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The environmental sustainability of bio-based fertilisers produced via integrated nutrient recycling technologies

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ABSTRACT

Bio-based fertilisers (BBFs) have been promoted by the EU as an emerging and promising solution to help manage bio-waste problems (by converting organic wastes to nutrient-rich products) and simultaneously substitute or reduce the use of mineral fertilisers. They are also considered as an effective tool for improving soil health conditions in Europe. By taking a full life cycle perspective, this paper investigates whether valorising biological waste streams to recover valuable components for the production of BBFs is indeed environmentally justified and can bring benefits to the soil and the environment. The environmental aspects of BBF were investigated by undertaking a Life Cycle Assessment (LCA) and supplemented with additional agronomic results from field trials. The LCA results indicate that the large difference in application rates (up to 35 times more by weight BBFs were applied than conventional fertilisers) disfavours waste-derived BBFs compared to mineral and organo-mineral fertilisers. On the other hand, the inclusion of biochar as a component of BBFs has a pronounced effect on the climate change and thus overall environmental performance of BBFs significantly increasing their attractiveness. Although associated with uncertainties, this paper provides useful insights to farmers, academics, policymakers and other stakeholders whether (and under what conditions) the production and application of waste-derived BBFs can enhance soil health, improve nutrient availability, and reduce reliance on synthetic fertilisers. It also provides LCA data for new biomass treatment technologies and materials, which is highly valuable for other researchers interested in recycling of organic wastes for sustainable BBF production and farming.

1. Introduction

Due to their very specific composition and general, low-cost availability, mineral fertilisers have been dominant in agricultural practices for decades leading to an explosive increase in crop production yields with the more efficient use of space [1,2]. This, however, has brought a range of serious ecological effects, such as contribution to climate change, eutrophication, depletion of resources, decline in organic matter soil content, loss of biodiversity and release of heavy metals into ecosystems [2,3]. As a result, the EU has committed to boost the use of bio-based fertilisers (BBF), particularly those derived from organic wastes and residues, with the aim to replace up to 30 % of currently used fossil-based fertilisers in the future [4]. Bio-based fertilisers are associated with the concept of 'nutrient recycling' or 'nutrient circularity', and the priority is therefore given to the recovery of nutrients from organic waste and residues streams – and thus minimising nutrient losses along the agri-food supply chain - to be reused in the agricultural production [5,6]. Bio-based is defined in this paper as derived from biomass -

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excluding material embedded in geological formations and/or fossilised – that may have undergone physical, chemical or biological treatment [7].

In Europe, approximately 43.7 Mt of fruit- and vegetable-derived wastes and residues are generated each year [8,9], a substantial and relatively homogeneous resource for BBF production. In this framing, BBFs promise dual benefits: (i) converting biowaste into value-added fertilising products and (ii) simultaneously improving soil condition and reducing dependence on non-renewable deposits (e.g., phosphate rock, potash) [10,11]. A growing body of work suggests that appropriately formulated and managed BBFs can serve as alternatives to, or complements for, mineral fertilisers, reducing GHG emissions and nitrate leaching while supporting long-term soil fertility, plant health and product quality [12–14]. Dasgan et al. [15] for example, demonstrated that BBFs can partially replace mineral inputs without sacrificing performance, while altering soil processes and showing trade-offs among different environmental impacts. A study from Oldfield et al. [16] proved that combing biochar and compost into the BBF blend produced yields of similar magnitude to mineral fertiliser, while reduce climate change, acidification and eutrophication impacts. Fryda et al. [17] demonstrated that biochar replacing peat in substrate and long term storage of the spent biochar in soil, contribute to GHG reductions. Other studies of Sharma et al. [18] and Ren et al. [16] also indicated that the utilization of BBFs in the soil can be the optimal choice for promoting the crop growth, as well as the biomass and soil enhancement. However, considering significant variability in the environmental performance of the analysed BBFs, there is a call for more research in this area supported by verifable environmental data derived from BBF production and integrated with field-scale experiments, assessments and validations [19–21].

Life Cycle Assessment (LCA) provides a standardised, consistent and scientifically credible cradle-to-grave framework for environmental assessment [22], which became an important tool for evaluating environmental impacts of biomass conversion systems [23–25] In fact, LCAs for individual BBFs - such as carboxylic acid [26], biochar [17], insect biomass [27] and digestate [28] - or a combination of two ingredients, like biochar and compost [16], already exist. LCAs of conventional fertilisers and fertilisation practices can be also found in the literature [29,30,31]. However, what is still lacking is an integrated, regionally-tailored LCA of waste-derived BBFs that combines multiple complementary waste processing technologies into coherent production chains, is adapted to local soils, crops and farmer practices, and is supported by extensive field experiments.

To address this gap, we combine the cascading valorisation of fruit- and vegetable-derived wastes and residues with a cradle-to-grave LCA. The production of novel BBFs in this paper relies on 6 technologies (4 emerging and 2 established) to produce different fertilisers ingredients (so called building blocks) from fruit and vegetable waste and residues. The emerging technologies are: (1) carboxylic acid technology [26]; (2) microbial cultivation [32]; (3) insect farming [29]; and, (4) pyrolysis [17]. Additionally, technology integration with composting and Anaerobic Digestion (AD) – both considered distinct and well-established technologies for treating organic waste [30] - was assessed to produce BBFs. The combinatory use of technologies resulted in the production of several fertiliser ingredients (microbial biomass, insect biomass, insect frass, biochar and compost), each of which having own specific characteristics and composition that also depending on the feedstock used in their production. These different ingredients were utilised to formulate specific BBF blends designed to match the current and future crop needs in four selected test regions in Europe: Flanders (Belgium), Almeria (Spain), Friuli Venezia Giulia (Italy) and Pays de la Loire (France). The designed blends were validated in the test regions by performing field trials with representative crops. By conducting this LCA study, we sought to: (i) assess how the choice of valorisation routes and blend composition affects environmental outcomes across four regions; (ii) isolate the drivers of differences among impact categories identify life-cycle hotspots; and (iii) derive design and implementation implications that can improve environmental outcomes.

2. Materials and methods

2.1. Waste and residues valorisation technologies and products

Biomass waste conversion into valuable products such as fertilisers is becoming increasingly popular as it allows to solve the problems related to waste disposal while boosting sustainability and circular economy [33]. Several established and emerging biomass transformations technologies can be utilised depending on the availability and the properties of the biomass [34]. Among the consolidate technologies composting and anaerobic digestion are the most utilised. Composting reduces waste sent to landfill and produce an end product rich in nutrients and stabilized organic matter. It can address food waste management and can be easily produced locally and at small scale. However, it can have highly operational costs when performed in large plants and may not completely remove pathogens and weed. Poorly managed compost can produce unpleasant odours, posing health and social problems in the area surrounding the plants and low-quality compost that the farmers are not willing to use [35].

Anaerobic digestion is a transformation method that is mainly targeted to produce methane-rich gas that can be exploited for energy and heat production. Beside this, the residue of the process represents a valid fertiliser. Principal limitations of this technology are related to the fact that is not suitable for ligno-cellulosic materials and is more easily operated on wet materials. There are strategies to overcome these limitations, but at the expense of higher equipment requirement and operating costs [29].

In anaerobic digestion, short chain carboxylic acids are formed from biowaste as intermediate to produce methane. An emerging alternative in recent year is to eliminate the final methanogenic step and to optimize the production of carboxylic acid as target products in the so-called carboxylic acid platforms (CAP). Carboxylic acids can be utilised in different industrial sectors as precursor of detergents, pharmaceuticals, plastics, dyes, textile, perfumes, and animal feed. To enhance the economic value of the process an interesting possibility is to steer the fermentation to release N, P, K, Ca, Mg and micronutrients contained in the residues in a mineral form which can more easily be recovered by electrodialysis or incorporated into microbial biomass to produce biofertilisers. The CAP performance could be improved by optimizing the process in such a way to obtain a stable acid spectrum independent of the variability of the feedstocks and a balance between carboxylic acid production and nutrient release [26].

