Biochar and organic matter co-composting: a critical review

David Chiaramonti
RE-CORD and Department of Industrial Engineering, University of Florence, Italy, david.chiaramonti@unifi.it

David Casini
RE-CORD, Florence

Tommaso Barsali
RE-CORD, Florence

Yuri Herreras Yambanis
Camelina Company España, Fuente el Saz de Jarama, España

Javi Prieto Ruiz
Camelina Company España, Fuente el Saz de Jarama, España

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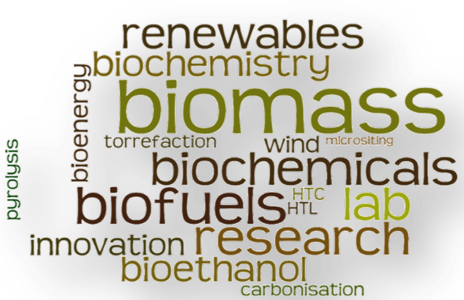

David Chiaramonti
David Casini
Tommaso Barsali
RE-CORD
Renewable Energy Consortium for Research and Development
c/o Dept.of Industrial Engineering
Florence, Italy

Biochar, Compost & Co-composting

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- Combining
  - ✓ *a stable recalcitrant material as **biochar** with*
  - ✓ ***organic matter**, as manure or from AD or OFMSW*

  can be a win-win solution

- It can be done either by blending or co-composting

- Several reviews recently addressed this matter

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Selected recent literature (1)

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- **Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soi**l. Getachew Agegnehu, Adrian M. Bass, Paul N. Nelson, Michael I. Bird. Science of the Total Environment 543 (**2016**) 295–306
- <u>**A systematic review of biochar use in animal waste composting**</u>. Neslihan Akdeniz. Waste Management 88 (**2019**) 291–300.
- **Soil properties, greenhouse gas emissions and crop yield under compost, biochar and co-composted biochar in two tropical agronomic systems**. Adrian M. Bass, Michael I. Bird, Gavin Kay, Brian Muirhead. Science of the Total Environment 550 (**2016**) 459–470.
- **The use of biochar-amended composting to improve the humification and degradation of sewage sludge**. Jining Zhang, Fan Lü, Liming Shao, Pinjing He. Bioresource Technology 168 (**2014**) 252–258.
- **Influence of biochar addition on the humic substances of composting manures**. Keiji Jindo, Tomonori Sonoki, Kazuhiro Matsumoto, Luciano Canellas, Asunción Roig, Miguel A. Sanchez-Monedero. Waste Management 49 (**2016**) 545–552.
- **Biochar and biochar-compost as soil amendments: Effects on peanut yield, soil properties and greenhouse gas emissions in tropical North Queensland, Australia**. Getachew Agegnehua, Adrian M. Bass, Paul N. Nelson, Brian Muirhead, Graeme Wright, Michael I. Bird. Agriculture, Ecosystems and Environment 213 (**2015**) 72–85

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<u>Underlined</u> = Review paper

Selected recent literature (2)

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- **Effects of biochar on the microbial activity and community structure during T sewage sludge composting**. Jingjing Dua, Yuyan Zhang, Mingxiang Qu, Yuting Yin, Kang Fan, Bin Hu, Hongzhong Zhang, Mingbao Weia, Chuang Ma. Bioresource Technology 272 (**2019**) 171–179
- **The role of biochar and biochar-compost in improving soil quality and crop performance: A review**. Getachew Agegnehu, A.K. Srivastava, Michael I. Bird. Applied Soil Ecology 119 (**2017**) 156–170
- **Biochar-mediated reductions in greenhouse gas emissions from soil amended with anaerobic digestates.** Sarah L. Martin, Michèle L. Clarke, Mukhrizah Othman, Stephen J. Ramsden, Helen M. West. biomass and bioenergy 79 (**2015**) 39-49
- **Insight into the potentiality of big biochar particle as an amendment in T aerobic composting of sewage sludge**. Jingjing Du, Yuyan Zhang, Bin Hu, Mingxiang Qv, Chuang Ma, Mingbao Wei, Hongzhong Zhang. Bioresource Technology 288 (**2019**) 121-469
- **Effects of biochar on the microbial activity and community structure during T sewage sludge composting**. Jingjing Du, Yuyan Zhang, Mingxiang Qu, Yuting Yin, Kang Fan, Bin Hu, Hongzhong Zhang, Mingbao Wei, Chuang Ma. Bioresource Technology 272 (**2019**) 171–179
- **Biochar for composting improvement and contaminants reduction. A review**. Paulina Godlewska, Hans Peter Schmidt, Yong Sik Ok, Patryk Oleszczuk. Bioresource Technology 246 (**2017**) 193–202

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Selected recent literature (3)

UNIVERSITÀ DEGLI STUDI FIRENZE

- **Biochar amendment for batch composting of nitrogen rich organic waste: T Effect on degradation kinetics, composting physics and nutritional properties**. Mayur Shirish Jain, Rohit Jambhulkar, Ajay S. Kalamdhad. Bioresource Technology 253 (**2018**) 204–213
- **Utilization of Biochar as an amendment during lignocellulose waste composting: Impact on composting physics and Realization (probability) amongst physical properties**. Mayur Shirish Jain, Siddhartha Paul, Ajay S. Kalamdhad. Process Safety and Environmental Protection 121 (**2019**) 229–238
- **Biochar effect associated with compost and iron to promote Pb and As soil stabilization and Salix viminalis L. growth.** Manhattan Lebrun, Florie Miar, Romain Nandillon, Gabriella S. Scippa, Sylvain Bourgerie, Domenico Morabito. Chemosphere 222 (**2019**) 810-822
- **Biochar is conducive to reduce thermal loss caused by mechanical turning during swine manure composting**. Hongtao Liu. **2019** (*accepted, in press* - https://doi.org/10.1016/j.biortech.2019.121810)
- **Biochar, compost and biochar-compost blend as options to recover nutrients and sequester carbon.** Thomas L. Oldfield, Natasa Sikirica, Claudio Mondini, Guadalupe Lopez, Peter J. Kuikman, Nicholas M. Holden. Journal of Environmental Management 218 (**2018**) 465-476.

