Evaluating the impact of novel biobased fertilisers on soil carbon sequestration integrating laboratory short-term mineralization and modelling

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Introduction

The shift toward circular food economies and sustainable agriculture promotes recycling of exogenous organic matter (EOM) through biobased fertilisers (BBFs) production. While this reduces reliance on mineral and synthetic fertilisers, the long-term impact of BBFs on soil organic matter dynamics remains uncertain.

This study aims to model the impact of novel BBFs—such as microbial biomass, insect biomass, insect frass, biochar, and derived blends, produced in the framework of H2020 project RUSTICA—on long term soil C storage.

For this purpose, we used a modified RothC model encompassing additional EOM pools to calibrate parameters (pool size and decay rates) of BBFs and their blends. This was done through inverse modelling of mineralization rates of amended soil samples, measured with an automated gas chromatography system (Cervera-Mata et al. 2022, Fig. 1a).

Approach

Soil, BBFs, and blends

For the experiment, a loam soil from a vine farm, with density of 1.41 t/m^3 and clay content of 11.83%, was air dried, sieved to 3 mm and stored at ambient temperature until starting of incubation.

The following novel BBFs (Fig. 1b-e) were used in the experiment: microbial biomass (MB), biochar (BI), insect biomass (IB), and insect frass (IF). In addition, several blends (Fig. 1g and Fig. 3b) of BBFs with compost (Fig. 1f) were utilised, therefore compost (comp) being a blend component was included among the BBFs.

Soil incubation

50 g (oven-dry bases) of soil was brought to 40% WHC and preconditioned for 4 days at 20°C. The soil was then amended (in triplicate) with a dose of 0.5% (w:w) of diverse BBFs and derived blends, placed in plastic jars (Fig. 1h) and aerobically incubated for 30 days at 40% WHC and 20 °C.

Sealed sample jars (Fig. 1a) were continuously aerated at a constant flow rate (15 ml min^{-1}). Every 4 hours, a valve directed the flux from a jar to a GC for CO_2 analysis. The system allows automated, continuous sampling and analysis of 30 samples.

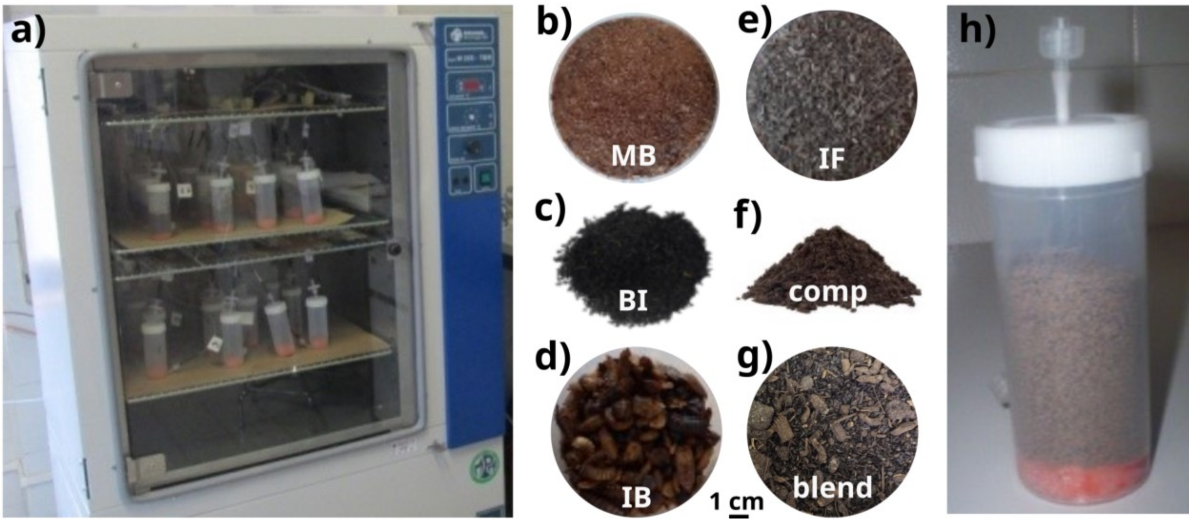


Figure 1 (a) Thermostat containing the incubation jars of the automated GC system. (b - g) Some BBFs before drying, grinding, and sieving at 1 mm. (h) Incubation jar with valves for aeration and humidity control.

