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Toward a functional integration of anaerobic digestion and pyrolysis for a sustainable resource management. Comparison between solid-digestate and its derived pyrochar as soil amendment

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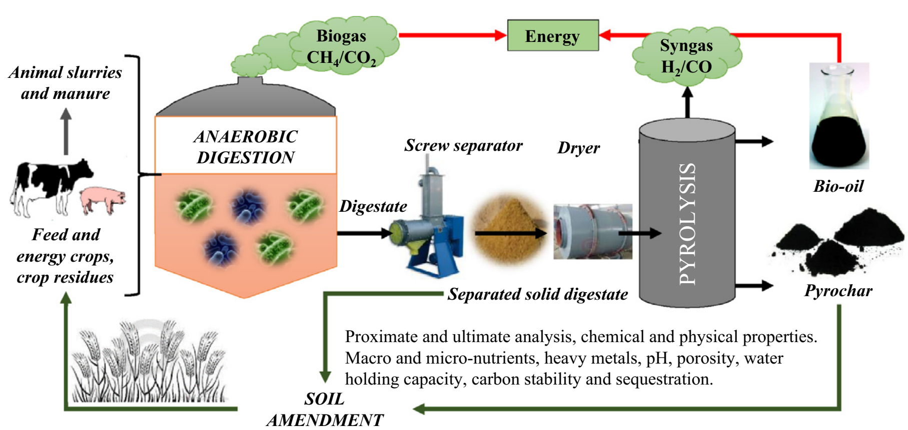
HIGHLIGHTS

- Coupling anaerobic digestion and pyrolysis is technologically efficient.
- This technology integration is environmentally sound and boosts circular economy.
- Digestate and pyrochar are soil amendments with different but complementary properties.
- While pyrochar sequesters carbon, digestate could contribute to soil microbiological processes.
- Their characteristics are fully consistent with those of agricultural soil amendments.

GRAPHICAL ABSTRACT



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ABSTRACT

The integration of different technologies acts as a leverage in boosting "circular economy" and improving resource use efficiency. In this respect, the coupling of anaerobic digestion with pyrolysis was the focus of this work. Solid-digestate obtained from anaerobic digestion was addressed to supply pyrolysis thus increasing the net energy gains and obtaining "biochar" (called "pyrochar" in our case) to be used as soil amendment alternatively to solid-digestate. The current interest on biochar is linked to its long-term soil carbon sequestration, thus contributing to global warming mitigation.

A parallel detailed screening of the physical and chemical properties of both solid-digestate and pyrochar was performed, inferring their effects on soil quality. Results showed that while P and K are enriched in pyrochar, total N showed no significant differences. Heavy metals revealed higher concentrations in pyrochar, but always largely below the biochar quality thresholds. Pyrochar exhibited a higher surface area (49–88 $m^2\ g^{-1}$), a greater water holding capacity (352–366%), and a more recalcitrant carbon structure. Both solid-digestate and pyrochar showed good soil amendments properties but with complementary effects. Although starting from the same biomass, being the original feedstock processed differently,

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their ability to improve the physical and chemical soil properties has proved to be different. While several other soil improvers of organic origin can substitute digestate, the important role played by biochar appears not-replaceable considering its precious "carbon negative" action.

1. Introduction

Our globalized society urgently needs ensuring food supply and energy to a growing population without further exploiting our latest fossil energy resources or causing environmental burdens and damages [1]. In this respect, biomass could supply a large amount of renewable energy but, on the counterpart, land use changes (from food/feed to bioenergy crops) might generate food scarcity, food prize volatility and a higher intensification in agricultural management, thus jeopardizing soil fertility and crop yield [2–4]. At the same time, a continuing increase in food supply, keeping the pace with population growth at planetary level, is leading to higher fossil energy consumptions due to higher cultivation inputs, thus eroding an already scarce non-renewable resource as well as worsening global warming.

The options for reducing fossil fuel dependency and greenhouse gases emissions (GHG), as well as benefitting of the social and economic advantages that might result from biomass energy, are great challenges on condition that these biomass resources are used effectively and sustainably.

