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Synergy of anaerobic digestion and pyrolysis processes for sustainable waste management: A critical review and future perspectives.

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Abstract

The worldwide growing population, challenged by an ever-increasing global demand for food production, is also concomitant with increased waste production, particularly organic waste. During the last decades, several waste processing technologies have been developed such as anaerobic digestion and pyrolysis. Recently, there has been an increased interest in creating industrial synergies by combining technologies in order to increase the efficacy of the process and improve waste management in the circular economy. In this review, we report on the importance of coupling anaerobic digestion and pyrolysis while providing evidence on the synergistic effects that may occur within such a combined waste bi-functional process. Specific attention has been paid to multiple symbiosis features that exist when coupling both processes, mainly 1) maximizing energy recovery through pyrolysis of solid digestate or feeding of the aqueous bio-oil phase in anaerobic digestion , 2) biogas purification by biochar or activated biochar, and 3) improving anaerobic digestion process stability by biochar addition to the system. In addition, the effects of coupling anaerobic digestate with biochar on soil biochemical properties and crop production were also presented. Improving the dual symbiosis of coupling anaerobic digestion and pyrolysis is likely to be a sustainable based approach that holds promise for wiser and more eco-efficient processing of organic wastes for versatile applications.

Keywords: Pyrolysis, anaerobic digestion, biochar, digestate, fertilizer, detoxification.

Abbreviations

APL: Aqueous Pyrolysis Liquid

BMP: Biochemical Methane Potential

COD: Chemical Oxygen Demand
DM: Dry Matter
EBC: European Biochar Certificate
GHG: Greenhouse Gases
HR: Heating Rate
HTL: Hydrothermal Liquefaction
IBI: International Biochar Initial
LCA: Life Cycle Assessment
OLR: Organic Loading Rate (kg VS Nm^{-3} day^{-1})
OFMSW: Organic Fraction of Municipal Solid Wastes
PAHs: Polycyclic Aromatic Hydrocarbons.
RT: Residence Time
S_{BET}: Specific surface area (m^2 g^{-1})
TAN: Total Ammonia Nitrogen
TRL: Technology Readiness Level
UASB: Up-flow Anaerobic Sludge Blanket
VFAs: Volatile Fatty Acids
VS: Volatile Solid

1. Introduction

As the world's population grows, food production should constantly increase to meet the increasing global demand. Moreover, considerable food waste accumulation needs to be processed in a sustainable manner to avoid possible environmental burdens associated with unprocessed organic waste. Several waste valorizations routes have been investigated and developed (pyrolysis, anaerobic digestion, composting). Recently, two main valorization routes have emerged through biological (anaerobic digestion) and thermochemical (pyrolysis) processes, allowing a large spectrum of wastes and biomasses [1,2] to be processed. Among the scientific communities, these two types of technologies have often been opposed, but in recent decades, the combination of pyrolysis and anaerobic digestion processes have attracted increasing attention [3–5]. Anaerobic digestion is defined as a biological-based degradation process anaerobically producing biogas (CH_4 and CO_2) and a residue called digestate. Meanwhile, pyrolysis consists in a thermochemical decomposition of biomass that occurs in the absence of oxygen producing syngas (a mixture of CO, H_2, and CO_2), bio-oil, and biochar. At the agricultural level, both processes can compete with each other in terms of biodegradation of a large biomass spectrum of substrates that are easily biodegradable and can be optimally degraded by the anaerobic digestion process, whereas treatment of hardly biodegraded substrates may be achieved by pyrolysis [6,7]. During the last decade, "cascading" use of biomass utilization, where the output of one process becomes the input of the following one (targeting the ''zero-waste" goal) with biomass progressing through a series of material flows and energy conversions, has attracted attention [8,9]. The integration of such technologies may offer interesting opportunities with the objective of contributing to the circular economy [10]. Coupling anaerobic digestion - pyrolysis processes through an industrial symbiosis approach can address several issues related to agricultural waste management by improving resource use efficiency, energy recovery, GHG emissions reduction, and soil preservation [8,9,11–13]. For example, pyrolysis could be used to convert the dried solid digestate into biochar, which could then be used for different applications and purposes [14,15], including its potential use to improve biogas production and quality [16], to reduce instabilities and inhibition in digesters during the process [17] or to purify or upgrade the biogas [18,19]. The syngas produced during the pyrolysis process can also be converted through biological methanation [20]. Finally, the aqueous pyrolysis liquid could be used as organic feedstock for anaerobic digestion [21], possibly with the addition of biochar for selective adsorption and mitigation of toxic inhibitors.