Calibration of BBFs' kinetic parameters

The parameters of BBFs' EOM pools were determined by inverse fitting of the Rothamsted carbon model (RothC) (Coleman and Jenkinson, 1996), modified for amended soils, to the cumulative respiration curves.

The modified RothC model enables the simulation of mineralization rates for EOM-amended soils by incorporating three additional C pools: decomposable (DEOM), resistant (REOM), and humidified (HEOM), each with specific partition coefficients. DEOM and REOM have assignable decomposition rates, while HEOM has a fixed rate of 0.02 y^{-1}. The RothC model was modified with a new R function based on Mondini et al. (2017), implemented and validated against the Excel version from the same study, yielding identical results.

To estimate optimal kinetic parameters of BBFs and blends, the R package "DREAM" (Guillaume and Andrews, 2012) was used to invert the measured mineralization rates (Fig. 2). This package employs the iterative Markov Chain Monte Carlo (MCMC) approach using the Differential Evolution Adaptive Metropolis (DREAM) algorithm (Vrugt et al., 2009) to sample the search space and infer the posterior probability density functions for C-pool sizes and decay rates.

Given the limited knowledge of kinetic parameters for novel BBFs, parameter estimates were guided by predefined search spaces based on minimum and maximum values from similar products in the literature (Woolf et al., 2023; Mondini et al., 2017), and expanded where necessary to ensure robust solutions.

The sum of all EOM pools equal to 1 allows us to express the sizes of the REOM and HEOM pools as functions of the DEOM pool size and a repartition factor. This narrows the search for optimal values to four parameters: DEOM pool size (f.DEOM), repartition factor (rep.f), and decomposition rate constants k.DEOM and k.REOM, each with defined remapped boundaries (Fig. 3b).

Main findings

Cumulative mineralization rates of amendments (Fig. 2) were calculated by removing outliers and averaging three replicate signals. The effect of the amendments was isolated by subtracting soil CO_2 efflux from a control (untreated soil).