For this purpose, new strategic approaches are required and new productive concepts are gaining momentum. The transition to a bio-based industry is taking place, among others, by means of:

(1) A progressive integration ("industrial symbiosis") of different conversion technologies, establishing functional connections and links across different processes according to a "systemic" view [5,6].
(2) The development of new value-chains implementing the "cascading" biomass utilization scheme, where the output of one process becomes the input of the following one (thus also targeting the "zero-waste" goal) with biomass progressing through a series of material flows and energy conversions [7].
(3) Processing biomasses in compliance with the "closed-loop" principle, i.e. favoring the returning of plant nutrients into the soil, thus making the farming system more ecologically sustainable and preserving soil quality, its fertility and organic matter (the latter to be also intended as an influential "carbon stock").

This multi-functional, cascading and closed-loop arrangement of new designed bioenergy systems is also offering significant efficiency gains, maximizing the value extracted from a given amount of biomass by fulfilling both material and energy needs from the same feedstock [8].

In a previous work from the same team [9], the opportunity of coupling two different energy conversion processes, anaerobic digestion (AD) and pyrolysis (PY), respectively, was investigated. While AD is a biological degradation process producing *biogas* (that consists mainly of CH_4 and CO_2), PY is a thermochemical decomposition of biomass occurring in the absence of oxygen [10,11], producing *syngas* (a mixture mainly formed by H_2 and CO_2) and bio-oil. In any case, both are energy conversion processes.

By applying this integrated approach, the solid-digestate resulting from a previous AD biological conversion, formerly treated through solid–liquid separation and a drying process, becomes the entering feedstock of the subsequent PY thermochemical conversion.

Very recently, other researchers have also proposed this peculiar approach. The "Supergen" Bioenergy Hub is currently working out a project developing a synergy between biological (AD) and thermal (PY) conversion processes in which the overall net energy yield can be significantly improved [12]. Differently from our approach, PY precedes AD thus allowing access within the biomass to lignin-bound components that are otherwise unavailable for anaerobic biological conversion. Although considering different technical operations, Shen et al. [13] proposed a similar integrated approach by adding biochar into the AD digester. An *in situ* biogas upgrading system was thus obtained with a significant increase in the methane yield, biomethanation rate constant and maximum methane production rate. In addition to the thermochemical conversion of digestate, the integrated AD + PY also allowed the bioconversion of the aqueous phase of pyrolysis liquor, the one derived from the pyrolysis of solid digestate [14]. Biochar, indeed, has the ability to catalyze AD by mitigating mild ammonia inhibition, supporting archaeal growth and the methanization of the biochar labile carbon [15]. Therefore, this option of coupling AD with PY could open up new interesting pathways for the integration of biological and thermochemical processes [16].

The AD + PY functional coupling is of great potential interest not only because the resulting energy gain is higher than the AD process individually considered (positive interaction or synergic effect), but also because relevant side-effects are generated [9,17].

Indeed, during the AD process, approximately 50–70% of the organic matter is decomposed, while the residual organic matter, more recalcitrant to degradation, generates the so-called "digestate" [18]. Digestate is generally characterized by high biological stability, a relative high content of organic molecules [19] and nutrients, such as nitrogen and phosphorus [20]. After the mechanical solid–liquid separation (by centrifugal screw, rotary or press separator), solid digestate can be utilized to replace soil organic amendments and synthetic fertilizers [21]. Indeed, from the concentrated solid fraction an organic amendment is obtained [22,23], while the remaining liquid fraction, being particularly rich in ammonia, is analogous to a mineral N fertilizer [20].

In recent years, a rapid growth in newly installed anaerobic digestion plants is observed and huge amounts of digestates are increasingly available. The use of liquid and solid manure for biogas production is becoming popular in many EU countries, together with the use (in co-digestion) of crop residues and dedicated energy crops (previously used as animal feed) to increase the energy yield of the process. Concerning these large amounts of digestate as crop fertilizer and soil amendment, there are relevant economic and environmental concerns that are constraining their extensive application, today, on cropland [24,25]. The high spatial density of the AD-facilities (for instance, a very high number of AD plants within a small geographic area is currently observed in the "Po Valley" in northern Italy) and the consequent limited cropland available for spreading, is leading to overcharge nearby fields with digestate. Therefore, excessive nitrogen loads may have negative effects on soil tilth properties, plant growth and grain yield, even significantly contributing to threaten water quality due to higher risks of nitrate leaching and groundwater contamination. Improper