detection of CO_2 by infrared after oxidation), total nitrogen (Kjeldahl method), and % carbonates were determined following officially recommended methods (MAPA, 1994). The particle sizes (diameter) considered for each soil fraction were: clay (< 0.002 mm), coarse sand (1–0.5 mm), fine sand (0.25–0.1 mm) and silt (0.05–0.002 mm) (Head, 1992). Bulk density was determined using an intact core soil sampler (0–15 cm depth and weighing the soil after drying. For water infiltration rate, a ring infiltrometer of 20 cm diameter was used. In order to determine the total concentrations of Cu, Ni, Pb, Zn, Cd and Cr in soil, samples were acid-digested with HCl and HNO_3 + H_2O_2 according to US-EPA Method 3051A (2007). The most probable number test was used to determine *Escherichia coli* and *Salmonella* sp. [ISO 16649-2 (Horizontal method) and UNE-EN ISO 6579, respectively]. Inert impurities (metals, plastics and glasses) diameter exceeded 2 mm.

2.5. Plant sampling and plant-health parameters

To assess whether different BSM doses affected the plant health status, the plant phenological and biometric parameters, photochemical efficiency, photosynthetic pigments and antioxidants were measured. First, at the early phenological stage BBCH-16-17 (Meier, 2001), i.e., at 57 days after sowing, the phenological development of the *B. napus* plants under BSM treatments was checked by counting the leaves of six plants per plot. Then, three whole young fully expanded leaves from three different plants were collected from each plot. They were kept in the dark, at 100% relative humidity (in plastic bags with wet paper) and room temperature (20–22 °C) for 12 h to reduce the effects of diurnal variations in pigments and provide comparable artificial predawn conditions (Hormaetxe et al., 2004).

At the final stage BBCH-89 (260 days after sowing) (Meier, 2001), all plants were harvested and the following biometric parameters were determined: (i) plant weight and (ii) height; (iii) number of siliques; (iv) number of seeds and (v) seed biomass per plant; and (vi) rapeseed yield (Kg ha^{-1}).

Photochemical efficiency of Photosystem II (Fv/Fm) provides important information concerning the effect of environmental stress on plants. The optimal value for most species is 0.83, and lower values indicate plant stress. Fv/Fm was measured in detached leaves after incubation for 12 h in darkness, with a relative humidity of 100% and at room temperature, using a FluorPen FP100 portable fluorometer (García-Plazaola et al., 2004). The maximum Chla fluorescence yield (F_m) was induced with a saturating pulse, while minimum Chl fluorescence (F_0) was recorded with low measuring light intensities. Fv/Fm was calculated as $(F_m - F_0)/F_m$. Three replications were used per treatment.

After the fluorescence measurements, *B. napus* leaves were frozen and stored at −80 °C. In the case of bioassays, after 72 h of incubation in soil, roots were also frozen and stored at −80 °C until pigment and tocopherol analysis. Extraction was made with a Tearor 985370 electric tissue homogeniser (BioSpec, Bartlesville, USA) with 1 mL of acetone (100%). The extracts were centrifuged at 16 100 g and 4 °C for 20 min, and supernatants were filtered with 0.2 µm PTFE filters (Teknokroma, Barcelona, Spain). The separation of photosynthetic pigments and antioxidants was performed by UHPLC as described by García-Plazaola and Becerril (2001).

2.6. Root elongation bioassays

To evaluate the potential phytotoxicity of soils, root elongation bioassays with *Cucumis sativus* (c.v. Marketmore) were performed, following the methods of Lacalle et al. (2018). Briefly, 3-day-old seeds of *C. sativus* with a radicle length of 5–10 mm were transferred to Petri dishes containing treated soils. These Petri dishes were then placed at 45° and incubated for 72 h in a germination chamber (14/10 h day/night; 25/18 °C day/night; and full darkness). Photographs were taken at the beginning and after 72 h of incubation with the soil. Images were processed by ImageJ software and root elongation was calculated for each seedling.

2.7. Analysis of soil health parameters

Soil microbial properties were selected as useful bioindicators of the status of soil health. One surface sample (0–15 cm) was taken from the centre of each plot at the above-mentioned sampling times (Plant phenological stages: BBCH-16, 17 and 89). After collection, soil samples were transported to the laboratory and kept at 4 °C until analysis. Soil sub-samples were ground and sieved at 2 mm prior to the analyses.