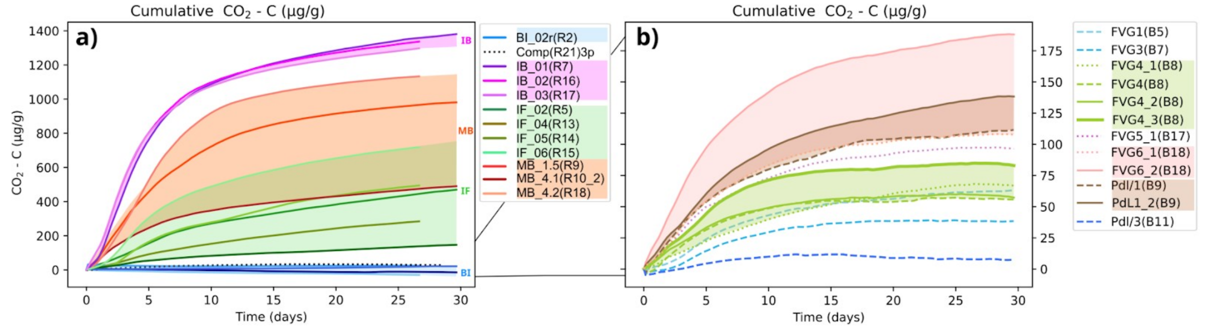


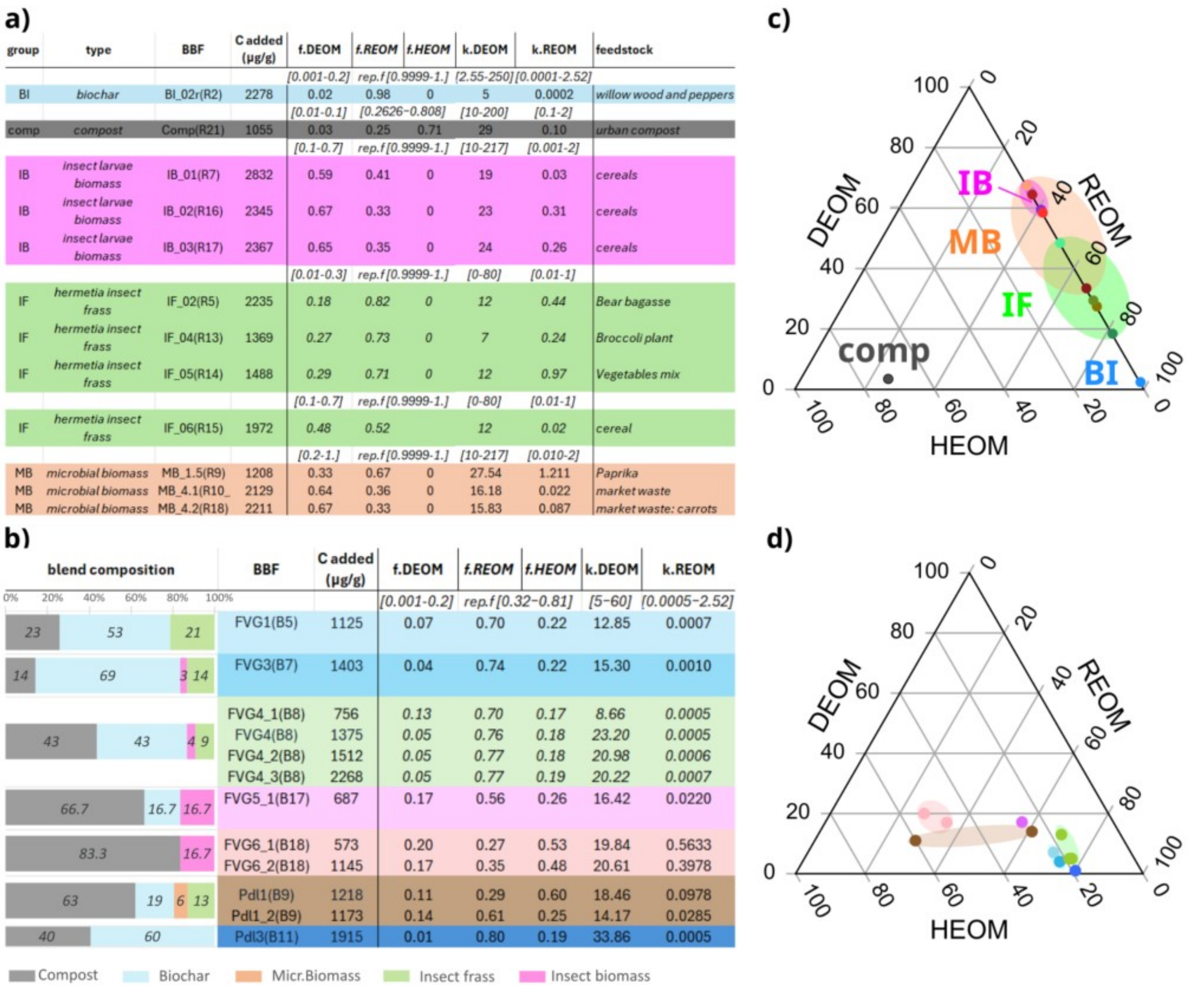
Figure 2 Cumulative respiration during the 30-days incubation expressed as µg CO_2-C g soil^{-1}, for (a) single-component BBFs and (b) blends of BBFs and compost.

BBFs' kinetic parameters

Calibrating soil C model pools typically requires long-term experiments (LTEs), but these are costly and labour-intensive. Laboratory incubation offers a practical alternative, provided that cumulative respiration curves are tracked accurately to reliably estimate SOM pools. The automated system in this study, with high measurement frequency, improves accuracy over traditional methods having fewer sampling points, compensating for the limitations of shorter incubation periods.