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Selected recent literature (4)

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- **Biomonitoring tools for biochar and biochar-compost amended soil under T viticulture: Looking at exposure and effects.** M. Prodana, A.C. Bastos, A. Amaro, D. Cardoso, R. Morgado, A.L. Machado, F.G.A. Verheijen, J.J. Keizer, S. Loureiro. Applied Soil Ecology 137 (**2019**) 120–128
- **Biochar reduces volatile organic compounds generated during chicken T manure composting.** M.A. Sánchez-Monedero, M. Sánchez-García, J.A. Alburquerque, M.L. Cayuela. Bioresource Technology 288 (**2019**) 121584.
- **<u>Role of biochar as an additive in organic waste composting</u>**. M.A. Sanchez-Monedero, M.L. Cayuela, A. Roiga, K. Jindo, C. Mondini, N. Bolan. Bioresource Technology 247 (**2018**) 1155–1164
- **Tree water use strategies and soil type determine growth responses to T biochar and compost organic amendments**. Peter D Somerville, Claire Farrell, Peter B May, Stephen J Livesley. Soil & Tillage Research 192 (**2019**) 12–21
- **<u>A quantitative understanding of the role of co-composted biochar in plant growth using meta-analysis</u>.** Yuchuan Wang, Maria B. Villamil, Paul C. Davidson, Neslihan Akdeniz. Science of the Total Environment 685 (**2019**) 741–752
- **Optimization of food waste compost with the use of biochar.** M. Waqas, A.S. Nizami, A.S. Aburiazaiza, M.A. Barakat, I.M.I. Ismail, M.I. Rashid. Journal of Environmental Management 216 (**2018**) 70-81

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<u>Underlined</u> = Review paper

Some definitions/key parameters

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- **Degree of compost maturity**
  - ✓ *1) **stable**: microbiological processes slow down & nearly cease, 2) **mature**: toxicity of phytotoxins is reduced, 3) **finished**: compost is stable & mature.*
- **Compost status indicators**:
  - ✓ ***Temperature, C/N** ratio, content of soluble organic carbon (**DOC**), **$NH4^+/NO3^-$** ratio, germination capacity (**GI**), Humic Acids to Fulvic Acids (**HA/FA**) ratio, oxygen uptake rate (**OUR**) and **biochemical** composition*
  - ✓ *<u>**Mature** compost</u>: **C/N < 21 or < 15**, **$NH4^+/NO3^-$ < 0.16**, **GI>50 or >100**, **HA/FA> 1.6 or >1.9***
  - ✓ ***In Compost+Biochar, C/N can be >21 in spite of the compost having attained maturity***
  - ✓ ***Optimum pH for plants: 6.5-7**. Also Heavy Metals mobility linked to pH (the higher pH, the lower metal mobility, the safer the material). Feedstock dependent*

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Biochar for composting improvement and contaminants reduction. A review. Paulina Godlewska, Hans Peter Schmidt, Yong Sik Ok, Patryk Oleszczuk. Bioresource Technology 246 (2017) 193–202

Main outcomes from reviews:
Composting improvement & contam.reduct.

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- Biochar main effects during composting

  - ✓ *(1)* ***faster*** *attainment of compost* ***maturity****,*
  - ✓ *(2) compost* ***pH adjustment***
  - ✓ *(3)* ***reduction of nutrient losses*** *(Ca, Mg, N etc.),*
  - ✓ *(4)* ***increase of nitrification****,*
  - ✓ *(5) formation of* ***stable humic-like substances****,*
  - ✓ *(6)* ***immobilization of heavy metals*** *(reduction of their bioavailability), and*
  - ✓ *7)* ***reduction of emission of greenhouse gases***

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Biochar for composting improvement and contaminants reduction. A review. Paulina Godlewska, Hans Peter Schmidt, Yong Sik Ok, Patryk Oleszczuk. Bioresource Technology 246 (2017) 193–202

Main outcomes from reviews:
Animal Manure

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- ✓ ***Biochar accelerates organic matter degradation***
  - ***Shortened period of entry into thermophilic phase*** *(3 vs 5-7 days)*
  - ***Higher temperature*** *(56 °C vs 50 °C) for* ***longer time*** *6 vs 4 days)*
  - ***Shorter thermophilic*** *(> 40 °C) phase due to* ***accelerated degradation***
- ✓ ***5-10% ratio*** *recommended. Excess biochar: reduced availability of readily degraded compounds, severe water loss & heat dissipation*
  - ***5-10% biochar reduces ammonia emissions by 30-44%****. However,* ***others noted no effects*** *on pH even if NH3 was adsorbed.*
- ✓ *Biochar with* ***insufficiently large particles can cause anaerobic spots***
  - *Some different results however also reported (change of microbial flora with T)*
- ✓ ***pH decrease due to NH3*** *(lowered emissions) and* ***NH4****$^{+}$ adsorption (favoring nitrifying bacteria, converting ammonia to nitrate and thus retaining N in the compost),* ***7.5-7.8 at the end of the composting phase vs 8.1*** *.*
- ✓ ***Biochar is a good amendment for composting N-rich matter***
- ✓ ***CH4 and N2O*** *emissions also show* ***significant reduction***
- ✓ ***Biochar-compost application more effective in improving soil properties & crop yields (field and horticulture crops) than biochar alone***

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A systematic review of biochar use in animal waste composting. Neslihan Akdeniz. Waste Management 88 (2019) 291–300.