The production of microbial biomass has recently gained interest due to higher protein prices, but to date microbial biomass production has been mainly studied with sugar or starch rich wastewater effluent. The range of applicability of this transformation route can be increased by its optimization for a larger biowaste spectrum. An interesting option is the integration of a carboxylic acid platform, utilising fruit and vegetable residues as feedstocks, with microbial biomass cultivation to produce microbial protein to be utilised as ingredient in organic fertilisers. This combined process is currently quite expansive and the challenge for its profitability is to decrease production costs and obtain more controlled process conditions resulting in a higher and constant quality end-product.

Since Hermetia illucens have shown to be quite efficient in turning biowaste into insect biomass, many companies have emerged around the world trying to industrialise insect breeding. Insect biomass is mainly utilised as animal feed, but an interesting, and to date neglected alternative, is its utilization as organic fertilisers, due to the positive properties in terms of nutrients content and growth stimulation of microorganisms and plants. Besides, one of the main by-products of industrial insect breeding is insect frass which can be conveniently valorised as organic amendment. One of the current limitations of insect cultivation, however, is the availability of sufficient feedstock to feed the larva without competing with animal feed. Such limitations can be overcome by breeding insect on new types of feedstocks, such as fruit and vegetable waste streams, and identifying optimal operational conditions to enhance macro- and micronutrients recover in insect biomass [29].

Lignocellulosic wastes can be conveniently transformed by pyrolysis, which main byproducts are biochar, a solid soil amendment, and syngas that can be utilised for production of energy and heat. Biochar has gained an exceptionally interest within the scientific community due to its outstanding properties in terms of climate change offsetting. In addition, biochar application to soil has shown to have a positive impact on soil fertility and the environment. However, the current utilization of biochar as soil amendment is quite low. Main limitations to pyrolysis large scale deployment are represented by the scarcity of appropriate feedstock, its suitability only for a limited range of wastes and higher operative costs. To enhance biochar utilization is important that production cost will be decreased by searching for economy of scale. Furthermore, technology improvements are needed in order to extend the range of feedstocks suitable to pyrolysis and to identify the operational conditions that favours biochar yield and quality with respect to the production of gas. Also, public incentives to farmers can play an effective role in promoting biochar utilization [17,36].

A combinatory and cascading use of waste valorisation technologies (established and emerging) for the production of different building blocks for BBFs in this study is shown in Fig. 1. Three types of waste flows, namely labile, moderately, and recalcitrant (lignin-rich) biodegradable enters a processing step. The labile degradable biowaste fractions are hydrolysed into carboxylic acids and nutrients in a CAP technology. The carboxylic solution is then converted to microbial biomass in an aerobic production reactor. Although both the CAP and microbial cultivation are two distinct and standalone technologies, by using the CAP as a pretreatment for the microbial cultivation, a wider range of feedstocks could be used for the production of microbial proteins. The CAP and microbial cultivation technologies are also compatible with the AD technology (e.g., solid waste from the CAP process has energetic value and is suitable for the AD, while the AD provides energy-electricity and heat-which are required for the CAP and microbial biomass production) and with composting (digestate from the AD is converted into compost). More moderately degradable biowaste is converted by insects to insect biomass and frass and/or by aerobic degradation into compost. Finally, the recalcitrant lignin-rich biowaste is more suitable for conversion into biochar by pyrolysis or composted, both of which are the ingredients in the formulation of BBFs.

2.2. Designing the BBF blends

Individual building blocks can be considered as effective fertilisers with specific properties that can be utilised to fulfil specific agronomic or environmental targets [23]. Nevertheless, a more proficient and effective way is to utilise the building blocks as ingredients of a blend [4,13]. In addition, mixing the building blocks in a blend is the only way to obtain a fertiliser capable to fulfil the specific functions and properties that are required for specific crops and soils in different countries and regions (e.g., increased mineralisation, resilience and crop nutrition, enhanced water retention, reduced erosion and GHG emissions and carbon sequestration).

The process of designing the BBF blends was aligned with the climate-smart fertilisers strategy, which implies - aside from more environmentally-conscious production of fertilisers – a greater control of the release of nutrients to the plant [37]. Hence, the main characteristics of the building blocks and their potential effect on the soil (e.g., increased mineralisation, resilience and crop nutrition, enhanced water retention, reduced erosion and GHG emissions and carbon sequestration) were first studied considering the literature and through building blocks characterisation. Table S1 shows an overview of BBF building blocks and their effects on the main characteristics in the soil. Simultaneously, regionally-desired functionalities of BBFs were formulated for the test regions via a questionnaire study with the regional stakeholders in the BBF sector (including farmers) also considering the target crops, properties of the receptor soil and agricultural management (e.g. crop rotation). For instance, in Friuli Venezia Giulia (Italy), it was identified that an ideal fertiliser to be applied in the vineyard should be capable to achieve simultaneously the following purposes: direct nutrient provision, enhanced biological activity, increased water retention and soil C sequestration, decreased GHG emissions and enhanced erosion control. Table S2 in the supplementary materials provides the regionally-desired functionalities of the blends specified by the regional stakeholders in the questionnaire study for all test regions.

Based on these requirements, the properties of the building blocks,

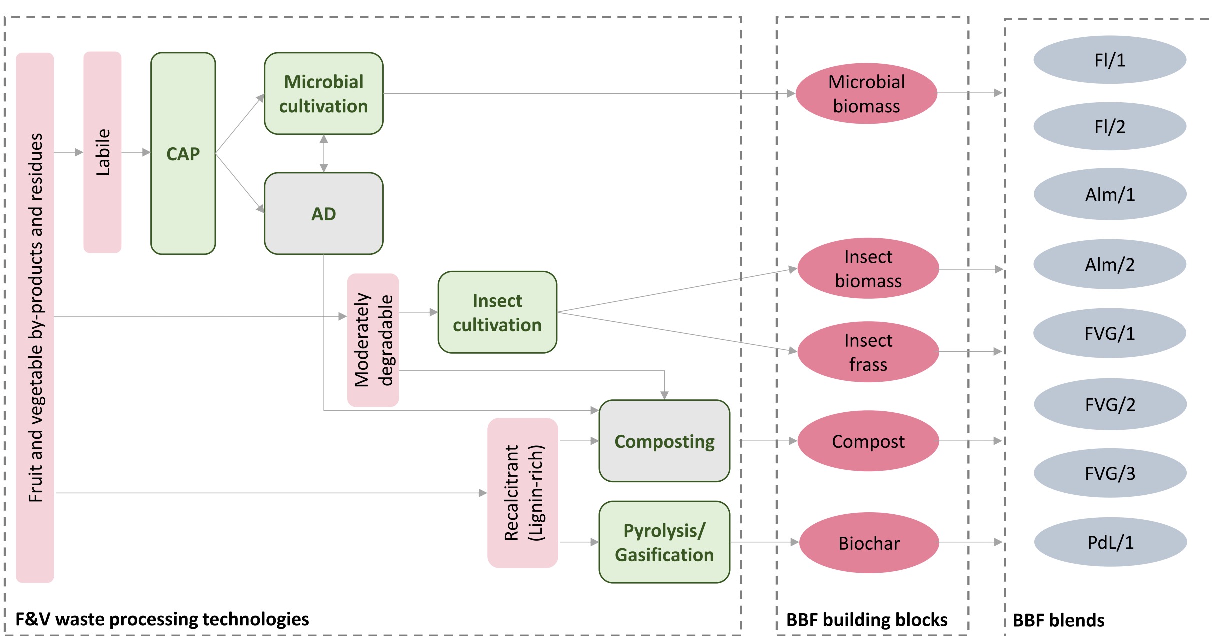

Fig. 1. Valorisation technological integration scheme for the production of BBF blends from fruit and vegetable waste and residues.

the availability of the feedstocks and the occurrence and potential development of the technologies prototypes of the blends were designed for each region. To meet all these requirements, it was necessary to formulate blends with different building blocks. Specifically, the need to meet both nutrients supply and increased soil fertility and quality made necessary to formulate blends with up to 4 different components.