All BBFs were considered to have two pools, except compost, which was modelled with three pools (Fig. 3a). This approach positioned compost away from the zero HEOM axis on the ternary plot (Fig. 3c), while other BBFs aligned along this axis, with IB and BI at the extremes of low and high REOM, respectively. The ternary plot shows overlapping but distinct ranges for each BBF group. Low variability among IB is likely due to their uniform origin as larvae of *Hermetia illucens* bred on cereals, whereas the greater variability in IF and MB groups likely reflects their diverse feedstocks (Fig. 3a).

All blends were modelled using three pools. Different amounts of the same blend added to the soil are represented by the same colour (Fig. 3b). The ternary plot (Fig. 3d) shows that blends with a high biochar content cluster around high REOM values, while even a moderate amount (16.7%) of IB in the blend lowers the REOM values. Increasing blend doses generally do not affect the parameter calibration results, demonstrating the stability of the calibration approach and the reliability of the respiration curves.



a)

group	type	BBF	C added (µg/g)	f.DEOM	f.REOM	f.HEOM	k.DEOM	k.REOM	feedstock
				[0.001-0.2]	rep.f [0.9999-1.]		[2.55-250]	[0.0001-2.52]	
BI	biochar	BI_02r(R2)	2278	0.02	0.98	0	5	0.0002	willow wood and peppers
				[0.01-0.1]	[0.2626−0.808]		[10-200]	[0.1-2]	
comp	compost	Comp(R21)	1055	0.03	0.25	0.71	29	0.10	urban compost
				[0.1-0.7]	rep.f [0.9999-1.]		[10-217]	[0.001-2]	
IB	insect larvae biomass	IB_01(R7)	2832	0.59	0.41	0	19	0.03	cereals
IB	insect larvae biomass	IB_02(R16)	2345	0.67	0.33	0	23	0.31	cereals
IB	insect larvae biomass	IB_03(R17)	2367	0.65	0.35	0	24	0.26	cereals
				[0.01-0.3]	rep.f [0.9999-1.]		[0-80]	[0.01-1]	
IF	hermetia insect frass	IF_02(R5)	2235	0.18	0.82	0	12	0.44	Bear bagasse
IF	hermetia insect frass	IF_04(R13)	1369	0.27	0.73	0	7	0.24	Broccoli plant
IF	hermetia insect frass	IF_05(R14)	1488	0.29	0.71	0	12	0.97	Vegetables mix
				[0.1-0.7]	rep.f [0.9999-1.]		[0-80]	[0.01-1]	
IF	hermetia insect frass	IF_06(R15)	1972	0.48	0.52		12	0.02	cereal
				[0.2-1.]	rep.f [0.9999-1.]		[10-217]	[0.010-2]	
MB	microbial biomass	MB_1.5(R9)	1208	0.33	0.67	0	27.54	1.211	Paprika
MB	microbial biomass	MB_4.1(R10_	2129	0.64	0.36	0	16.18	0.022	market waste
MB	microbial biomass	MB_4.2(R18)	2211	0.67	0.33	0	15.83	0.087	market waste: carrots

b)

blend composition	BBF	C added (µg/g)	f.DEOM	f.REOM	f.HEOM	k.DEOM	k.REOM
0% 20% 40% 60% 80% 100%			[0.001-0.2]	rep.f [0.32−0.81]		[5−60]	[0.0005−2.52]
23 53 21	FVG1(B5)	1125	0.07	0.70	0.22	12.85	0.0007
14 69 3 14	FVG3(B7)	1403	0.04	0.74	0.22	15.30	0.0010
43 43 4 9	FVG4_1(B8)	756	0.13	0.70	0.17	8.66	0.0005
	FVG4(B8)	1375	0.05	0.76	0.18	23.20	0.0005
	FVG4_2(B8)	1512	0.05	0.77	0.18	20.98	0.0006
	FVG4_3(B8)	2268	0.05	0.77	0.19	20.22	0.0007
66.7 16.7 16.7	FVG5_1(B17)	687	0.17	0.56	0.26	16.42	0.0220
83.3 16.7	FVG6_1(B18)	573	0.20	0.27	0.53	19.84	0.5633
	FVG6_2(B18)	1145	0.17	0.35	0.48	20.61	0.3978
63 19 6 13	Pdl1(B9)	1218	0.11	0.29	0.60	18.46	0.0978
	Pdl1_2(B9)	1173	0.14	0.61	0.25	14.17	0.0285
40 60	Pdl3(B11)	1915	0.01	0.80	0.19	33.86	0.0005