The role of biochar and biochar-compost in improving soil quality and crop performance: A review. Getachew Agegnehu, A.K. Srivastava, Michael I. Bird. Applied Soil Ecology 119 (2017) 156–170

Main outcomes from reviews:
Biochar as additive in composting

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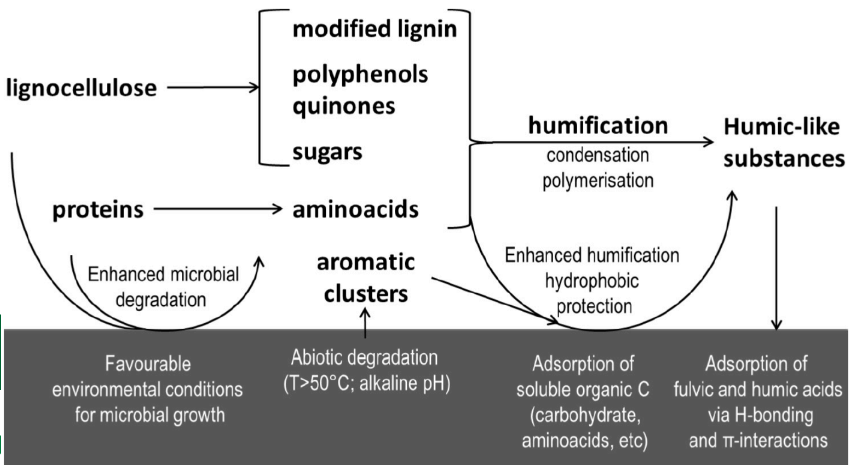
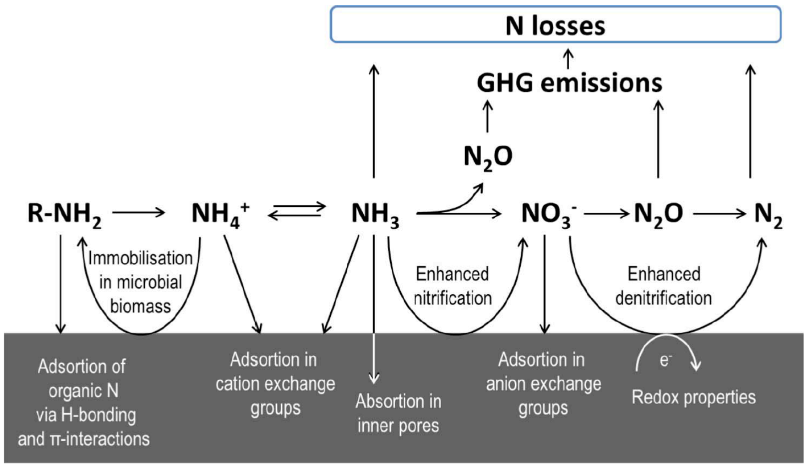
- ✓ ***Low dose*** *(3-5 % on dry weight base)* ***recommended***
- ✓ ***Clean wood, T=500-600 ° C, particles < 2 mm up to >16 mm normally tested****.* ***No clear recommendation yet on particle size!***
- ✓ *Biochar* ***CEC*** *during composting: "****oxidative ageing****" or "****weathering****" (devel.of more oxygenated functional groups on biochar surface due to oxidative process) as well as* ***adsorption*** *of of dissolved organic matter & microbial residues*
  - ✓ ***Increased CEC → increased ability to retain nutrients.***
  - ✓ ***Release rate?***
- ✓ ***Modification of pores*** *(increase of* ***micropores****), larger surface area*
- ✓ ***Microbial colonization****, thanks to water & nutrient retention by biochar*



Biochar Impact on OM degrad.&Humification in composting



Biochar Impact on N cycle/dynamics in composting

Role of biochar as an additive in organic waste composting. M.A. Sanchez-Monedero, M.L. Cayuela, A. Roiga, K. Jindo, C. Mondini, N. Bolan. Bioresource Technology 247 (2018) 1155–1164

Main outcomes from reviews:
Role of COMBI in plant growth (meta-analysis)

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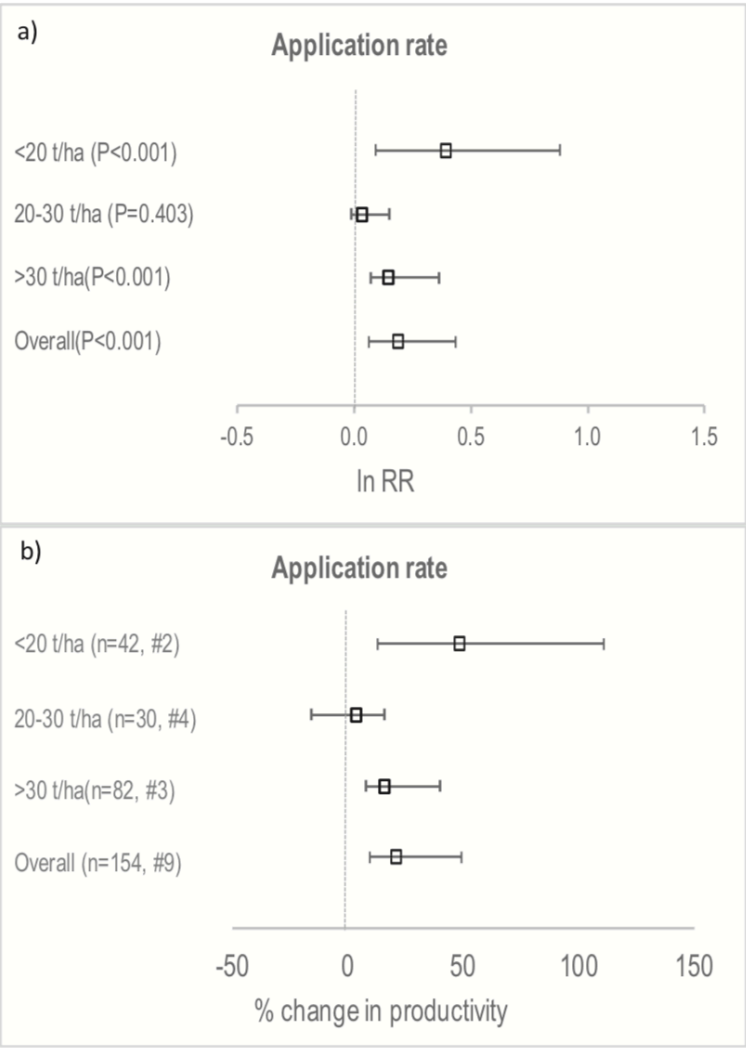
Quantitative review on COMBI (14 papers, 2007-2018), response-ratio as effect size.