The number of components depend, besides to the properties sought in the blend, also on the technology available or likely to be developed in the future in the specific region. So, for instance, microbial biomass was not foreseen for Almeria as AD plants are not developed in the region, while they are frequent in the other regions. AD plants can be transformed for CAP production as prerequisite for microbial biomass production. Also, economic considerations led in some case to utilise only insect frass in the blends because insect biomass was valorised in other sectors where it can be sold at higher prices (e.g. animal feed). Consequently, several BBF prototypes were defined in Table 1, the characteristics of which (including N,P,K and C content) are available in Table S3 (along with test methods used for blend characterisation). These blends were the subject of subsequent characterization, experimentation and adaptation through a series of lab and pot studies [38].

2.3. Field trials

The field trials for the BBFs were conducted between 2023 and 2024 in Flanders (Belgium), Almeria (Spain), Friuli Venezia Giulia (Italy) and Pays de la Loire (France), which provided input and yield data for the LCA modelling.

2.3.1. Flanders

The field trial of Flanders was located at Viaverda, Karreweg 6 in Kruisem, with coordinates 50°56′ 44.261″N - 3°31′35.777″E. The soil texture was sand, which is typical for Flanders with pH 6.2 and total organic C (TOC) concentration 1.4 %, both in the target zone. The field trial was a double one with the first crop being leek, followed by the cauliflower crop. The field trial included four treatments: control, reference N mineral fertiliser and two BBF treatments. Nitrogen taken up by the crop from the control plots was delivered by the soil. The reference treatment was a standard practice in the Flanders region calcium ammonium nitrate and urea.

2.3.2. Almeria

The trials were conducted in a greenhouse with a total area of 576 m^2, located in the facilities of the Experimental Centre of Tecnova Foundation 36°53′N - 2°22′W, in the South-East coastal area of Spain, in the province of Almeria. The soil in the greenhouse was a loam imported soil (30 cm thick) with the following characteristics 43.4 % sand; 43.1 % silt; 13.5 % clay, 7.45 pH, 0.73 % TOC, and placed on top of the original soil. Five treatments with four repetitions per treatment were evaluated in the trials for tomato and cucumber crops: (1) control; (2) first reference treatment using sheep semi-dried manure (as a conventional amendment used in the region of Almeria by farmers); (3) second reference treatment using compost produced from local vegetable crops; (4) and (5) BBF treatments.

2.3.3. Friuli Venezia Giulia

The field trial of Friuli-Venezia Giulia was performed in the organic farm Ronco delle Betulle (46°00′59.7″N - 13°24′16.7″E) located in Oleis di Manzano (Udine, Italy). The field trial included six treatments to evaluate three BBF blends in comparison to a control without fertilisation and two fertiliser reference treatments: bovine manure and organo-mineral fertiliser. The crop utilised for the trial was grapevine, variety Refosco dal peduncolo rosso. The soil of the vineyard, in the area utilised for the trial was a silty clay roam soil with the following general characteristics: 11.6 % sand; 52.8 % silt; 35.6 % clay, 6.5 pH, 1.2 % TOC.

2.3.4. Pays de la Loire

The field trials of Pays de la Loire were located at Sainte-Gemmes-sur-Loire (47°25′22.553″N - 0°33′23.136″W). The aim of these trials was to compare the BBF blend with the organo-mineral fertiliser on a summer lettuce crop in open field, and with the mineral fertiliser on a winter lettuce crop in greenhouse. An additional field trial was performed on grapevine in a 7-year-old vineyard of grape variety Chenin. The soil was silty-sandy with a content of rock between 5 and 15 %. The BBF blend was compared with the control and reference organic fertiliser, which is a standard treatment practice for vineyards in the region.

2.4. Life cycle assessment

2.4.1. Goal and scope

The goal of this LCA study was to compare the BBF blends with the reference, representing the business-as-usual scenario individually defined for each test region, from the environmental perspective and on a regional level. The functional unit, including the desired product properties and reference flow, for this LCA was 'the same crop yield (1 tonne) over 1 ha in the specific test region, considering specific climate conditions and during a particular period of time (up to 1 year in this case)'. The reference flow was the mass of fertiliser needed to obtain 1 tonne of crop per ha of area (land). This allows to compare the environmental performance of different fertiliser products with different nutrient compositions by estimating the right dosage that needs to be applied in order to obtain the desired crop yields.

The system boundaries for this LCA study was from the cradle-to-grave (Fig. 2) with three main processes throughout the life cycle: material sourcing and treatment, fertiliser production and fertiliser use (application). All transportation activities, including the organic waste, fertiliser building blocks and final fertiliser products, were also included in the analysis. Emissions from capital goods, buildings as well as from production of machinery were not available for this study and thus had to be excluded. However, previous studies revealed that these sources have only little impact on the end results [2,39].

The allocation procedure had to be addressed due to the multi-functionality of some waste processing technologies [40]. In order to deal with the multi-functionality issue, the system expansion (especially for biomass cascades, in which different processes take place within the boundary of a single entity) and allocation cut-off by classification were the main methods used for handling multi-output processes in this LCA. For example, a single entity in Friuli Venezia Giulia employs a combination of different technologies (1) pyrolysis, the two main products are

Table 1
Composition of the BBF prototypes for the four test regions.

Building block type	BBF blend code (% of air-dried weight)							
	Flanders		Almeria		Friuli Venezia Giulia			Pays de la Loire
	Fl/1	Fl/2	Alm/1	Alm/2	FVG/1	FVG/2	FVG/3	PdL/1
Compost	76.9	30.8	50	26	66.7	83	62.5	62.8
Biochar	7.7	30.8	20	52	16.7		18.7	18.6
Microbial biomass	7.7	15.4					6.3	5.8
Insect biomass			20		16.6	17		
Insect frass	7.7	23.0	10	22			12.5	12.8

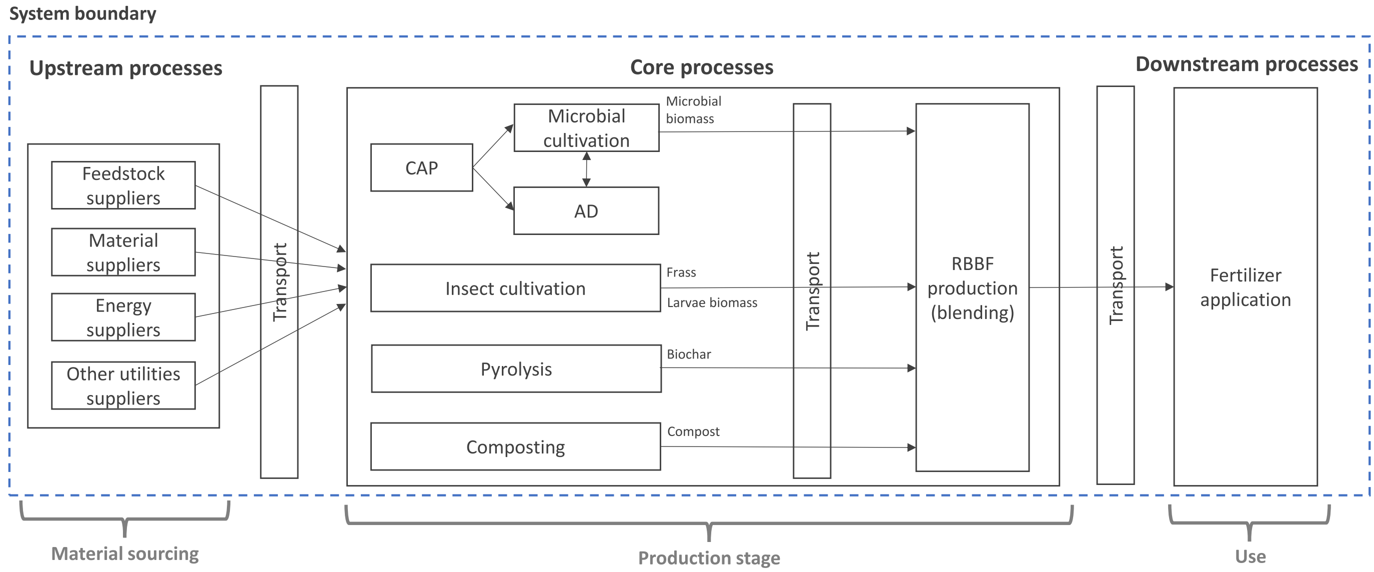

Fig. 2. A simplified LCA model and system boundaries for the BBF.

energy and biochar; (2) CAP/microbial cultivation producing microbial biomass, and; composting. All these technologies were assumed as a single production process (system expanded to account for all impacts and flows) and the environmental impacts were distributed among multiple by-products (biochar, energy, microbial biomass and compost) based on their economic value.