Figure 3 (**a, b**) Tables showing estimated C-pool sizes and decay rates from DREAM, with parameter bounds in brackets, for (a) single-component BBFs and (b) blended BBFs. (**c, d**) Ternary plots illustrating BBF group distributions based on optimised C-pool sizes for (c) single-component and (d) blended BBFs (colour-coded as in panel b).

Long-term predictions of SOC in amended soil

We hypothesised two long term (100 years) scenarios of soil amendment: (1) single initial addition of 10 ton C/ha and (2) annual addition of 1 ton C/ha.

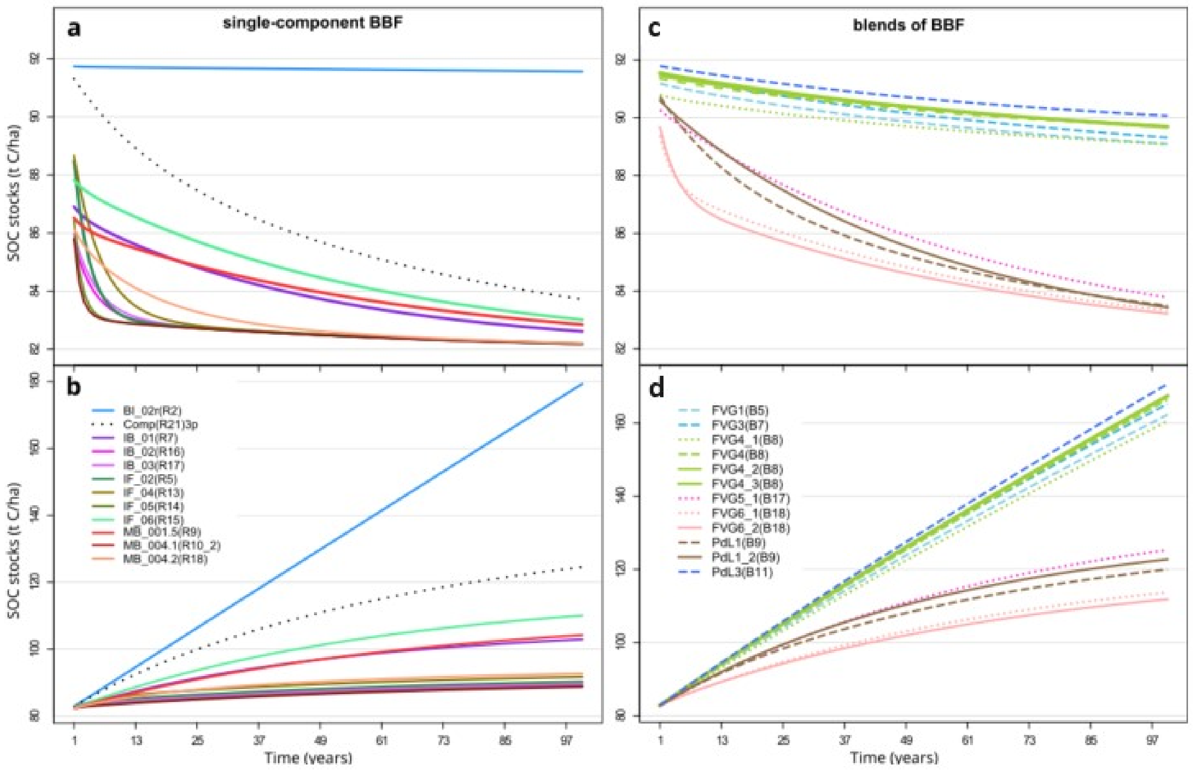


Figure 4 Long-term SOC predictions for (a, b) single-component BBFs and (c, d) BBFs blends. (a, c) Single initial addition of 10 ton C/ha, (c, d) annual addition of 1 ton C/ha.