- ✓ *COMBI significantly* ***increased grain yields of cereal grasses (39.7%)****.*
- ✓ *Best:* ***< 20 t/ha (+48.3%)*** *or* ***>30 t/ha (+15.7%)***
- ✓ ***Greatest increase*** *in productivity observed* ***at 4-5 soil pH***
- ✓ *COMBI application rate given, but* ***no details on biochar content in co-composting***

$$\ln(RR) = \ln\left(\frac{\overline{x}_t}{\overline{x}_c}\right)$$

where $\overline{x}_t$ and $\overline{x}_c$ are the mean plant productivity values of the treatment and control groups, respectively. A response ratio >1 suggests that COMBI has a stronger effect on plant productivity than control. To nor-



A quantitative understanding of the role of co-composted biochar in plant growth using meta-analysis. Yuchuan Wang, Maria B. Villamil, Paul C. Davidson, Neslihan Akdeniz. Science of the Total Environment 685 (2019) 741–752

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Main outcomes from reviews:
Composting improvement & contam.reduct.

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- Open issues:
  *(1) **How different biochars influence the composting process**?*
  *(2) To what extent the **properties of raw material** for composting will determine the **interaction of biochar with pollutants**?*
  *(3) Which **optimum dose of biochar during composting** (to achieve best run of the process, immobilisation of pollutants and reduction of toxicity)?*
  *(4) How **sorption of heavy metals** from compost rich in those ions (e.g. sewage sludge) will affect **loss of macroelements** (ions of Ca, Mg, etc.) from compost – does biochar prefer the sorption of heavy metals or macroelements?*
  *(5) **What kinds of biochar and compost for which soil and plants**?*
  *(6) Will the **degradation of humic like substances** formed in the presence of biochar be slowed down relative to their equivalent formed without biochar addition, when the compost is applied to soil?*
  *(7) **How does biochar affect the fate of various organic pollutants**, and first of all will the ageing of biochar during composting affect in any way the bioavailability of contaminants contained in biochar or in the compost mass?*

Biochar for composting improvement and contaminants reduction. A review. Paulina Godlewska, Hans Peter Schmidt, Yong Sik Ok, Patryk Oleszczuk. Bioresource Technology 246 (2017) 193–202

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Main outcomes from reviews:
Biochar as additive in composting

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Additional elements that need further investigation

- ✓ ***Biochar particle size, doses & feedstock*** *etc.*
- ✓ ***Interaction of biochar with microorganisms and correlation with composting*** *(humification, biodegradation, greenhouse gas emissions, etc)*
- ✓ ***Identification of non-biochar carbon species adsorbed onto biochar surface*** *for better understanding the interaction of biochar with key processes such as humification and the reduction of GHG emissions and volatile compounds.*
- ✓ ***Development of optimal microscopic techniques*** *and the use of* ***advanced spectroscopic*** *(e.g., NMR) and* ***isotope labelling*** *(e.g., ^{13}C and ^{15}N) techniques.*
- ✓ ***Impact on the growth promoting substances*** *when biochar blended compost used as soil amendment or as component for growing media in soil-less cultivation.*
- ✓ *Determination of* ***soluble and extractable C and N compounds*** *involved in the calculation of conventional compost maturation indices (methodological challenge, given the strong sorption capacity of biochar).*
- ✓ ***Re-evaluation of some maturity indices*** *(e.g., C/N, dissolved organic C, humification indices, NH_4^+/NO_3^-, etc.) for biochar blended composts*

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Role of biochar as an additive in organic waste composting. M.A. Sanchez-Monedero, M.L. Cayuela, A. Roiga, K. Jindo, C. Mondini, N. Bolan. Bioresource Technology 247 (2018) 1155–1164

Other outcomes from literature

- **Sewage sludge co-composting**: evidence that **biochar promotes the functions of bacterial community. Amending sewage sludge with biochar accelerates the humification process of sludge organics**
- **Large biochar (20-40 mm) particles in sewage sludge composting: inhibition of OM degradation**
- Biochar **10 % w/w addition** showed a **potential to mitigate thermal losses due to turning** during **swine manure composting** (decreased heat exchange and increased water vaporization heat)
- **GHG in sandy loam soil** amended with **biochar** (*Fraxinus excelsior* L., *Fagus sylvatica* L. and *Quercus robur* L, 450 ° C, 48 h batch, pH 9) and **digestate** from maize (not co-composting): N_2O emissions greatest from soil amended with anaerobic digestate, while **biochar amendment reduced N2O emissions** (greatest effect in treatments with maximum emissions).
- **VOC emissions during composting of a 90% poultry manure and 10% straw were reduced by addition 3 % biochar** during the **thermophilic phase**
- **Biochar and compost blend** seems **synergic towards plant diseases**
- OM amendments may improve soil water properties of **sand-based soils** that increase the growth of xeric tree species.