Based on the science direct database between 2015 and 2021, the following **Table 1** summarizes some of the recent and interesting literature reviews dealing with the benefits of integrated pyrolysis or other thermochemical processes with anaerobic digestion processes and the different synergies between the processes and their products.

Table 1: Recent literature reviews of coupling anaerobic digestion and pyrolysis with the interactions of their products for energy, bioremediation, and agronomic purposes.

Review title	**Journal name, year (IF: impact factor)**	**Main topics**	**Ref.**
New opportunities for agricultural digestate valorization: current situation and perspectives.	Energy & Environmental Science, 2015 (IF: 38.5)	-Discussion of the use of both solid and liquid digestate for several applications (microalgae, biofuels, thermos-chemical processes…). -Investigation of coupling anaerobic digestion and pyrolysis for energy production through the conversion of solid digestate into added-value products (char , bio-oil, syngas)	[22]
Linking pyrolysis and anaerobic digestion (Py-AD) for the conversion of lignocellulosic biomass	Current Opinion in Biotechnology, 2016 (IF: 9.7)	-Investigation of the pyrolysis process applied downstream the anaerobic digestion as pretreatment for recalcitrant biomasses. -Study of converting the aqueous and organic bio-oil phases through anaerobic digestion process. -Biological methanation of the syngas -Investigation of the boundaries and perspectives of coupling pyrolysis and anaerobic digestion.	[8]
Integrated processes of anaerobic digestion and pyrolysis for higher bioenergy recovery from lignocellulosic biomass: A brief review	Renewable and Sustainable Energy Reviews, 2017 (14.9)	-Reviewing recent development, feasibility, and advantages of integrated processes of anaerobic digestion and pyrolysis. -Discussion of the various strategies of combination: anaerobic digestion-pyrolysis, pyrolysis-anaerobic digestion, anaerobic digestion-pyrolysis-anaerobic digestion .	[9]
A review of biochar properties and their roles in mitigating challenges with anaerobic digestion	Renewable and Sustainable Energy Reviews, 2019 (IF:14.9)	-Discussion of the challenges of integrating biochar in anaerobic digestion process. -Summarize of the characteristics of biochar and its physicochemical properties that can simultaneously promote anaerobic digestion process stability, increase biomethane yield rate. - Biochar for digestate quality improvement. - Biochar for CO_2 adsorption and other impurities in biogas.	[23]
Coupling anaerobic digestion with gasification, pyrolysis, or hydrothermal carbonization: A review	Renewable and Sustainable Energy Reviews, 2019 (14.9)	-Summarizing the literature for the coupling of the biological process of anaerobic digestion with one of three thermal processes: gasification, pyrolysis, and hydrothermal carbonization. -Investigation the thermochemical processes as pre and/or post treatments for anaerobic digestion, and the synergies between the processes and their products. -Overview of the most promising future research investigations.	[4]

Review of biochar role as additive in anaerobic digestion processes	Renewable and Sustainable Energy Reviews, 2020 (IF: 14.9)	-Investigation of the influence of biochar properties on anaerobic digestion performances and its stability. - Discussion of microbial attachment and acclimation. - Study of biochar capacity for adsorption of inhibitors of anaerobic digestion. - Effect of biochar for biogas upgrading. -Evaluation of the economic and environmental advantages connected to biochar use in anaerobic digestion processes, compared to conventional solutions..	[10]
The role of biochar to enhance anaerobic digestion: a review	Journal of Renewable Materials, 2020 (IF: 8.0)	-Discussion the noting physicochemical properties of biochar, and its roles and related mechanisms in anaerobic digestion. -Highlighted the advantages and drawbacks and pointed out the corresponding challenges and prospects for future research and application of biochar amending anaerobic digestion.	[24]
Potential of coupling anaerobic digestion with thermochemical technologies for waste valorization	Fuel, 2021 (IF: 6.6)	-Evaluation on the viability of integrating anaerobic digestion with thermochemical processes. -Comparison of three thermos-chemical processes: pyrolysis, gasification and hydrothermal carbonization.	[25]
A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge	Journal of Cleaner Production, 2021 (IF: 9.2)	-Discussions of the biochar integration into the anaerobic digestion process of food waste and sludge. -Roles and mechanisms of biochar in anaerobic digestion. -Techno-economic and life cycle analysis.	[26]