2.4.2. Life cycle inventory

2.4.2.1. Waste collection, transportation and fertiliser field distribution. LCI data for waste collection and transport was assumed a diesel driven, Euro 5, cargo truck taken from the Agri-footprint 5 database. The collection of MSW is carried out by varyingly sized collecting vehicles [41], hence the fuel consumption for road transport was based on primary activity data of multiple types of vehicles (small trucks <10 t, medium sized trucks 10–20 t and large trucks >20 t), where small vehicles were assumed for waste collection activities, while large trucks for long-distance transportation. Three types of roads are defined in the Agri-footprint 5 database and average time trucks spent on these roads: urban area (17.5 %), country roads (22.1 %) and highways (60.4 %). An average (round trip) of 40 km (for fruit and vegetable waste) - 60 km (green waste) was assumed for waste collection activities, as well as for distribution of fertilisers to farmers, which is in line with distances reported in Sausa et al. [42] and Oldfield et al. [16]. All transportation activities were modelled assuming an empty return trip, meaning that the emissions account for a return trip of the same distance, but with a load factor of 0 % for the return trip, compared to 100 % for the first trip.

Fertiliser spreading on the field was modelled by first estimating a typical travel distance of a tractor with a fertiliser broadcaster (500 l capacity, 6 m working width) for fertilising 1 ha of soil. Transportation distance from the farm to the field was assumed 2 km [43], while traveling distance for fertilising 1 ha of field was estimated at 1.7 km.

2.4.2.2. Waste processing and BBF production. Mixture of different building blocks and waste processing technologies were required for each of four test regions in order to produce the BBF blends. For example, to produce Alm/1 only compost, biochar and insect frass were required, wheareas for Alm/2 and PdL/1 four building blocks had to be available. An overview of the waste processing and BBF production scenarios defined for each region, including feedstock type and volumes, employed waste processing technologies and their combinations, is provided in the supplementary materials (Figs. S1–S5).

Inventory data for the CAP and microbial cultivation technologies were derived from the pilots and technology owners (DRANCO and AVECOM) and upscaled accordingly to the waste volumes available in the regions. Production data for the AD technology and composting of digestate (conversion rates) were also obtained from DRANCO (a former subsidiary company of OWS, a leading company in the construction and operation of AD plants) and supplemented by the literature (e.g., emission factors for biogas burning and composting of digestate). The LCI data for the insect cultivation considers two scenarios: (1) when the required building blocks are the insect frass and dried larvae biomass, without separating the fresh larvae into chitosan, fat and insect proteins; and, (2) when the required building block is only insect frass, and the larvae biomass undergoes transformation to produce (aside from frass) chitosan, fats and insect proteins. Reference LCI data for insect cultivation was derived from Entomo Agroindustrial, a leading company in industrial insect farming. LCI data for the biochar production were obtained from TNO, a research company from the Netherlands specialising in the pyrolysis technology for over a decade. LCI data for the BBF production (blending of fertilizer ingredients) was provided by ZETADEC, which is a consultancy and contract R&D organisation from the Netherlands for the feed, food and biomass industry. All inventory data is provided in Tables S4–S10 of the supplementary materials.

2.4.2.3. Reference fertiliser production. The NPK content of reference fertilisers is presented in Table S11. The Ecoinvent 3.9.1 database was used to estimate emissions from the reference fertiliser production (the supply of nutrients from various organic and inorganic fertiliser use), by connecting the production of relevant ingredients (e.g., ammonia, urea, phosphate rock, potassium sulphate, manure, compost, etc.) with their generic use as a fertiliser by also considering their NPK content. For organo-mineral fertilisers, a mixture of inorganic fertilisers (e.g., phosphate rock and potassium sulphate) with organic fertilisers (e.g., N supply from manure) was assumed, while for the organic fertiliser (PdL region), the poultry dried manured was assumed based on the product technical data sheet (NPK nutrient supply from poultry manure, dried). Emissions associated to the application of the fertiliser are not included in the Ecoinvent database and had to be calculated in the crop production activity.

2.4.2.4. Crop production. The main emission flows from the crop production due to fertiliser application are denitrification (N_2O emissions direct and indirect), volatilisation of ammonia and NO_x, nitrate leaching and runoff, phosphorus emissions (leaching) and carbon dioxide emission from fossil-based material (urea) [44,45]. Direct N_2O emissions were measured for the control and individual building blocks in the laboratory trials. Direct N_2O emissions from control soil and soil amended with individual building blocks were measured with an automated gas chromatographic system (Agilent 7890A equipped with a micro ECD detector) for continuous gas sampling and analysis of soil aerobically incubated in the laboratory under standard conditions of humidity and temperature. Based on this, emission factors (EF) for direct nitrogen emissions were calculated as follows [5]:

$$EF(\%) = \frac{E_t - E_b}{N} * 100\% \quad (1)$$

where, E_t is the total emission of N (t N/ha) from fertilised treatments, E_b is the background emission from the control without N fertiliser application and N refers to the applied fertiliser rate (t/ha). Other emission factors for all potential N and P loss pathways for both BBFs and reference amendments were taken from the literature (e.g. [46]; [47]; Oldfield et al., 2018), and are available in Table S12 N and P potential losses were calculated as a proportion of total N and P that would be transformed to compounds associated with the relevant impact categories, like Climate Change (N_2O), Acidification Potential (NH_3, NO_x) and Eutrophication (NO_3^-, NH_3, NO_x and P compounds). For the separation of NO_x to NO and NO_2 a ratio of 2:1 was assumed, as suggested in Oldfield et al. (2018).

Table 2 presents the field experiment design in each of the test regions, that includes the type of crops selected for the experiment, fertiliser application dose, dry matter, N, P, K and C input for the crops and estimated emissions based on the proportional use (doses) of individual building blocks in the blends. The rate of the blend application in Flanders, Friuli Venezia Giulia and Pays de la Loire was based on the assumption that they would provide the same amount of available N of reference fertiliser. However, in some cases more N had to be applied because a large part of the total N in the BBFs does not become available to the crop in the growing season after application. In Almeria trials, nutrients were applied with the use of amendments, and, additionally, through fertigation (supplying nutrients with irrigation water). Each treatment received equal amount of nutrient through fertigation (N 128.65 kg/ha, P 29.98 kg/ha and K 183.94 kg/ha), and, in addition, the corresponding nutrients provided by the different amendments.

For organo-mineral fertiliser, it was assumed that N was of organic origin while P was derived from the mineral fertiliser. For organic fertiliser, a mix of compost and manure was assumed for emission calculations. N emissions for Almeria region were calculated by using disaggregated emission factors from IPCC for dry climate. All emissions were aggregated and multiplied with relevant molar mass share of N_2O, NH_3, NO, NO_2, NO_3 and P compounds.

Carbon dioxide (CO_2) emissions were estimated mostly for urea (minor additions of urea were in Flanders), according to the IPCC Tier 1 method [48]. In this LCA study, the 0/0 standard method was used to account for biogenic carbon, which is in line with the EC's Product Environmental Footprint (PEF) method for products with a life time of less than 100 years [45]. The 0/0 approach assumes a characterisation factor of 0 for any C uptake and release, whereas induced carbon sequestration (long term storage of C) is accounted as negative inventory and is multiplied by as a characterisation factor of 1.

2.4.3. Carbon sequestration

The evaluation of soil C sequestration potential of fertiliser ingredients (building blocks) and BBF was performed with an approach integrating short term soil mineralisation of amendments and soil C modelling.