The following soil microbial properties were analysed: (i) microbial activity, determined as soil basal respiration (BR) (Epelde et al., 2008); (ii) microbial catabolic activity, estimated by β-glucosidase activity (Epelde et al., 2008); (iii) potentially mineralizable nitrogen (PMN), i.e. the fraction of organic nitrogen converted to available forms, estimated in soil by measuring ammonium and nitrate produced in soil incubated under aerobic conditions for 30 days (Stanford and Smith, 1972); (iv) microbial biomass, estimated by microbial biomass carbon (MBC), using the chloroform-fumigation-extraction method described by Vance et al. (1987); (v) microbial functional diversity, based on the

Average Well Colour Development (AWCD); and (vi) number of substrates used (NUS) with Biolog EcoPlates™ (Epelde et al., 2008).

2.8. Statistical treatment of data

The data were subjected to one-way ANOVA when data complied with assumptions of normality and homoscedasticity, and the means were compared by the Duncan post-hoc test. Normality and homoscedasticity were tested with Kolmogorov-Smirnoff and Levene tests, respectively. Data with a distribution deviating from normality were analysed with the Kruskal-Wallis test. The statistical software used was IBM SPSS (v24).

3. Results and discussion

3.1. Energy crops in urban greening

Traditionally, green areas in cities include parks, gardens and urban forests (Burgess et al., 1988). Nevertheless, phytomanagement and urban agriculture in general are appearing in cities, as new opportunities to extend food and energy production in order to respond to part of the food/energy demand of the local population (Thornbush, 2015). Here, we focused on energy production, an aspect of paramount importance since local sources of energy may act as temporary buffers for communities when supply failures or disruptions occur (Saha and Eckelman, 2015). Apart from the benefits associated with traditional green areas, such as reduction of the visual impact of empty land, improvement of environmental and human health, increases in carbon sequestration and social pleasure; the implementation of energy crops can also help to create employment opportunities and reduce poverty in cities, as well as strengthen communities (Satterthwaite et al., 2010). Due to population increase, food and energy demand is increasing exponentially. Furthermore, the establishment of energy crops in vacant lands around cities eases the pressure on the vast agricultural areas that are presently used for energy crops to the detriment of food production.

This study goes beyond the establishment of a crop in a single vacant area, as our area of study is part of a larger ecological reclamation project named the 'Jundiz Green Corridor'. It is therefore in a transitional step in the change from derelict land to environmental and recreational land uses in the near future. The successful establishment of *B. napus* in a peri-urban ecosystem was a challenging task, due to the low nutrient content and physicochemical characteristics of the soil (Table 1). *B. napus*, renowned for its multipurpose uses, was selected as a profitable crop due to its adequacy for biodiesel production (Mahmudul et al., 2017) and its considerable tolerance to multiple biotic and abiotic stresses (Van Ginneken et al., 2007; Lacalle et al., 2018).

3.2. Soil physicochemical properties

The soil physicochemical characteristics are listed in Table 1. This peri-urban soil was a loam with an alkaline pH and high carbonate content, typical of the region as shown by other studies in nearby areas (Huérfano et al., 2016). The electrical conductivity (EC) showed values similar to those found by Scharenbroch & Catania (2012) and are adequate for plants with no special requirements. The macronutrient concentrations in the soil of the experimental field were lower than in the soil of a nearby agricultural field (Table 1). Particularly, the OM and N contents were one-third and one-half, respectively, of those in the neighboring agricultural soil (Huérfano et al., 2016). The contents of trace elements were also lower in the vacant-land soil (Table 1). Nevertheless, soil nutrient concentrations improved considerably after BSM addition. In particular, following the incorporation of

100 t ha^{-1} of BSM into the soil to a depth of 30 cm, significant increases occurred for organic matter, which rose to 1.68%; total nitrogen 0.13%; phosphorus 41.5 mg Kg^{-1} DW and potassium 300 mg Kg^{-1} DW. After the BSM amendment, the trace elements did not exceed the critical values for agricultural purposes (IHOBE, 1998)

In spite of the low nutrient concentration in the original soil, the bulk density (1.26 g cm^{-3}) and water infiltration rate (18.62 mm h^{-1}) indicated that the levels of compaction were not high. This meant that the experimental soil had no physical problems regarding plant rooting, good soil oxygenation and water percolation.