Based on **Table 1**, the study of coupling anaerobic diegstion and thermochemical process (especially pyrolysis) has been recently investigated in terms of energy recovery and by using pyrolysis biochar as an anaerobic digestion stabilizer/biomethane enhancer, or for biogas upgrading. Up to date, two main strategies has been investigated by means of anaerobic digestion followed by subsequent solid digestate pyrolysis and pyrolysis of recalcitrant biomasses prior to anaerobic digestion. However, the agronomic interest of coupling biochar and digestate or liquid digestate has been little studied in the different published review (Table 1). For these purposes, the following review proposes to investigate the overall synergy possible between anaerobic digestion and pyrolysis process with a special focus on coupling biochar and digestate for agronomic purposes. A specific paragraph is also dedicated to the economic, environmental, and societal consideration of the dual approach. Finally, some promising perspectives of coupling anaerobic digestion-pyrolysis process are also discussed in this review.

2. Anaerobic digestion and pyrolysis processes

2.1 Pyrolysis Process

Pyrolysis is defined as the thermal decomposition of the organic matrix under non-oxidizing or very low-oxidizing stoichiometric atmospheres [27], and it occurs between 250 and 1200 °C [28]. During pyrolysis, organic matter such as lignin, protein, cellulose, and hemicelluloses are thermally broken down to form three major products: biochar (carbonaceous solid fraction), bio-oil (mainly composed of 15–30% w/w_{liquid} of wide variety of organic components and 70–85% aqueous pyrolysis liquid (APL)) [29], and syngas composed of non-condensable gases (CO, CO_2, CH_4, and H_2) [30,31]. Depending on the operating pyrolysis conditions (temperature, heating rate, residence time (RT)) the pyrolysis process can be classified as: slow, fast, and flash (**Fig. 1**) [28]. According to the typology of pyrolysis applied and the biomass treated, the distribution of biochar, bio-oil, and syngas will be different.

Due to its high calorific content, pyrolysis gas can represent an interesting supplementary energy source that can be further converted into heat or heat/electricity alone or mixed with biogas in boilers, engines, and other equipment [32]. Furthermore, the product gas can be transformed to methanol, dimethyl ether and other important chemical feedstocks *via* Fischer-Tropsch (FT) synthesis [25]. In parallel, the pyrolysis liquid presents a light- to dark-brown color consisting mainly of a mixture containing hundreds of organic molecules [33]. Often, pyrolysis liquid separates into an organic, light non-aqueous phase (bio-oil), and aqueous phase known as APL. The bio-oil produced is of primary interest as it can replace diesel in internal combustion engines to produce electricity [34]. On the contrary, APL currently has no apparent use and should be carefully managed due to its high organic strength that can cause environmental burdens [32]. Biochar produced by pyrolysis due to its rich phosphorous content and physicochemical properties (porosity, surface area…), can be use in agronomic applications or for bioremediation [35,36]. Biochar can be also converted into activated carbons through physical and chemical activation processes to increase its physicochemical properties, especially, the accessible surface area and porosity. However, the use of activated biochar related to anaerobic digestion applications have been poorly investigated until yet [37,38].