First, the building blocks and BBF were added (at a rate of 0.5 % w:w) to 50 g (oven-dry bases) of preconditioned soil (40 % water holding capacity, 20 °C). The preconditioned amended soil was then placed in plastic jars and aerobically incubated for 30 days at 40 % water holding capacity and 20 °C. The jars were connected to a gas chromatographic system that allowed the determination of soil CO_2 efflux every 4 h. A cumulative respiration curve was calculated from the results of the CO_2 efflux during the incubation period.

In the second step of the evaluation, the cumulative response of the amended soil was used to parametrize a version of the Rothamsted soil carbon model (RothC) [49], specifically modified for amended soils [50]. The parameterization was performed by inverse fitting of the respiration curves utilising the R package "DREAM" [51]. The modified RothC was then used to perform long term simulation (100 years) of SOC utilising the optimised parameters.

2.4.4. Life cycle impact assessment

The LCIA of fertiliser products was modelled via the SimaPro software tool (Pre Sustainability, the Netherlands) by using the EF 3.1 method (adapted). Impact categories selected for this study were prioritised based on their relevance to the evaluated product systems. All impact categories were normalised using global normalisation factors [52] and multiplied by a set of weighting factors (see Table S13), from [53]. Those impact categories that contributed less than 5 % of the single overall score were cut off from the analysis.

2.4.5. Data interpretation and uncertainty analysis

LCA results were interpretated by conducting the comparative analysis (a relative comparison of impact categories and single score for the selected BBF blends and reference treatments in the regions) and contribution analysis (determining which LCA stages and processes have the highest impact over the fertiliser life cycle). To account for uncertainties in data - the source of which lies mostly by the use of mix of industrial, pilot and lab-scale data - the Pedigree matrix was used (see Table S14), which is a standard tool in LCA to systematically assess and document the quality of input data based on five indicators: reliability, completeness, temporal correlation, geographical correlation, technology correlation [54,55]. Each indicator was assigned scores, which were then used to calculate an uncertainty factor (Table S15). This was followed by the Monte Carlo simulation (10,000 simulations were run for each crop and treatment) to provide a probability distribution for the overall single score result.

3. Results

3.1. Comparative analysis

The LCIA results for all test regions are presented in Fig. 3, while the background characterised data are provided in Table S16.

The results for Flanders demonstrate that BBF performs better in climate change, eutrophication marine (due to nitrate leaching from MF), and resource use (mineral). Freshwater eutrophication is much worse for BBF due to the P application and leaching (not available in mineral fertiliser). In other impact categories, BBF performs worse or slightly worse than the reference. In Almeria both Alm/1 and Alm/2 perform better than the reference (compost and manure) in the climate change impact category due to the improved carbon sequestration potential of biochar-enriched amendments. Alm/2 performs also better than manure in terms of particulate matter and terrestrial eutrophication (compounds of ammonia from manure) and better than compost in freshwater eutrophication (P leaching). In all other impact categories, manure and compost perform comparably (at least with Alm/2) or better than BBFs. In FVG, BBFs perform better than manure in the climate change (apart from FVG/2), particulate matter and marine and terrestrial eutrophication categories (due to nitrate leaching from manure). FVG/2 performs much worse than FVG/1 and FVG/3 in the climate change category (and worse than manure) because it does not contain biochar, and thus the carbon storage potential of FVG/2 is low. Compared to the OMF, BBFs perform better in climate change (apart

Table 2
Dry matter, N, P, K and C input for crop production and associated emissions in all region.

Region	Flanders						Almeria				Friuli Venezia Giulia					Pays de la Loire				
Crop type	Leek			Cauliflower			Tomato + cucumber				Vineyard					Lettuce			Vineyard	
Treatment	Fl/1	Fl/2	MF	Fl/1 + MF	Fl/2 + MF	MF	Alm/1	Alm/2	Manure (sheep)	Compost	FVG/1	FVG/2	FVG/3	Manure (bovine)	OMF	PdL/1	OMF	MF	PdL/1	OF
Fertiliser dose (kg/ha)	13,000	6500	370	13,000	6500	925.9	10,500	11,500	4000	15,000	17,050	17,050	17,050	20,000	1390	6500	750	570	3300	570
Dry matter (kg/ha)	7488	4615	–	8346	4914	–	6510	7199	1840	11,040	11,458	10,822	11,243	4024	1277	3906.5	750	570	1983.3	484.5
N (kg N/ha)	154.3	136.6	100	133.5 Fl/1 + 100 MF	153.8 Fl/2 + 100 MF	250	178.4	97.9	31.28	405	185.6	221.8	124.8	114.3	29.2	79.3	82.5	79.8	40.3	39.9
P (kg P/ha)	43.4	35.5	–	40.9	33.9	–	32.6	29.5	23.92	70.5	40.1	48.7	61.8	–	44.6	27.0	37.5	28.5	13.7	14.4
K (kg K/ha)	89.9	69.2	100	91.8	88.5	83	78.1	93.6	73.6	60	114.6	108.2	112.4	–	106.0	47.3	105.0	114.0	24.0	18.9
TOC (kg C/ha)	2179	2238	–	1920	2914	–	2812	3535	496.8	4920	3606	2512	5815	1630	202	1832.1	118.5	0.0	930.2	196.2
Emissions to air																				
CO_2 (kg/ha)	–	–	122.2	–	–	305.8	–	–	–	–	–	–	–	–	–	–	–	–	–	–
N_2O direct and indirect (kg/ha)	0.3	0.4	3.2	3.4	3.6	7.9	0.4	0.1	0.3	0.3	0.5	0.6	0.2	0.5	2.1	0.1	1.5	2.5	0.1	0.7
NH_3 (kg/ha)	5.2	9.9	12.0	16.5	23.2	30.1	11.4	3.4	7.2	1.6	7.8	9.5	4.6	6.7	26.4	2.9	19.0	9.6	1.5	9.2
NO_x (kg/ha NO)	0.5	0.7	1.6	2.0	2.4	3.9	1.1	0.1	0.9	0.2	1.0	1.2	0.3	0.8	3.3	0.2	2.4	1.3	0.1	1.1
NO_x (kg/ha NO_2)	0.3	0.5	1.2	1.5	1.8	3.0	0.9	0.1	0.7	0.2	0.7	0.3	0.2	0.6	2.5	0.1	1.8	1.0	0.1	0.9
Emissions to water																				
NO_3 (kg/ha)	32.2	33.2	106.3	134.1	143.6	265.7	53.9	57.8	33.2	44.9	51.5	67.1	22.2	31.1	121.5	13.8	87.7	84.8	7.0	42.4
P (kg/ha)	0.8	0.7	0	0.8	0.7	0	0.6	0.5	0.3	0.8	0.7	0.9	1.1	0.9	0	0.5	0.8	0.9	0.2	0.1
C-sequestrated (kg/ha)	**1165**	**2838**	**0**	**1026**	**3694**	**0**	**2547**	**6928**	**151**	**1063**	**2932**	**681**	**5167**	**60**	**485**	**1617**	**35**	**0**	**822**	**16**
Crop yield (T/ha)	**37.6**	**34.8**	**36.6**	**31.6**	**31**	**37.4**	**194.7**	**202.1**	**216.2**	**206.1**	**2.25**	**2.25**	**2.25**	**2.25**	**2.25**	**43**	**43**	**43**	**2.25**	**2.25**
Field experiment period (months)	**7**	**7**	**7**	**2.5**	**2.5**	**2.5**	**10**	**10**	**10**	**10**	**6**	**6**	**6**	**6**	**6**	**8**	**8**	**8**	**8**	**8**

MF = Mineral Fertilizer, OMF = Organo-Mineral Fertilizer, OF = Organic Fertilizer (dried pultry manure).