3.3. Effect of BSM amendment on plant growth and yield

Several studies have emphasised the agronomic benefits of composts made from source-separated MSW, for example higher plant biomass and better nutritional status (Hargreaves et al., 2008; Scharenbroch and Catania, 2012; Chen et al., 2018). However, data supporting the suitability for BSM made from commingled MSW as a soil amendment remain insufficient (Srivastava et al., 2016). We emphasise, once again, the importance of meticulous mechanical pre-treatment and composting of the BSM to meet strict government safety standards before it could be applied to soils. Since BSM is being considered as a new-found resource for amending soils, its effects on the physiological and agronomic parameters of crops must be addressed.

Phenological and physiological monitoring of a *B. napus* crop at an early growth stage could be essential to reveal early potential negative impacts of BSM application, allowing rapid decision-taking in relation to soil management. In the present study, the early-growth *B. napus* plants in the 50BSM and 100BSM treatments showed an accelerated phenological stage (BBCH17) compared to 0BSM (BBCH-16), with higher leaf chlorophyll content and photosynthetic area (Fig. 1A). The chlorophyll content increased slightly (by 17 and 19%) in 50BSM and 100BSM, respectively, compared to 0BSM. In a two-year study, Alvarenga et al. (2017) also found increases in chlorophyll content and leaf area of ryegrass (*Lolium multiflorum* L.), using MSW under field conditions. A sharp increase of 180 to 230% in leaf area was observed in 50BSM- and 100BSM-amended soils, respectively, evidencing the adequacy of the BSM as an efficient nutrient supplier.

Stressful abiotic environmental conditions often elicit the overproduction of highly reactive and harmful Reactive Oxygen Species (ROS). To counteract this oxidative damage, plants generally accumulate α-tocopherol and increase the biosynthesis of VAZ pigments (Gill and Tuteja, 2010). Under our experimental conditions, there were no significant differences in either the Fv/Fm ratio or the concentrations of α-tocopherol and VAZ pigments among the BSM treatments, which indicated no phytotoxicity of the BSM doses used. Absence of phytotoxicity was further corroborated by root-elongation bioassays with *C. sativus* seedlings (Table 2). We observed neither significant root inhibition nor α-tocopherol accumulation in *C. sativus* seedlings exposed to BSM-amended soils, compared to the control (Table 2). Inhibitory effects due to the use of commingled MSW are associated with the presence of metals (Hargreaves et al., 2008). However, considering the metal concentration in BSM (Table 1) and the doses applied, BSM did not contribute significantly to the increase of metal concentrations in the soil, and in no case were the allowed legal limits for a soil to receive a compost amendment exceeded. Furthermore, no pathogenic bacteria were found (Table 2).

At harvest time, when the plants reached the final BBCH-89 stage, parameters related to plant production were measured (Fig. 1B). Relative to control soils (0BSM), the soil enrichment with BSM amendment, particularly 100 t ha^{-1} application dose, significantly increased the plant height (+23%), weight (+67%), seed number (+76%), and seed biomass (+77%) per plant. As a result, the grain yield was significantly increased, by around 160% in the BSM-amended plots. The rapeseed yield in the control soils (2675 kg ha^{-1}) was similar to the average production of this crop in northern Spain (GENVCE, 2014–2015). Considering that 40–45% of the seed is oil, our vacant soil amended with 100BSM could eventually produce a substantial amount, 1925 L ha^{-1} of biodiesel (Singh and Singh, 2010) in a sustainable manner.

The results for crop production could be attributed partly to the high contents of macronutrients (NPK) present in BSM (Table 1) that meet the nutritional requirements of *B. napus* plants grown in peri-urban vacant soils, as stated above. The reported increase in leaf area in early-stage plants grown in BSM-amended soils could also explain the improvements in all biometric parameters at harvest time. A larger leaf area allows higher light interception and larger amounts of assimilates (Ellsworth and Reich, 1993). Hence, leaf area is often positively correlated with silique formation and seed filling, which in turn may be channelled towards the development of seeds and grains. García-Gil et al. (2000) and Lakhdar et al. (2011) obtained similar positive responses in barley (*Hordeum vulgare*) and Mediterranean barley (*Hordeum maritimum*), respectively, grown in soils treated with composts of MSW. Cherif et al. (2009) reported an enhanced wheat yield in a 5-year experiment using composted MSW (alone or combined with farmyard manure) as an amendment. Moreover, Civeira (2010) demonstrated the suitability of composts of MSW for revegetation of peri-urban soils with meadow-grass (*Poa pratensis* L.). The application of the amendment and the food performance of the crop could have additional benefits in reversing soil degradation and restoring other important aspects such as soil microbial properties and processes.