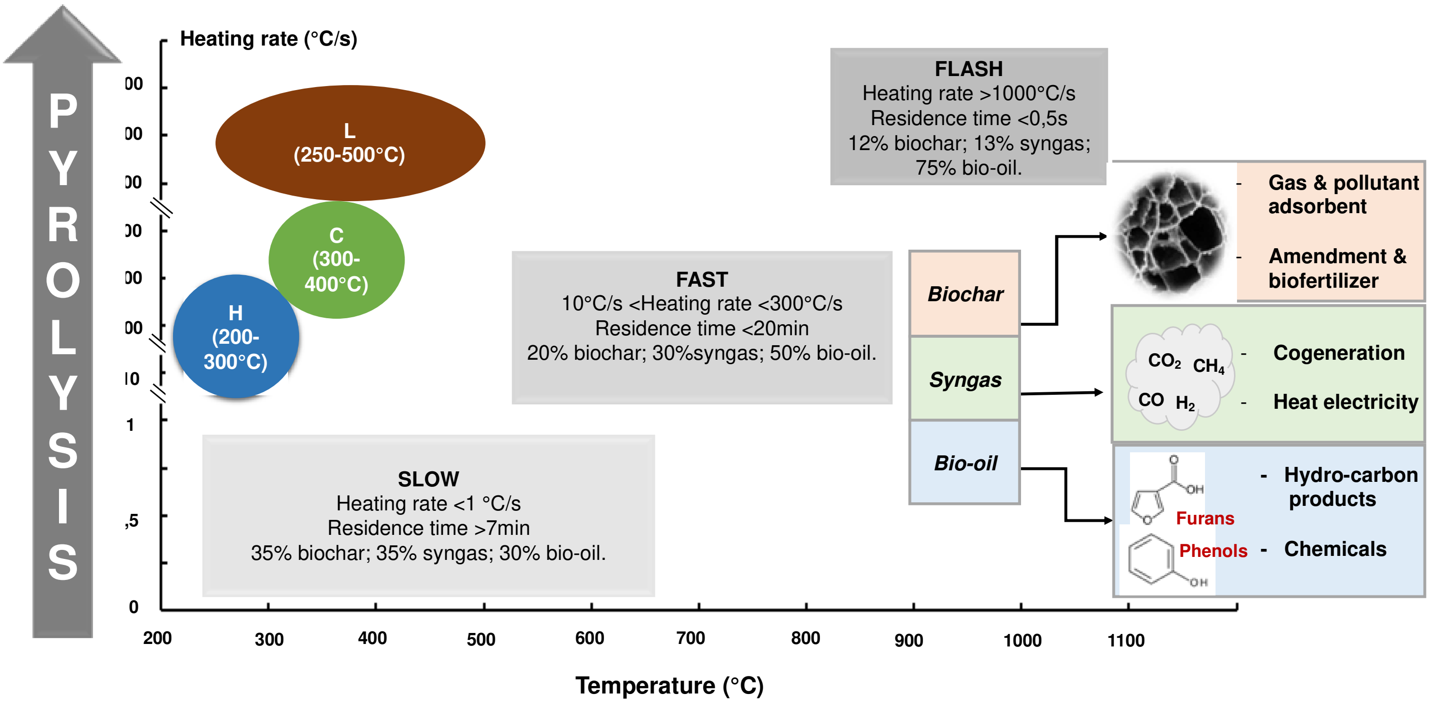

Fig. 1. Operating conditions, distribution of pyrolysis products for each pyrolysis type, and degradation temperature ranges of lignocellulosic compounds (Cellulose (C), Hemicelluloses (H), and lignin (L)). The scheme was inspired from Arnold et al. [39].

2.2 Anaerobic digestion process

Anaerobic digestion represents one of the most promising processes to convert diverse organic substrates (animal manure, food waste, municipal solid waste, and lignocellulosic biomass as agricultural waste) into energy carriers [40,41]. This process corresponds to a microbiological degradation of organic matter under anaerobic conditions leading to stabilization of organic matter (digestate) and formation of biogas [42]. The anaerobic digestion process could be divided into two types according the feedstock dry matter (DM): wet state [43] and solid state [44], and it involves four successive stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [45]. The anaerobic digestion biogas composed mainly of CH_4 (55–75%) and CO_2 (25–45%) [42]. The produced biogas is used as a source of renewable energy by combined heat and power (CHP) generation, and/or upgraded to bio-methane to be used as transportation fuels, or injected into natural gas grid [46,47]. In parallel, digestate is also generated through anaerobic digestion process and correspond to recalcitrant fraction or not degraded during the anaerobic digestion process [48]. To improve its transport and handling, digestate is generally separated into a liquid (rich in nutrients N and K) and a solid phase (rich in P and organic matter) through various technologies: screw press, vibrating sieve, and centrifuge [48,49].