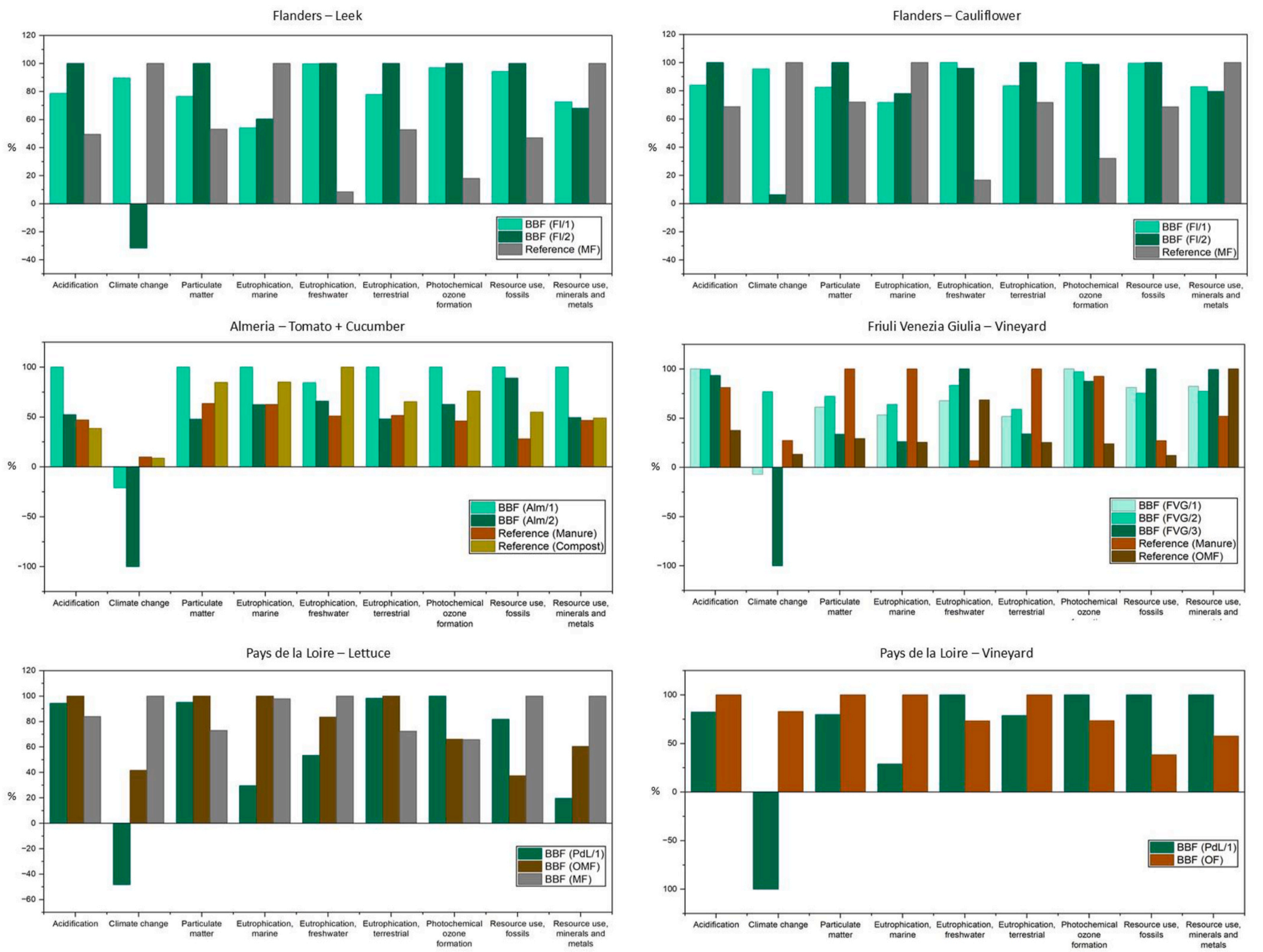

Fig. 3. LCIA characterised results for BBFs and refence fertilisers in Flanders, Almeria, Friuli Venezia Giulia and Pays de la Loire regions (FU = 1 tonne of crop/ha) showed on the % basis (a relative comparison in relation to a reference/higher value).

from FVG/2), eutrophication freshwater (only FVG/1) and resource depletion (mineral) categories and worse or comparable in the remaining impact categories. In PdL, the BBF performs better in most impact categories than OMF (apart from resource depletion, fossil) and MF (apart from acidification, particulate matter, eutrophication terrestrial and photochemical ozone creation potential). In the case of the

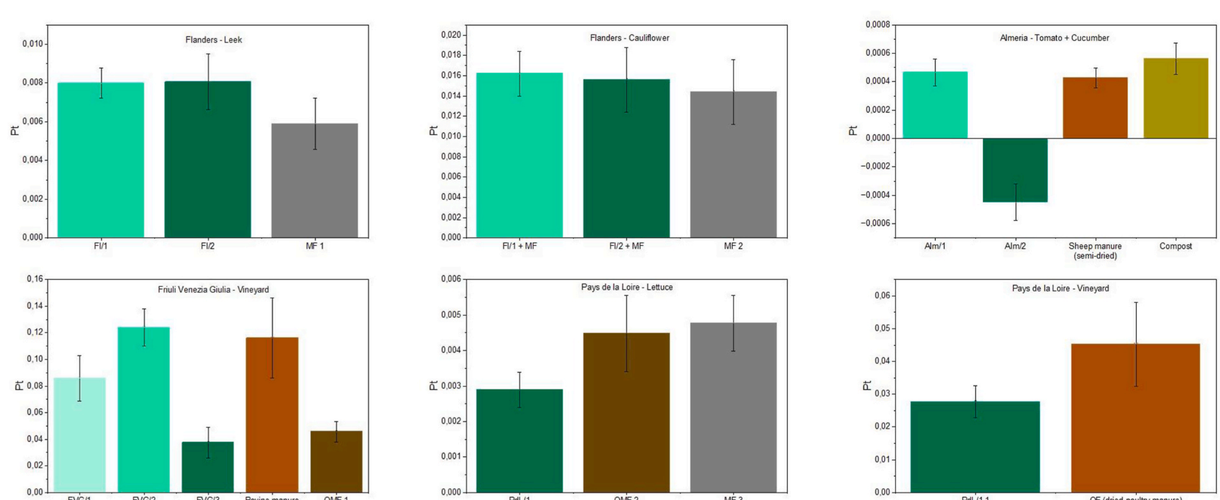

Fig. 4. LCIA results after normalisation and weighting for BBFs and reference fertilisers in Flanders, Almeria, Friuli Venezia Giulia and Pays de la Loire regions (FU = 1 tonne of crop/ha), expressed in a single-score unit (with uncertainty indication) that represent the total environmental impact.

grape crop, the climate change category is better for PdL/1 than the reference poultry manure. In air quality impacts, PdL/1 performs comparable or better than the reference. PdL/1 performs worse than the organic fertiliser in freshwater eutrophication (due to P leaching), but better in marine and terrestrial eutrophication due to the higher nitrate leaching and airborne ammonia emission from the organic fertiliser during the field application.

Fig. 4 presents the LCIA results after normalisation and weighting for BBFs and reference fertilisers in Flanders, Almeria, Friuli Venezia Giulia and Pays de la Loire regions (FU = 1 tonne of crop/ha), along with uncertainty values based on Monte Carlo simulations.

It is evident that the overall environmental performance of BBFs (Fl/1 and Fl/2) is worse if compared to the MF mostly because the substantial difference in fertiliser doses between the BBF and reference (up to 35 times more BBF fertiliser applied than the MF to supply required N for the plants). The air quality impact categories (acidification and particulate matter due to the NOx and ammonia emissions) from the microbial proteins production are the main contributors to the total environmental score of BBFs, followed by terrestrial eutrophication. The overall environmental performance of Alm/1 is better than compost and comparable to manure. On the other hand, Alm/2 performs much better than manure and compost due to the relatively high proportional use of biochar in the blend (52 % by mass) - and thus the enhanced carbon sequestration potential of the blend - leading to the negative climate change impact. The overall environmental performance of FVG/1 is better than manure but is also worse than the OMF. FVG/2 performs worse than both manure and OMF. On the other hand, the overall impact of FVG/3 (net off carbon sequestration) is lower than both manure and organo-mineral fertiliser. The fossil resource use also contributes largely to BBFs (especially for FVG/3) due to the transportation activities for the blend production and distribution of BBF on the field. The overall environmental performance of PdL/1 is nearly twice as good as of OMF and MF for lettuce production, and nearly twice better than dried poultry manure for the vineyard production.