Our results for crop yield support the suitability of a phytomanagement strategy to enhance the provisioning service (e.g., raw materials) provided by an ecosystem in a sustainable manner. This ecosystem service provides inputs to different sectors of the global economy and has been demonstrated to be of high monetary value (de Groot et al., 2012).

3.4. Effect of BSM amendment on soil microbial activity, biomass and diversity

Phytomanagement of peri-urban vacant lands needs to be promoted as a means of restoring/sustaining soil health and increasing economic and social gains. Within this context, phytomanagement of soils should require a follow-up, not only of the crop but also of the soil microbial properties (Gómez-Sagasti et al., 2018), as follow-up information provides an integrated view of the impacts of BSM on the health of peri-urban vacant soils. Here, we analysed the activity, biomass, and functional biodiversity of soil microbial communities at the beginning and end of the crop growing period.

Fifty-seven days after sowing, the presence of BSM in the soils (regardless of dose) led to significant increases in BR (89% and 111% in 50BSM and 100BSM, respectively) compared to the control (Fig. 2A). At this early BBCH-17 stage, both the 50BSM and 100BSM treatments had slight effects on the remaining microbial parameters. Other field studies (Jorge-Mardomingo et al., 2013; Yazdanpanah et al., 2016) consistently found a similar increase in BR after incorporation of composted organic municipal wastes into soil, due to the load of labile organic substances and greater soil hydraulic conductivity. Nonetheless, the reported BR values in BSM-treated soils were lower than those obtained for agricultural loamy soils (Mijangos et al., 2006).

Fig. 2

At harvest (260 days after sowing), larger differences in microbial activities were found between the unamended and BSM-amended soils (Fig. 2B). We observed a significant stimulation of BR (69% and 87% in 50BSM and 100BSM, respectively) as well as β-glucosidase activity (54% in 50BSM) and PMN (172% and 155% in 50BSM and 100BSM, respectively) in BSM-amended plots compared to unamended ones. However, none of the BMS treatments significantly altered the biomass and diversity of microbial functional groups (Fig. 2B). Lacalle et al. (2018) conducted a microcosm experiment with the unamended and BSM-amended soils used in the present study, collected 10 months after the amendment application (July 2016). The authors still recorded higher BR in BSM-amended soils in comparison to unamended ones, which were even higher in soils planted with *B. napus*. At that time they also observed non-significant differences in functional diversity between unamended and BSM-amended soils. Although microbial diversity is sensitive to organic management of soils (Gómez-Sagasti et al., 2018), the application of some organic amendments, such as composts of industrial (Galende et al., 2014) and municipal sewage sludges, as well as some composts made from MSW (Sciubba et al., 2014), did not significantly impact microbial diversity.

In general terms, soil respiration and enzymatic activities are considered good indicators of soil health/quality (Schloter et al., 2018). Thus, the use of soil microbial activity to assess the effects of soil-management practices, such as organic fertilization with composted MSW, is increasingly reported (Gómez-Sagasti et al., 2018). The increase of soil microbial activity mediated by composted MSW is significantly and positively correlated with the increased availability of readily metabolizable organic carbon, nitrogen and phosphorus in degraded soils (Carlson et al., 2015; Alvarenga et al., 2017). Soil microbial communities accomplish the biochemical transformations of organic matter that underpin essential ecosystem functions, including decomposition, mineralization of plant available nutrients, and nutrient retention (Bowles et al., 2014). Plant-microbe interactions in the rhizosphere are the most influential chemical processes contributing to plant health, productivity, and soil fertility (Souza et al., 2015). We interpret this increase in the activity of microbial communities at harvest time to be a consequence of *B. napus* growth in BSM-amended peri-urban soils (Fig. 1B), and vice-versa. Although the roles of root exudates in acquiring nutrients from the rhizosphere are not fully known, they are widely recognised as an important carbon and energy source for soil microorganisms (Haichar et al., 2014). Additionally, release of organic exudates such as citric, oxalic and malic acids has been reported to be associated with rhizosphere acidification (Hinsinge et al., 2003), which in turn could maximise/stimulate organic-matter decomposition and nitrogen mineralization.