3. Complementary of pyrolysis and anaerobic digestion processes

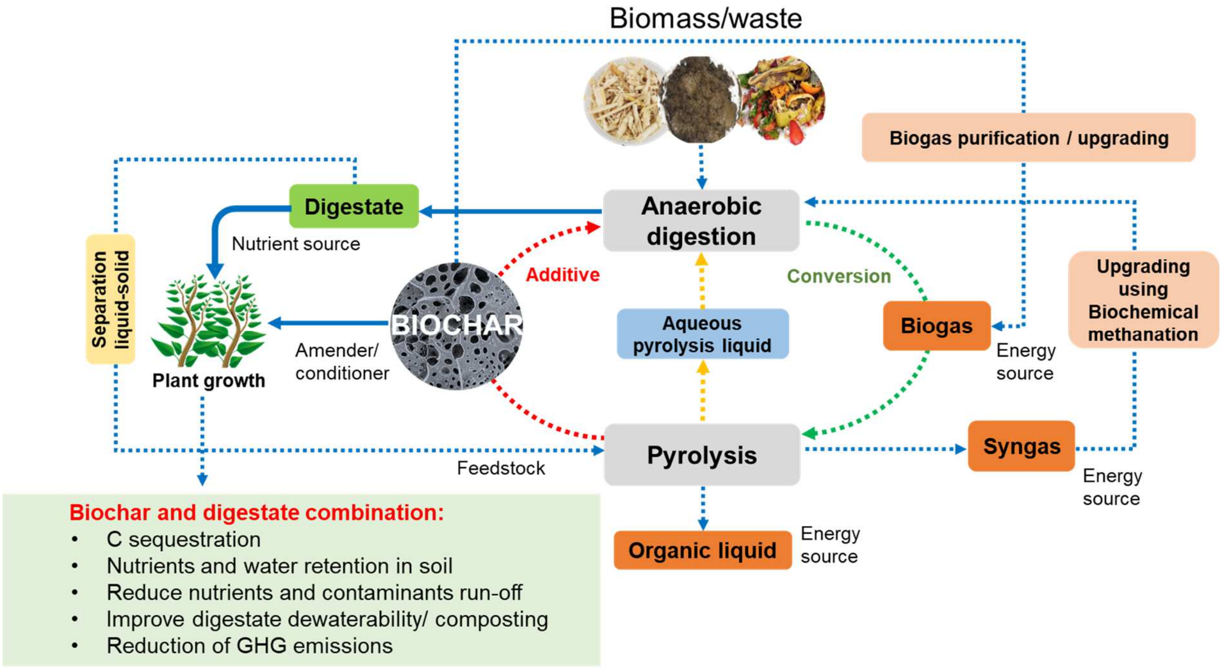

Fig. 2. Synergies between pyrolysis and anaerobic digestion processes by using biochar as central element. The scheme shows biochar interactions with anaerobic digestion by means of stabilizer/enhancer, biogas purification and/or upgrading and also for soil preservation.

Recently, the combination of anaerobic digestion and pyrolysis processes has started attracting attention among the scientific communities (567 publications between 2010 and 2019 in Science Direct using the keywords: coupling anaerobic digestion and pyrolysis). As mentioned by Fabbri and Torri [8], this low number of papers on a potentially interesting topic could be easily explained considering the relatively recent progress in commercialization of anaerobic digestion plants and pyrolysis/gasification technologies. Furthermore, in academia, thermochemical approaches are often parallel or competing with biochemical ones. Nevertheless, it is evident from literature data that these two processes can be associated according to a progressive integration ("industrial symbiosis") approach, establishing a functional relationship. Recently, two main scenarios have been investigated with the pyrolysis process applied: 1) upstream of the anaerobic digestion process by biological upgrading of the liquid pyrolysis fraction (APL phase) through anaerobic digestion, and 2) downstream by converting the digestate recalcitrant solid phase [8,9,50]. Additionally, to improve energy recovery from initial biomasses, pyrolysis applied upstream or downstream of the anaerobic digestion process has revealed many benefits (**Fig. 2**) including:

- The treatment of a large range of substrates: easily biodegradable substrates are sent to anaerobic digestion whereas hardly biodegradable (wood, straw, solid fraction of digestate) are sent to pyrolysis.
- The dual symbiosis approach of coupling anaerobic digestion and pyrolysis is interesting because a pretreatment unit preceding anaerobic digestion could be avoided, as pyrolysis could handle the dry, poorly biodegradable materials that otherwise would have required hydrolysis before anaerobic digestion.
- The ex-situ or *in-situ* addition of biochar for inhibitors uptake.

- The *in-situ* addition of biochar for biofilms formation and stability performance improvement of the anaerobic digestion process
- The *ex-situ* or *in-situ* addition of biochar for biogas purification or upgrading.
- The aqueous bio-oil treatment by the anaerobic digestion process.
- The syngas upgrading through the biological methanation process (*in-situ* or *ex-situ*).
- The complementary in using digestate with biochar for agronomic issues.

3.1. Biogas purification and/or upgrading using biochar.

Biogas produced can be valorized as transport biofuel, injected in the national gas grid (biomethane after purification), or further converted into heat and electricity through a cogeneration (Combined Heat and Power – CHP) system [51]. Electricity can be sold to the public grid at a fixed rate dependent on the national policy and provide economic benefits to farmers [52]. According to the biogas valorization routes, some elements, such as H_2S and CO_2, should be removed from the biogas before use [53,54]. Biogas contains H_2S at concentrations ranging from 0.1 to 2.0% (v/v) depending on the types of substrate fed into the digester, which is a very corrosive gas [55]. If the valorization through the CHP system required only the removal of H_2S, upgrading biogas into biomethane would also require the removal of CO_2. Due to its physicochemical properties, biochar can be readily used to purify/upgrade biogas [16,18,19,56]. Recently, Xu et al. [16] investigated the performances of two biochars (produced from pig manure and sewage sludge) for their abilities to remove hydrogen sulfide (H_2S) from biogas. Biochar from pig manure exhibited a higher capacity for H_2S sorption than sewage sludge biochar in both dynamic and static systems [16]. Similarly, Kanjanarong et al. [18], introduced biochar (produced at 600 °C from a mix of woodchips/DG) in a continuously stirred tank reactor for treating sulfate-laden wastewater. With an H_2S concentration varied from 105 to 1020 ppm, the biochar was able to remove more than 98% of H_2S at high pH (7.98) and high moisture content (80%–85%) conditions. Pelaez-Samaniego et al. [57] investigated the effect of pyrolysis temperature (from 300 °C to 600 °C) on the capacity of biochar to adsorb H_2S and demonstrated that the most attractive biochars were those produced at 600 ºC for 60 min. Kanjanarong et al. [18] highlighted that the sorption of H_2S was mainly due to the presence of carboxylic and hydroxide radicals groups on the biochar.