The LCIA results clearly shows that the large difference in application rates disfavours BBFs compared to OMF and MF (this is especially evident in Flanders). These elevated application rates result in a marked increase in emissions associated with fertiliser production and transportation leading to increased resource consumption and environmental burdens. Hence, substituting the most impactful building blocks in the blend could potentially improve the sustainability performance of BBFs.

On the other hand, the results demonstrate that the inclusion of biochar as a component in BBFs clearly has a pronounced effect on the climate change and thus overall environmental performance of BBFs. Under the EU Fertilising Products Regulation (Regulation (EU) 2019/1009) as amended by Commission Delegated Regulation (EU) 2021/2088, pyrolysis and gasification materials (biochar) were added as Component Material Category CMC 14, enabling their use in EU-labelled fertilising products subject to quality and safety. BBF blends containing biochar (e.g., Fl/2, Alm/2, FVG/3, PdL/1) demonstrated significantly lower, and in some scenarios even negative, net contributions to climate change. Field results from locations such as Flanders, Almeria, and Friuli Venezia Giulia confirmed an increase in the SOC, a key indicator of carbon retention.

3.2. Contribution analysis

Fig. 5 presents the contribution analysis of different life cycle stages of BBFs based on normalised and weighted LCIA results.

For Fl/1 and Fl/2 (leek), the main contribution to the overall environmental score comes from the microbial biomass production (68–72 %) due to the energy-intensive drying process. Although the energy for microbial biomass production is supplied from renewable sources (the AD technology in this case), the biogas burning is still the source of methane (unburned), NO_x and NMVOC emissions. Furthermore, the microbial biomass cultivation process requires the use of mineral additives, such as diammonium phosphate and sodium hydroxide. The next main contribution comes from transport (10 %–13 %) followed by field application emissions (12 %–13 %). For the cauliflower crop, the microbial biomass production is still the main contributor to the total environmental score (40 %–42 %), followed by the field application (approx. 39 % due to addition of N mineral fertiliser) and transport (6 %–8 %).

The use of larvae biomass in Alm/1 contributes 46.6 % to the total life cycle impact of this blend (due to the energy required during the breeding, fattening and shifting processes and special diet prepared for larvae breeding process). It appears that, when only insect frass is used as a building block, the overall environmental performance of the blend improves (as in the case of Alm/2). This is because the allocation of environmental burden to frass is reduced when insect biomass is destined for valorisation in other more industrial sectors (e.g., animal feed) to obtain more valuable by-products (proteins, fats and chitosan). The next main contribution is related to all transport activities (26 %–34 %) and composting (24 %–26 %). All impacts coming from the BBF production are partly (Alm/1) or fully (Alm/2) compensated by negative emissions from the field application (carbon sequestered in the soil).

The contribution analysis showed that for FVG/1 and FVG/2, the main impacts come from the insect biomass production (34 %–46 %), followed by compost production (24 %–26 %) and transport activities (8 %–16 %). Emissions from the field application contribute largely to the total impact of FVG/2 (nearly 33 %) because this blend does not contain biochar, and thus receives no compensation for carbon storage in the soil. Similarly to Fl/1 and Fl/2, for FVG/3 and PdL/1, the main contributors are microbial biomass production and transport activities, which are partly compensated by the carbon sequestration from the field application.

Fig. 5 demonstrates that the main environmental impacts of BBFs are linked to the production processes – especially the generation of microbial and insect biomass – rather than to their field application. Even when powered by renewable energy (e.g. via anaerobic digestion), the processes of composting, fermentation, drying, and combustion can result in substantial NOx, NH_3, and NMVOC emissions, contributing notably to acidification and particulate matter formation. The production of microbial and insect-derived biomass also requires substantial energy (e.g., for drying) and chemical inputs (e.g., DAP, NaOH).

3.3. Other agronomic and environmental properties of BBFs

Beside the impacts of blend application on the categories selected for

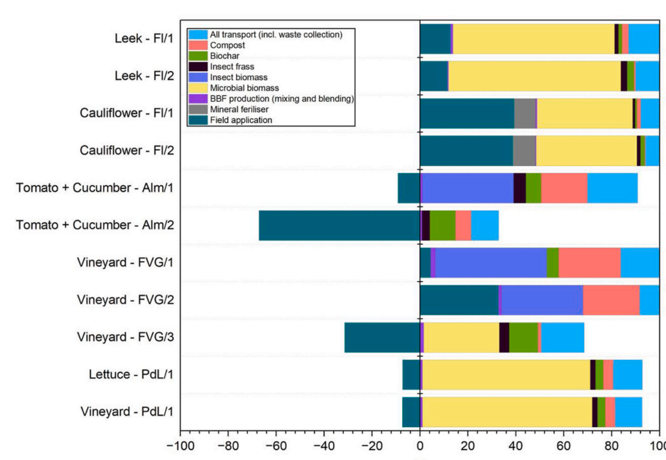

Fig. 5. Contribution analysis of different life cycle stages of BBFs based on normalised and weighted LCIA results (negative values for field application for some regions means that the benefits from carbon sequestration outweighs impacts emerging from, for example, N and P runoff and leaching).

LCIA, further agronomic and environmental properties of the blends (not captured via LCA) were highlighted from the results of field trials and are summarised in Table 3.

First of all, no negative effects on the blends on soil quality were observed. An increase in soil organic C, a proxy for soil organic matter content was recorded in Flanders (for Fl/2), Almeria and FVG. For the blends containing biochar, it is expected that its C will persist in the soil for a long period favouring the long-term C sequestration. The enhanced SOM is reflected in the improved capacity of water retention as recorded in Almeria and FVG.

BBF showed also a significant impact on the microbial pool, at least for the trials performed in Almeria and FVG. In Almeria, the placement of Alm/1 and Alm/2 blends on the imported soil induced larger enzymatic activities, while in Friuli Venezia Giulia, blend application resulted in an enhancement of both the content and the activity of soil microbial biomass. In Flanders, blend application did not result in negative effects on the microbial pool.

Regarding the effects on nutrients, results were mixed. There was an increase in FVG, while in PdL there was a similar (lettuce) or lower (grape trial) amount of mineral N in soil for the BBF blends compared to the reference organic fertiliser. In Flanders, soil mineral N was increased by the blends, but such increase, while sufficient for leek, was lower than the required amount for cauliflower. In Flanders, a relative larger part of the mineral N was present in the topsoil layer for the BBFs compared to the mineral N fertiliser. Consequently, roots can easily access the mineral N and less N is prone to leaching and environmental impact.

Yield effects were less pronounced in the trials. In general, the yields for the BBFs were similar compared to the reference. In the case of cauliflower in Flanders, lower yields were recorded for the blends. On the other side, lettuce yields were larger in field trials in PdL. In FVG blends application to the soil showed a tendency to increase grape productivity and mean cluster weight and a significant larger mean berry weight.

Differences in crop quality were sometimes more pronounced. Leek visually scored better with the Fl/2 fertiliser compared to the reference. In Almeria, a higher quality of tomatoes was observed for BBFs compared to the references. In addition, lower levels of oxidative stress were observed in tomato and cucumber. The must derived from the grapes in FVG was of higher quality (i.e., more prone to produce high quality vine) for the BBFs compared to the references.

4. Discussion

Across all test regions, LCIA results confirm that the environmental performance of bio-based fertilisers (BBFs) is shaped primarily by two cross-cutting factors: (i) the difference in application rates between BBFs and reference fertilisers (up to 35 times more than mineral fertilisers in the case of Flanders), and (ii) the presence and dosage of biochar in the blend. Because the functional unit (FU) is agronomic (yield- or area-based), high application rates penalise BBFs through upstream production and transport burdens and through greater potential for NH_3/NO_x emissions at application, which drive acidification, particulate matter and eutrophication impacts.

Table 3
Agronomic and other environmental properties of BBFs not captured via LCA for the four test regions (+; there is a beneficial effect, +/−; the effects were not clear/varying, -; there was a negative effect, x; no effect, nd; no data).