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Various sources, see initial list

Our work on COMBI

- **COMBI** produced, characterized and tested in two sites in Spain, in the framework of the H2020 BIO4A project on HEFA biojet (**www.bio4a.eu**)

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Biomass Conversion and Biorefinery
https://doi.org/10.1007/s13399-019-00482-6

ORIGINAL ARTICLE

Check for updates

Production and characterization of co-composted biochar and digestate from biomass anaerobic digestion

David Casini[1] · Tommaso Barsali[1] · Andrea Maria Rizzo[1] · David Chiaramonti[1,2]

Open Access

Received: 30 March 2019 / Revised: 15 July 2019 / Accepted: 16 July 2019

Abstract
Biochar, produced through pyrolysis of lignocellulosic biomass, is attracting increasing interest as soil amendment thanks to its potential numerous benefits to agriculture, as well as its ability to sequester carbon in soil. Solid fraction of digestate from anaerobic digestion is a well-known N-rich substrate, most often composted in large and small agro-industrial plants. Co-composting biochar and digestate has the potential to synergistically increase the agronomic value of both components: however, it needs further process and on-field research. The present research work reports on the experimental tests on producing biochar and co-composting various biochar amounts with digestate from biomass anaerobic digestion (product here named COMBI). Biochar was produced by feeding wood chips from chestnut to an innovative oxidative reactor. In order to evaluate the quality of the products obtained by composting and co-composting, correlating this with the final biochar rate in the material, the net organic matter yield, the humified organic matter, the compliance with the European Compost Network Quality Assurance Scheme (ECN-QAS) limits for inorganic pollutants, and the product stabilization and sanitization indexes were investigated. The 11.2% *w/w* d.b. biochar rate in the initial blend (19.8% *w/w* d.b final concentration in the co-composted products) offered the best performances and is recommended for further investigation. Additional benefits from co-composting were also assessed, as the reduced dust load that favors safety and health during logistics and use.

Keywords Biochar · Compost · Digestate · Co-composting · Soil amendment

1 Introduction

Sustainable production of biomethane is a key option to substitute conventional natural gas and decarbonize the energy system [1]: anaerobic digestion (AD) is the leading route to generate biogas, which can then be further upgraded to biomethane by CH4 separation. Today, the AD process is a well-mature process, bringing environmental and social benefits at both local and global level [2, 3]: the main co-product of biomass anaerobic digestion is a sludge (digestate), which can be applied to soil for agronomic purposes as an organic amendment. Composting is another well-known pathway to stabilize organic matter of various origins through a bio-oxidative process [4], which brings benefits as volume reduction, sanitization from pathogens, reduction of liquid contaminants, and economic and environmental returns [5, 6]. In anaerobic digestion plants, the composting stage of the solid fraction of digestate generally occupies large volumes and requires long residence time, in addition to complex logistical steps [7, 8]. The addition of a bulking agent in the compost pile is normally recommended, in particular when substrates as digestates are used. The small particle size of the material generates risks of anaerobic conditions within the pile, leading to the production of undesired phenomena as ammonia volatilization [9, 10].

Biochar is the solid product from lignocellulosic biomass pyrolysis, characterized by a high content of stable C, mostly produced through slow pyrolysis. Biochars from intermediate/fast pyrolysis and gasification are often discussed in literature, even if these show different characteristics. Biochar is a highly porous material with a wide range of possible uses, including

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s13399-019-00482-6) contains supplementary material, which is available to authorized users.

✉ David Chiaramonti
david.chiaramonti@unifi.it

[1] Renewable Energy COnsortium for R&D (RE-CORD) Viale J. F. Kennedy, 182, Scarperia e San Piero, 50038 San Piero, Italy

[2] CREAR/Department of industrial Engineering, University of Florence, Viale Morgagni 40, 50134 Florence, Italy

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Our work on COMBI

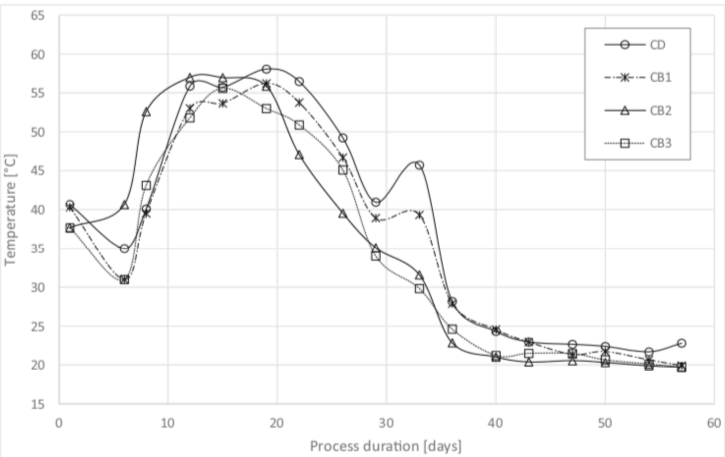

Table 2 Initial windrows compositions

	U.M.	CD	CB1	CB2	CB3
Windrow	kg d.b.	160.6	156.5	153.0	149.6
Starting moisture	% *w/w* w.b.	61.6	60.0	59.2	58.3
Biochar content	kg w.b.	0.0	12.0	18.0	24.0
Biochar rate	% *w/w* d.b.	0.0	7.3	11.2	15.2
C/N index		36.3	40.4	42.7	45.2

Biochar concentration in the final product:
14.9 - 19.8 - 22.8% w/w d.b.

- **CB2 and CB3 completed the bio-oxidative phase about 4 days earlier than CD and CB1, keeping the same peak temp**
- **CB2 showed the lowest stabilization time, the highest degree of humification, and the lowest ammonium/nitrate ratio index**
- **CB3 was the only case with *E.Choli* proliferation**

Bio4A

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RE-CORD · TOTAL · SkyNRG · CENER · etaflorence renewableenergies · Camelina Company | España · European Commission

A

	Rep 1	Rep 2	Rep 3	Rep 4
No fertilization	1	2	3	4
NPK	5	6	7	8
10% Biochar + Compost	9	10	11	12
15% Biochar + Compost	13	14	15	16
20% Biochar + Compost	17	18	19	20
100% Biochar + NPK	21	22	23	24
100% Compost	25	26	27	28

B C

D

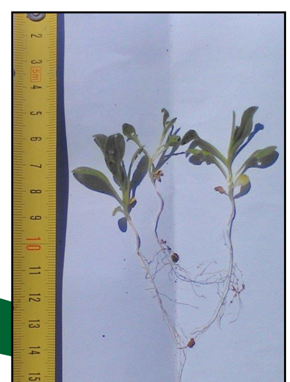
Field trials: Ciudad Real (ES)

Background fertilization: 11/01/19

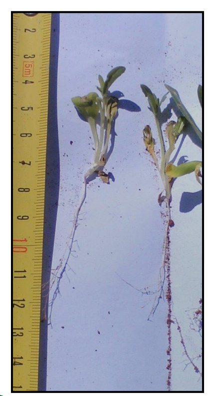
Seeding date: 14/01/19

Camelina Company | España

No fertilization

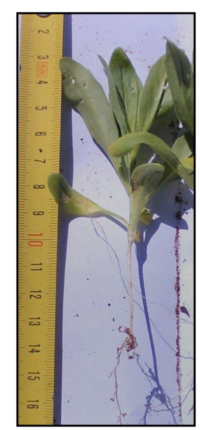


Mineral fertilization



100% Compost

100% Biochar



Biochar+ Compost 10%

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Thus…. Is co-composting worth?