Mineralization of organic matter may provide substrates for β-glucosidase and enhance its activity, as stated by Jorge-Mardomingo et al. (2013). The delayed response of β-glucosidase activity to field BSM amendments is consistent with the observations of Carlson et al. (2015), who attributed it to the significant amount of β-glucosidase stabilised in the soil matrix, which accumulates or changes slowly.

BSM application is assumed to provide a significant input of nitrogen into soil (Table 1). However, composted MSWs contain large amounts of recalcitrant organic N compounds (Cordovil et al., 2012) that may remain immobilised in the soil (Zarabi and Jalali, 2013). As the urban soil used here was loamy and alkaline (pH 8.5), organic N was probably mineralised as nitrate (Sciubba et al., 2014). The temporal course of N mineralization differs according to the quality and quantity of the amendment and the soil (Jin et al., 2011). For instance, Zarabi and Jalali (2013) reported slow N mineralization in a sandy-loam soil amended with MSW compost. The same trend was described by Hernández et al. (2002) in a study of N mineralization potential in calcareous soils amended with sewage sludge. It has often been shown that the addition of MSW composts increases soil N mineralization (NO_3^--N + NH_4^+-N) (Jin et al., 2011; Cordovil et al., 2012). From a fertility standpoint, PMN represents mineralizable organic N and therefore is generally accepted as an indicator of plant-available nitrogen (Hadas et al., 2004). In our study, PMN was the most-stimulated microbial parameter at harvest time and was understood as an indicator of soil fertility and health. More interestingly, our results for PMN indicated that the BSM amendment was effective in restoring soil nutritional status a year after the application.

Taken together, our results demonstrate the potential of BSM amendment to enhance soil microbial properties and processes, and hence to increase soil fertility for crops. In order to facilitate the interpretation of soil microbial properties during the reclamation process and thus streamline decision-making, Epelde et al. (2014) suggested that these properties should be classified as ecosystem services. In light of the proposed classifications, we concluded that our field intervention contributed to the services of removal, retention and delivery of nutrients for plants (based on PMN) and to the decomposition of wastes and organic matter (based on BR and β-glucosidase). In terms of ecological attributes, our intervention promoted more stable and vigorous urban soil. This is important for the future implementation of the Green Corridor in the context of urban greening, as richer soils will be more suitable for short-rotation crops with higher nutrient demands.

4. Conclusions

The present results suggest that the use of BSM as a soil amendment has significant beneficial effects on plant parameters (productivity), i.e., leaf area and yield, and soil properties (functionality), i.e., microbial activities related to C and N cycling. As such, they can be used as helpful bioindicators in urban land management. Moreover, a one-time addition of 50 t ha^{-1} BSM effected these improvements in the short to medium term. Taken together, these effects are particularly important for reclamation of Mediterranean-temperate urban vacant soils, where the low nutrient content is the dominant constraint on sustainable land management. With respect to urban greening, the phytomanagement technique used in this study has been incorporated by the green-belt service (city of Vitoria-Gasteiz) as a low-cost ecological reclamation tool. The increase of nutrients combined with crop restoration was understood as a necessary step in the land recovery, as it would make the soil suitable for plants with higher requirements. Positive outcomes such as C sequestration or biodiversity increase helped to convince the city managers of the benefits of phytomanagement for these peripheral areas, especially in a context of global change that may increase their vulnerability.

While most attempts for redevelopment of urban vacant lands are directed toward greening, our findings highlighted the potential of applied phytomanagement strategies using BSM-assisted phytoremediation to achieve agro-economic performance of urban soils in the short term. This study can be considered a successful field experience framed within the so-called circular-economy model. Both commingled MSW and vacant lands have been revalorised, giving them a second life; the former as low-cost resources for the suitable recovery of health and agronomic competency of degraded soils, and the latter as new locations for the establishment of energy crops with economic value. Nonetheless, further field experiments are required to evaluate the biofuel produced, and, even more crucially, more thorough studies of the interaction between urban soil-plant-amendment are needed to guarantee the agronomic quality of BSM amendment over a prolonged period of time.

5. Author contributions

FM, MTGS and AH contributed significantly to developing the experiment and composing and revising the manuscript. UA and FB have been actively involved in the sample analysis, and in generating and interpreting the results. JHC participated in field conditioning and soil samplings. JVL, CG and JMB contributed greatly to the conception of the study and to revising and supervising the manuscript. All authors meet all the established criteria for inclusion in the authorship.