In parallel, biochar has also been investigated for biogas upgrading into biomethane. Two main strategies by ex-situ use of biochar [56] or direct in-situ biochar addition during the anaerobic digestion process have been investigated [58]. Sethupathi et al. [56] investigated the effect of four different types of biochars produced from several biomasses (perilla leaf, soybean stover, korean oak, japanese oak) on the H_2S and CO_2 removal from a synthetic biogas composed of 0.3% of H_2S; 40% of CO_2, and 59.7% CH_4. The various biochars exhibited different performances with the optimal one using perilla although all were efficient in reducing H_2S and CO_2, whereas CH_4 was not adsorbed [56]. Direct addition of biochar in-situ during anaerobic digestion has also been investigated from biogas upgrading. Shen et al. [58] investigated the in-situ addition of biochar from corn stover for biogas upgrading. Besides to improve anaerobic digestion performances, biochar addition also conducted to produce high quality biomethane (> 90% CH_4, < 5 ppb H_2S), with CO_2 removal until 86.3%. Therefore, the biochar improved process stability and considerably reduced energy/cost biogas upgrading. Similarly, Linville et al. [59] investigated biogas purification by in-situ addition of coarse and fine walnut shell biochar and demonstrated that fine biochar was the most efficient. It was demonstrated that addition of 0.96–3.83 g biochar g^{-1} VS_{added} fine walnut shell biochar into the digester resulted in biogas with 77.5%–98.1% CH_4 content by removing 40%–96% of the CO_2 compared with the control digesters at mesophilic and thermophilic temperature conditions [59]. To improve the purification efficiency and removal of H_2S and CO_2, biochar can be also used as a precursor of activated carbon [37,38]. Indeed, activated carbon has been found to be an effective carbonaceous sorbent for H_2S and CO_2 removal due to its high surface area and porosity [57,60,61]. For instance, Pelaez-Samaniego et al. [57] demonstrated that the activation of biochar with Na_2CO_3 impregnation improved the H_2S scrubbing capacity by 37% [57]. Finally, once the biochar is exhausted, it can be regenerated [60,62] or used as a nutrient-rich soil amendment for sulfur deficient soils [47,63].

3.2. Bio-oil and syngas valorization through integrated approach.

Pyrolysis liquid is composed of two phases: an organic phase (bottom phase consisting of 15–30% w/w of bio-oil) and an aqueous phase (85–70% w/w of bio-oil). The aqueous phase (APL) is formed by water, water soluble substances (C_2–C_6 sugars, volatile fatty acids, oligomers), and slightly soluble substances (mainly phenols and furans) [29,64–66]. It is characterized by low heating value, high pH, high N-NH_3 concentration, and high water content and currently, no apparent use has been defined [32]. For this purpose, the use of APL in anaerobic digestion (Fig.2) has gained attention in recent decades [29,32,67].

Torri and Fabbri [29] investigated the methane potential of APL (from corn stalks pyrolysis at 400 °C for 10 min) in batch tests and reported a methane production corresponding to 34% of the theoretical value. Similarly, Hubner and Mumme [67] investigated the methane potential of various APL of pyrolysis liquid produced from solid digestate at 300 °C, 430°C, and 530°C and added in batch tests at four COD-based concentrations of 3, 6, 12, and 30 g L^{-1}. The lower concentrations (based on COD) of APL where converted during the anaerobic digestion process, while a concentration of 30 g L^{-1} caused process inhibition [67]. The temperature of pyrolysis process also influenced the APL anaerobic digestion. For instance, at a COD concentrations of 12 g L^{-1}, methane yield of 220 mL CH_4 g COD^{-1} was observed for APL produced at 330°C, followed by the 430°C with methane yield of 199 mL CH_4 g COD^{-1}, whereas the 530°C sample was inhibited with a methane yield of 38 ± 10 mL CH_4 g COD^{-1} [67]. Similarly, Seyedi et al. [32] have investigated the potential toxicity of various pyrolysis liquids (derived from catalyzed and non-catalyzed pyrolysis at 800°C of anaerobically digested primary sludge and waste activated sludge) on the methane potential. Using the anaerobic toxicity assay, APL digester loading rates higher than 0.5 g COD L^{-1} for non-catalyzed and 0.10 g COD L^{-1} for catalyzed APL were not sustainable due to toxicity [32]. NH_3-N was not the main inhibitory constituent and other organics including 3,5-dimethoxy-4-hydroxybenzaldehyde, 2,5-dimethoxybenzyl alcohol, benzene, cresol, ethylbenzene, phenols, styrene, and xylenes as well as nitrogenated organics (e.g., benzonitrile, pyridine) generated methane production inhibition [32].