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- If the amount (tons) of biochar in co-composting or blend is the same → no major difference in sequestered fixed C, no strong motivations for co-composting from the C monetary value point of view. Therefore:

→ ***Does co-composting pay off, or is instead blending sufficient and a better economic choice?***

- Answering this question is **site- and policy-dependent**, and requires extensive further work.
- AD plants (expecially OFMSW AD) largely implement ***pasteurization* step** –> thus **composting not strictly needed** from the sanitary point of view

Thus…. Is co-composting worth?

- If thus digestate can be directly spread on soil, avoiding composting save CAPEX and OPEX. **Blend will most likely be the preferred choice**
- **If composting process acceleration is instead required, adding Biochar could be an option**. This could be the case of some OFMSW composting units.
- If **biochar deployment (dust)** is an issue, **co-composting will help** (but other options are possible)
- **Detailed analysis of local (soil) benefits from collected nutrients favour co-composting**, but customer must pay for this (market to be developed).

Policy-driven economy

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- The deployment of biochar, biochar & compost and COMBI will necessarily be a **policy-driven issue** (EU: LULUCF in CAP)
- **Multiple policies** could interact impact. Studies needed to provide policy makers with recommendations. E.g. :

Biomass and Bioenergy xxx (xxxx) xxx-xxx

Contents lists available at ScienceDirect

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BIOMASS & BIOENERGY

Research paper

Policy measures for sustainable sunflower cropping in EU-MED marginal lands amended by biochar: Case study in Tuscany, Italy

David Chiaramonti [a], *, Calliope Panoutsou [b]

[a] RE-CORD and CREAR, Industrial Engineering Department, University of Florence, Viale Morgagni 40, 50134, Florence, Italy
[b] Imperial College, Faculty of Natural Sciences, Centre for Environmental Policy, 16-18 Prince's Gardens, SW71NA, London, UK

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Thanks for the attention

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www.re-cord.org

David Chiaramonti

Contacts

david.chiaramonti@re-cord.org

info@re-cord.org

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Composting in Italy

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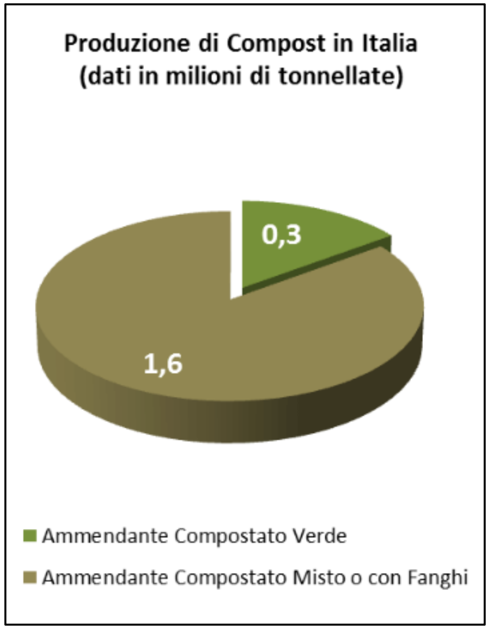
- The combination of **compost/digestate & biochar (COMBI)** can bring **short-term** and **long-term benefits** to the **soil** and to **agriculture**
- **The case of Italy** ***(source: Consorzio Italiano Compostatori, www.compost.it)***
  - ✓ **6.71 Mt/y organic waste** (2015) recovered, out of **~9 Mt/y** (on 14 Mt/y RD): **4** Mt/y OFMSW+ **2.71** Mt/y green waste *(66+34=100 kg/pers/y)*
  - ✓ **1.761.000 t/y** compost produced and used in agriculture. **71%** from composting of OFMSW, **29%** from AD + composting mixed composted amendment or sludge composted amendment (1.655 t/y)
  - ✓ **Anaerobic Digestion**: **1700 plants** built (agriculture + sewage + waste + industrial)
  - ✓ **2017** data: **1.95 Mt/y** compost produced. **85%**

(source: L.Maggioni/CIB, 2017)