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Tables and Figures

Figure legends

Fig. 1. Sun ray plot of plant and microbial parameters. (A) Physiological plant parameters measured at early growth stage (57 days). (Control values: Total chlorophyll: 247 nmol g^{-1} FW; Total VAZ: 22.47 nmol g^{-1} FW; Total carotenoids: 87.16 nmol g^{-1} FW; α-Tocopherol: 15.87 nmol g^{-1} FW; Fv/Fm: 0.77; Leaf area per plant: 122 cm^{-2}). (B) Plant parameters at harvest time (260 days); Biometric parameters are expressed per plant. (Control values: Plant weight: 27.9 g; Plant height: 129 cm; Number of siliques: 144; Seed biomass: 5.7 g; Number of seeds: 1623; Seed yield: 2675 kg ha^{-1}). All parameters are represented as percentage of control (inner narrow hexagon = 100%). Asterisks indicate significant differences compared to control soil at $P < 0.05$. See supplementary S1 for more-detailed data.

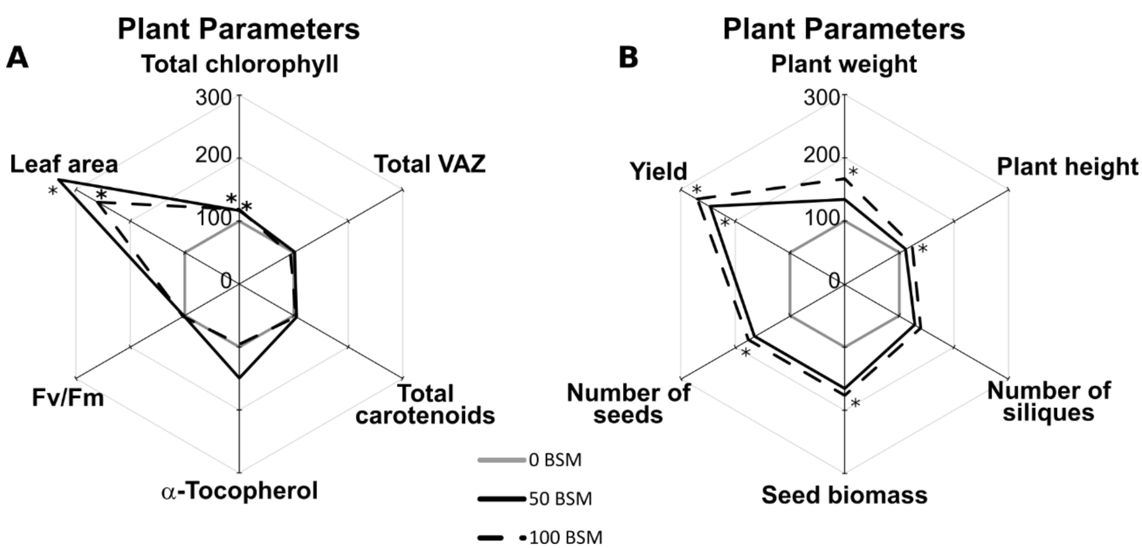

Fig. 2. Sun ray plot of plant and microbial parameters. A) Microbial parameters of soil measured at intermediate growth stage (57 d). (Control values: BR: 0.9 mg C h^{-1} kg^{-1} DW; β-Glucosidase: 187 mg NP kg^{-1} FW; MBC: 298 mg C kg^{-1} DW; PMN: 17 mg N-NH_4^+ kg^{-1} DW; AWCD: 0.99; NUS: 26); B) Microbial parameters of soil at harvest time (260 d). (Control values: BR: 1.6 mg C-CO_2 h^{-1} kg^{-1} DW; β-Glucosidase: 175 mg p-nitrophenol kg^{-1} FW; MBC: 337 mg C kg^{-1} DW; PMN: 29 mg N-NH_4^+ kg^{-1} DW; AWCD: 0.77; NUS: 19). BR: Basal respiration, MBC: microbial biomass carbon, PMN: potentially mineralizable nitrogen, AWCD: average well colour development, NUS: number of used substrates. All parameters are represented as percentage of control soil (inner narrow hexagon = 100%). Asterisks indicate significant differences compared to control soil at $P < 0.05$. See supplementary S1 for more-detailed data.