	Flanders	Pays de la Loire	Almeria	Friuli Venezia Giulia
Crop	**Leek**	**Lettuce**	**Cucumber**	**Grapes**
Soil quality (organic matter and water retention)	+	nd	+	+
Soil nutrients	+	+/−	nd	+
Soil biological activity	+/−	+/−	+	+
Yield	+/−	+	+/−	+/−
Product quality	+	+/−	+/−	+
Crop	**Cauliflower**	**Grapes**	**Tomato**	
Soil quality	+	x	+	
Soil nutrients	x	x	nd	
Soil biological activity	+/−	nd	+	
Productivity	x	+	+/−	
Product quality	x	nd	+	

The doses of BBF are usually higher than of MFs since a large part of the BBF consists of organic material, which is not present in mineral counterparts. Moreover, a large part of the total N in the BBF does not become available to the crop in the growing season after application. For example, maximum 15 % of N in composts becomes available to the crop, because it is not mineralised. Hence, although the N dose may look large for the BBF, the mineral N dose is much lower compared to MFs. This was especially evident in the field trial in Flanders, where mineral N measured in the soil after application was larger for the MF compared to the two BBFs, despite the fact that the doses of MF were much lower.

Hence, it is difficult to match N delivery form MF and organic amendments because N in MF is all readily available, the same is not the case of amendments. N availability in amendments depends from their decomposition rate that is regulated by different factors (amendment properties, soil temperature and humidity, crop management) and therefore difficult to foresee. A rough indication can be provided by laboratory tests, but as conditions in the laboratory and the field are different, the match between laboratory and field results could be not very straight. Soil analyses of field trials showed that the amount of available N provided by the blends were larger than hypothesized from the tests performed in the laboratory. This is not surprisingly as the conditions are different between laboratory and field conditions. As a matter of fact, laboratory incubations are performed as a tool for a fast ranking of several amendments in terms of their impact on soil properties rather than to provide absolute values of parameters. Results of laboratory test are rough indication of the impact of an amendment that need to be further verified in field trials.

In the Italian field trial, all the productivity parameters were higher for the BBF with respect to the control and the reference treatments, but these larger values were not always statistically significant. For this reason, in the LCA analysis the same productivity was assigned to the blends and the references treatment. The results of the field trial indicated that is likely possible to decrease the rate of BBF without compromising the productivity levels, increasing the performance of the blends in term of their environmental impact.

The inclusion of biochar emerges as a consistent driver of improved climate performance. Scenarios with a high share of biochar (e.g. Alm/2, FVG/3, PdL/1) exhibit markedly lower, and in some cases even negative, net contributions to climate change due to soil carbon sequestration. In contrast, BBFs without biochar (e.g. FVG/2) perform worse despite similar logistical and application practices, confirming the role of biochar in soil organic carbon (SOC) storage [56]. These findings are corroborated by independent experimental and modelling evidence. An environmental assessment of activated biochar nitrogen fertiliser showed up to 63 % savings in reactive nitrogen emissions compared to urea, ammonium nitrate, or DAP, with reduced nitrate leaching [57]. Furthermore, while biochar contributes to negative emissions through CO_2 sequestration, its environmental role should not be reduced to this single function. Additional literature (e.g. Matthews et al. [58]) suggests that even temporary carbon storage may contribute to climate stabilization by lowering peak global temperatures – provided that fossil fuel emissions are simultaneously reduced. LCA methodologies should evolve to better reflect such dynamics, including carbon retention stability and soil system interactions. Environmental assessments should also carefully distinguish between negative emissions (e.g., from carbon sequestration) and avoided emissions (e.g., by replacing more GHG-intensive products like mineral fertilisers). While this conceptual distinction is valid, it was not the central modelling framework in this

LCA study; rather, such considerations are embedded implicitly in system boundary and allocation choices.

Apart from reducing GHG emissions, BBFs often deliver additional agronomic functions beyond nutrient supply, such as improving soil structure, water retention, and biological activity. These findings were recently also confirmed by Bauhzam et al. [19] and Torres-Guerrero et al. [21]. These aspects may, in some contexts, outweigh their role as simple nutrient carriers. Consequently, relying solely on nutrient-based functional units may overlook important co-benefits of BBFs, and complementary metrics such as nutrient-use efficiency and soil health indicators should be considered. In future studies, it would be worthwhile to include parallel reporting normalised to the nutrients delivered (e.g., per kg of N and P) and – where possible – to nutrient use efficiency. Such dual reporting facilitates benchmarking of BBFs as nutrient carriers rather than merely 'yield triggers' [21]. Although some of the soil quality aspects are measured, at least indirectly, in LCA (e.g., land use, acidification, ecotoxicity, carbon dioxide emissions will lead to changes in soil quality), this added value is not fully grasped by LCA methods and was thus reported separately in this paper (in Table 3).

Finally, a comprehensive agronomic assessment of BBFs requires a multi-season monitoring of long-term effects on soil structure, carbon balance, nutrient accumulation and availability, as well as microbial community dynamics—all of which play key roles in nutrient cycling and plant health. For example, as some BBF treatments may require continued inputs over the years, biochar can remain in the soil for hundreds or even thousands of years. As this has a pronounced effect on the carbon sequestration and thus the environmental impact in general, continued addition of biochar in the soil could have derogatory effects on soil pH and overall productivity depending on soil type [59]. In the context of sustainable agriculture, BBFs should be regarded not merely as nutrient suppliers but as instruments for building long-term soil fertility and resilience. This requires moving beyond short-term agronomic trials toward integrated monitoring programs that include physical, chemical, biological, and climatic parameters. Future BBF strategies should therefore prioritise precision formulation based on local soil diagnostics, crop requirements, and environmental-technological settings. Transitioning from universal products to regionally tailored BBFs is essential for maximizing both environmental effectiveness and market viability.

5. Conclusions

This study assessed the environmental performance of BBF over its life cycle (from waste collection and processing, BBF production to field application), and comparing this performance with the reference scenario, which was individually defined for the selected test regions in Europe. Although associated with uncertainties, the results presented in this paper are promising and constitute an attractive option for further research and optimization. The results confirmed that BBFs with differing compositions produced divergent environmental profiles, even when developed for the same region. The large difference in application rates (up to 35 times more by weight BBFs were applied than conventional fertilisers) disfavours waste-derived BBFs compared to mineral and organo-mineral fertilisers. On the other hand, the inclusion of biochar as a component of BBFs has a pronounced effect on the climate change and thus overall environmental performance of BBFs significantly increasing their attractiveness. Apart from reducing GHG emissions, BBFs deliver additional agronomic functions beyond nutrient supply, such as improving soil structure, water retention, and biological activity, which are not fully grasped by existing LCA methods and which provide an attractive scope for future work. Findings from this paper provides useful insights to farmers, academics, policymakers and other stakeholders whether (and under what conditions) the production and application of waste-derived BBFs can enhance soil health, improve nutrient availability, and reduce reliance on synthetic fertilisers. Also, LCA data provided in this paper for new biomass treatment technologies and materials, may be highly valuable for other researchers interested in recycling of organic wastes for sustainable BBF production and farming.

CRediT authorship contribution statement

Dominik Jasiński: Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Erika De Keyser:** Writing – original draft, Methodology, Investigation, Conceptualization. **Claudio Mondini:** Writing – original draft, Methodology, Formal analysis, Data curation. **Fien Amery:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Jolanta Baran:** Writing – original draft, Methodology, Formal analysis. **Erika Ronchin:** Writing – original draft, Methodology, Formal analysis. **Federica Cisilino:** Writing – review & editing, Methodology, Conceptualization. **Annalisa Angeloni:** Writing – review & editing, Methodology, Conceptualization. **Daan Kuiper:** Writing – review & editing, Supervision, Methodology. **Rianne Visser:** Writing – review & editing, Data curation. **Nathan Deman:** Writing – review & editing, Data curation. **Alba Alonso Adame:** Writing – review & editing, Conceptualization. **Carolina C. Martínez-Gaitán:** Writing – review & editing, Conceptualization. **Rebeca Ramos:** Writing – review & editing, Conceptualization. **Luka Dobrović:** Writing – review & editing, Supervision, Funding acquisition.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2025.108705.

Data availability

Data will be made available on request.

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