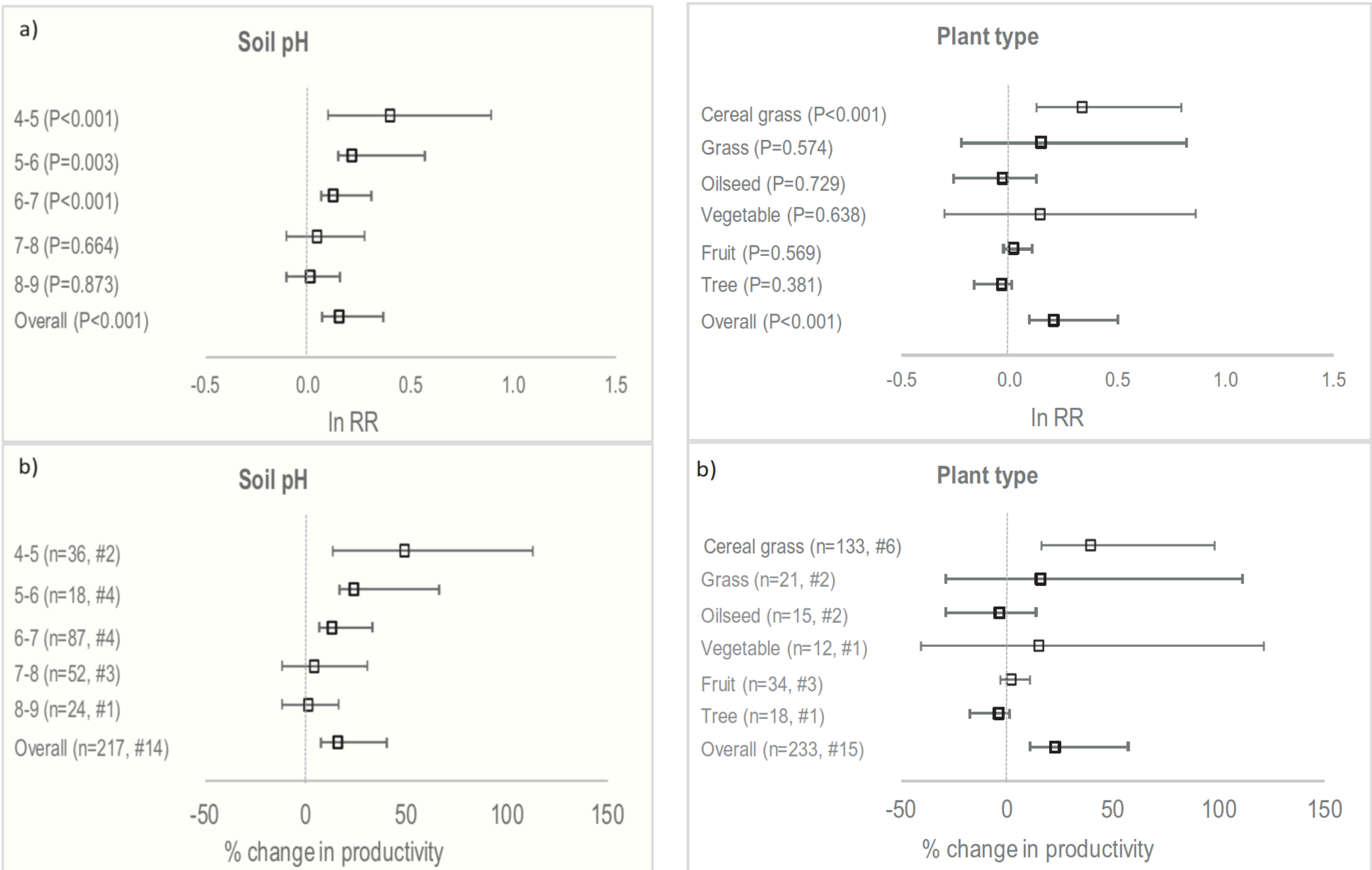
RE·CORD

Main outcomes from reviews:
Role of COMBI in plant growth (meta-analysis)

UNIVERSITÀ DEGLI STUDI FIRENZE

$$\ln(RR) = \ln\left(\frac{\bar{x}_t}{\bar{x}_c}\right)$$

where $\bar{x}_t$ and $\bar{x}_c$ are the mean plant productivity values of the treatment and control groups, respectively. A response ratio >1 suggests that COMBI has a stronger effect on plant productivity than control. To nor-



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A quantitative understanding of the role of co-composted biochar in plant growth using meta-analysis. Yuchuan Wang, Maria B. Villamil, Paul C. Davidson, Neslihan Akdeniz. Science of the Total Environment 685 (2019) 741–752

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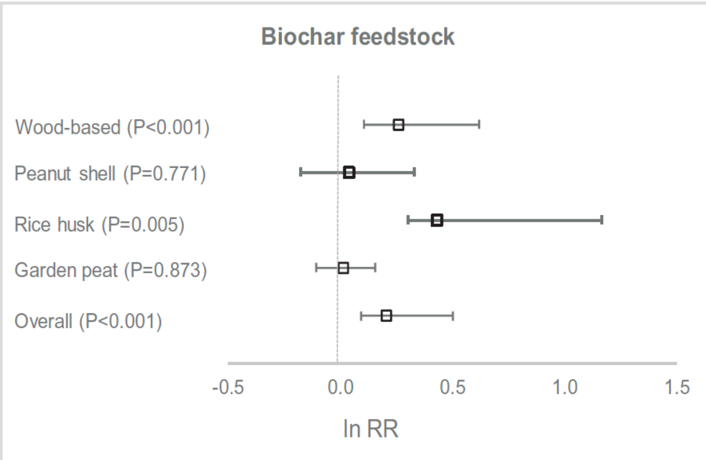