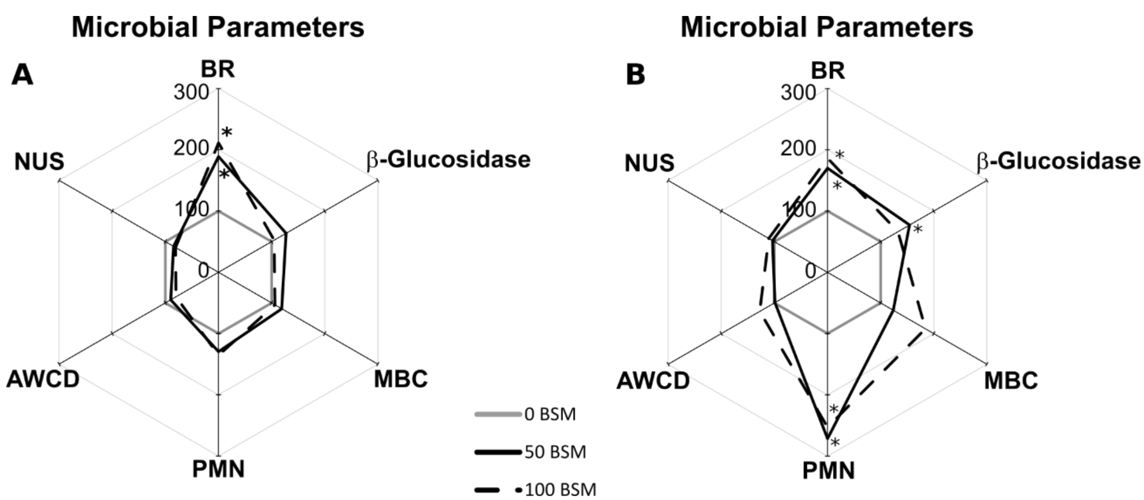

Table 1. Physico-chemical characteristics of soil and bio-stabilised material. Dash (–) indicates no data.

	Soil	**Bio-stabilised material (BSM)**
Water content (%)	14.54	22.6
Total clay (%)	23.20	–
Coarse sand (%)	18.00	–
Fine sand (%)	21.40	–
Total silt (%)	37.70	–
Texture class (USDA)	Loam	–
pH (1:2.5)	8.55	7.61
Electrical conductivity ($\mu S\ cm^{-1}$)	180	–
Carbonates (%)	54.70	–
Bulk density ($g\ cm^{-3}$)	1.26	–
Infiltration rate ($mm\ h^{-1}$)	18.62	–
Organic matter (% OM DW)	1.04	37.03
Total nitrogen (% N DW)	0.09	2.22
Total organic carbon (% DW)	0.60	23.30
Organic carbon (C)/ Organic nitrogen (N)	6.73	12.91
Phosphorus (mg P kg^{-1} DW)	7.20	19800
Potassium (mg K kg^{-1} DW)	90	12040
Magnesium (mg Mg kg^{-1} DW)	146.4	–

Calcium (mg Ca kg^{-1} DW)	10104	–
Iron (mg Fe kg^{-1} DW)	14291	–
Cadmium (mg Cd kg^{-1} DW)	0.51	1.33
Copper (mg Cu kg^{-1} DW)	5.40	240.91
Nickel (mg Ni kg^{-1} DW)	12.35	25.20
Lead (mg Pb kg^{-1} DW)	9.02	57.20
Zinc (mg Zn kg^{-1} DW)	35.20	368.05
Chromium (mg Cr kg^{-1} DW)	11.18	32.02
Escherichia coli count (Most Probable Number g^{-1} DW)	–	0
Salmonella (Colony-Forming Units g^{-1})	–	0
Inert impurities fraction (metals, plastics and glasses) (% DW)	–	2.42

* Trace elements did not exceed critical values for agricultural purposes, before or after BSM addition.

Table 2. Root elongation bioassay. Root elongation and α-tocopherol content in roots of *Cucumis sativus* plants. Values followed by different letters are significantly different ($P < 0.05$ or lower) according to one-way ANOVA with Duncan *post-hoc*. Means ($n = 3$) ± standard errors.

	Treatment											
	Control				**50 t ha $^{-1}$**				**100 t ha $^{-1}$**			
Root elongation (mm)	32.07	±	1.58	a	30.23	±	2.71	a	31.64	±	2.67	a
α-tocopherol (nmol g^{-1} FW)	0.94	±	0.15	a	0.93	±	0.17	a	0.72	±	0.14	a