Single initial addition results show biochar's high degree of stability, with 96.6% C remaining after 100 years, indicating its effectiveness in soil C sequestration (Fig. 4a). In contrast, compost, insect biomass, insect frass, and microbial biomass degrade faster, with 18.2, 4.3, 5.0, and 4.7% C remaining, respectively. Continuous annual amendment simulations reveal biochar significantly increases SOC stocks by 119% (Fig. 4b), while compost contributes 52%. Other BBFs contribute less to long-term sequestration, with annual rate of C sequestration around 0.13 ton C/ha/y, but offer other soil benefits.

Blends with biochar show varying C retention after 100 years (13.1% to 82%) (Fig. 4c), depending on biochar content (0% to 60%). Biochar stabilises more degradable materials in blends, like IB and MB, impacting SOC accrual. Blend FVG4 (41% biochar), and FVG3 and PdL3 (69 and 60% biochar, respectively) show similar remaining C values (Fig. 4c). Continuous annual amendment (Fig. 4d and Fig. 5) result in SOC stocks increase of 36% to 108% over 100 years, correlating with biochar content ($r = 0.91$; $p < 0.05$). The blends show a significant C sequestration potential, with annual rates ranging from 0.30 to 0.89 ton C/ha/y.

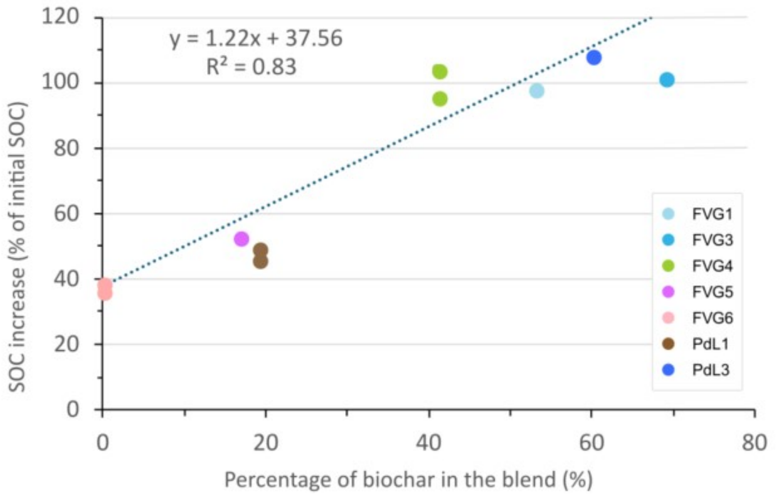


Figure 5 SOC increase vs. % of biochar in the blend

Conclusions

Our findings provide valuable insights for agriculture and environmental managers, particularly for sustainable soil management and carbon sequestration. By classifying BBFs and blends based on stability and C sequestration potential, the research offers insights to guide their development and application. For example, biochar's stability makes it ideal for enhancing soil organic carbon (SOC) storage and reducing greenhouse gas emissions, while rapidly degrading BBFs like insect and microbial biomass provide fast nutrients but require careful use to prevent carbon loss. These insights help the industry optimise fertiliser application, improving crop productivity and environmental sustainability.

Learning objectives

This study enhances understanding the use of BBFs in soil management and carbon sequestration. Attendees will learn to apply the modified RothC model for calibrating EOM kinetics and predicting long-term soil carbon dynamics. This will help them assess soil amendments' sustainability and develop practices that optimise soil health, carbon storage, agricultural productivity, and environmental conservation.

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