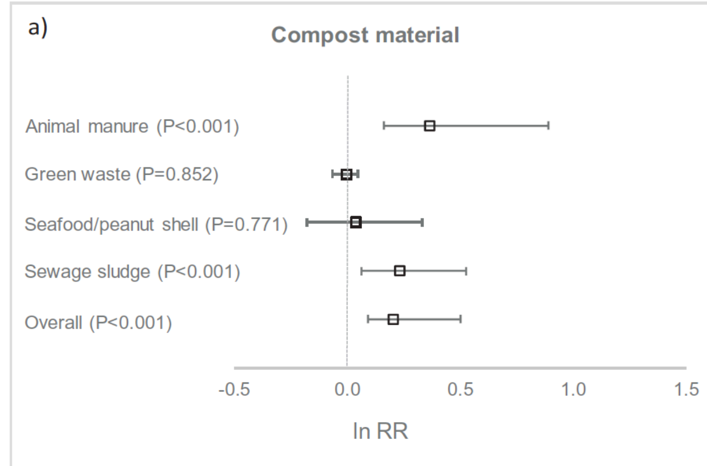

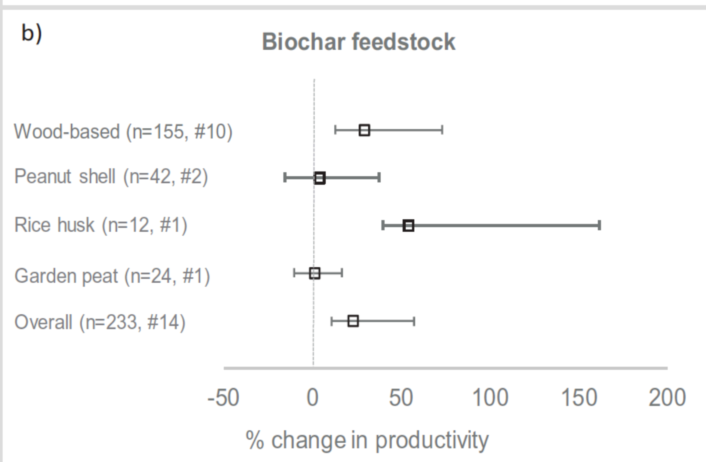

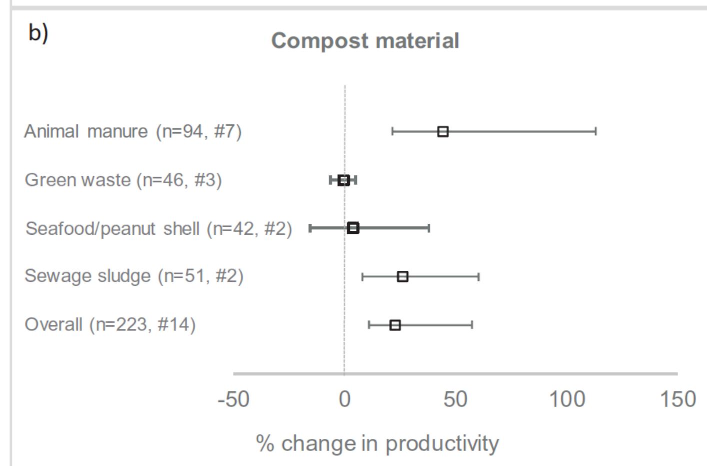

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Other outcomes:
Effects on yields, SOC, SWC, N2O

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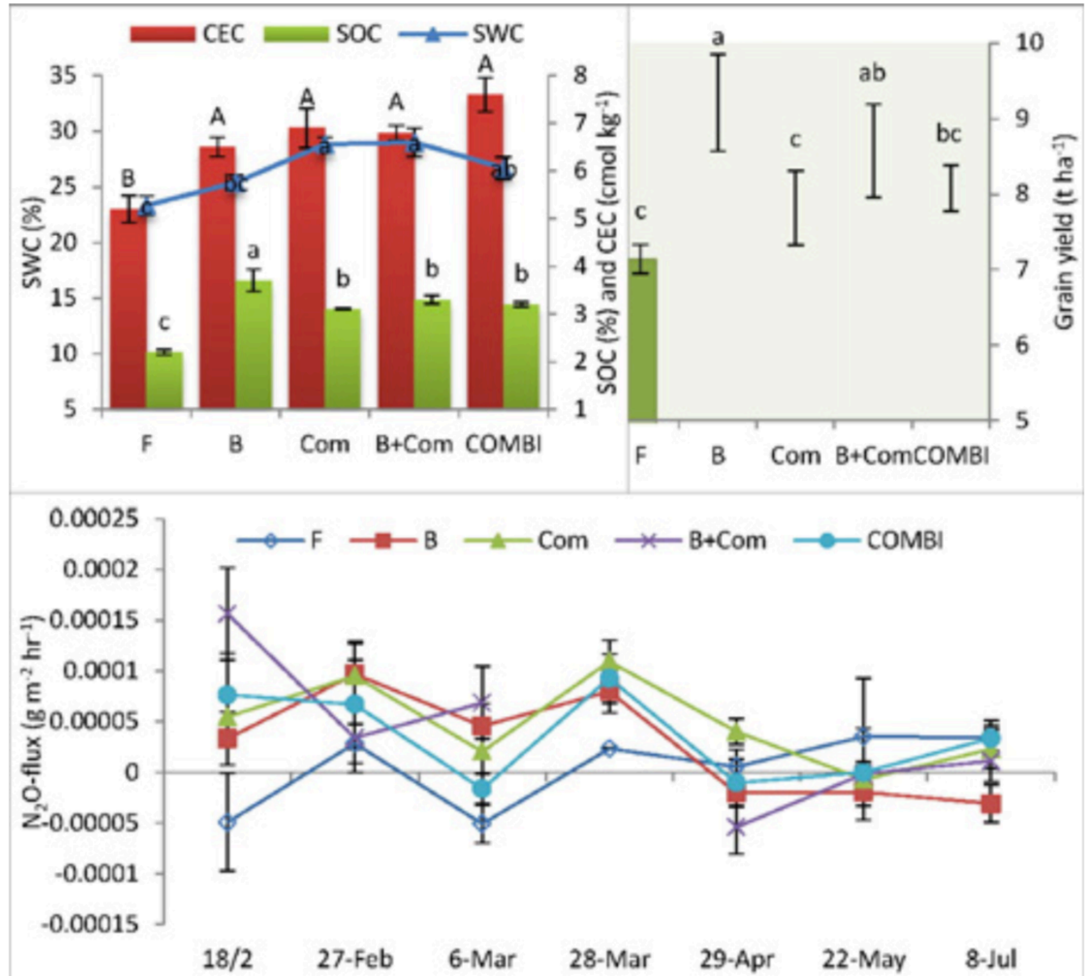
Grain yield, cation exchange capacity (CEC), soil organic carbon (SOC), soil water content (SWC) and N2O emission as influenced by fertilizer (F), biochar (B), compost (Com), Com + B and co-composted biochar–compost (COMBI)



Benefits of biochar, compost and biochar–compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Getachew Agegnehu, Adrian M. Bass, Paul N. Nelson, Michael I. Bird. Science of the Total Environment 543 (2016) 295–306

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