Currently, few studies have reported at continuous pilot scale the anaerobic digestion of APL [29,68]. Torri and Fabbri [29] demonstrated the difficulties to maintain stable semi-continuous anaerobic digestion of APL at daily addition higher than 15 g COD L^{-1} d^{-1}. Similarly, Seyedi et al. [68] investigated the co-digestion of synthetic sludge with APL in semi-continuous assay and a daily methane production of 38 mL was reported which was comparable with the control treating only synthetic sludge (38.8 mL). For microbial communities, for both digesters, similar bacteria communities dominated by *Clostridium* genus and similar archaea communities dominated by *Methanosaeta* genus were observed. Nonetheless, a higher concentration of APL can generate instability in the anaerobic digestion process causing microbial communities to shift. Chen et al. [69] investigated the methane potential of hydrothermal liquefaction (HTL) wastewater. Interestingly, different microbial community compositions were observed from wastewater produced at different temperatures probably due to different organic compound concentrations. For low temperature of HTL, *Petrimonas*, which could degrade sugars, was the predominant in the anaerobic digestion of samples, whereas *Syntrophorhabdus sp,* were more abundant in the anaerobic digestion of samples with higher HTL temperatures probably due to its capacity to degrade phenols compounds [69]. If the anaerobic digestion process of APL of pyrolytic bio-oil is technically feasible at low concentration (0.06 to 0.3 g COD L^{-1}) [67], at higher concentration APL can be a hardly substrate to be degraded through anaerobic digestion process due to potential anaerobic digestion inhibitors in higher quantity (*i.e* furans, phenols) [32]. Indeed, the APL of bio-oil is rich in furans, polyphenols, and ammonium, which have been previously recognized as potential inhibitors of the anaerobic digestion process [42,70]. To overcome this limitation, APL can be co-digested with other biomasses [68] or biochar can be added in-situ during anaerobic digestion to improve the mitigation of the potential inhibitors such as furans and phenols compounds [29]. Indeed, Monlau et al. [71] investigated the use of biochar produced from anaerobic digestate to treat synthetic medium rich in furans compounds. At a concentration of 40 g L^{-1} of biochar, more than 94% of 5-HMF and 99% of furfural were removed after 24 h of contact time in a synthetic medium, whereas sugar concentrations remained unchanged. During the trials, furfural adsorption was faster than 5-HMF [71]. Recently, Torri and Fabbri [29] demonstrated in BMP tests within-situ incorporation of biochar increased methane yield (60 % of theoretical value) with respect to pure APL (34 % of theoretical value) [29]. At the semi-continuous digestion scale, they demonstrated the benefits of adding biochar; with a daily input of 5 g d^{-1} L^{-1} of APL, where no intoxication signal was revealed and a relatively stable methane production was observed [29].

Besides bio-oil, syngas can also be upgraded into methane through biological methanation [72,73]. Several parameters such as cell concentration and microorganisms origin, reactor typology, pressure, pH, and temperature can influence the performances of the biological methanation process [74]. Biological methanation can be realized in a separate reactor or *in-situ* during anaerobic digestion, [74,75]. Indeed, such a configuration, even if it presents several technological barriers can improve the CH_4 amount produced by adding inorganic electron donors such as H_2 and CO, both which can be produced as syngas from solid digestate or other biomass [75,76]. Recently, some authors have investigated and simulated the incorporation of syngas into biological methanation process for upgrading into methane [75,76]. Guiot et al. [75] investigated several aspects of syngas BM, including the dominant metabolic pathways used by anaerobic sludge when converting CO into methane and its tolerance level to syngas impurities. They demonstrated that direct methane generation from CO was very low, and CO was converted (CO acetogenesis) through an intermediate step mainly into acetate, which was further converted into methane. Furthermore, acetoclastic methanogens were the most sensitive to CO and syngas impurities, but higher impurity concentrations affected all activities [75].

From a technical point of view, one major limitation is the poor solubility of hydrogen and CO that limit the mass transfer between the gas phase and the microbial cell [72,77]. Indeed, in aqueous medium, CO_2 is around twenty-three times more soluble than hydrogen [74]. For this purpose, Guiot et al. [75] investigated in three bioreactor designs: a fluidized bed reactor (FBR), a closed-loop gas-lift reactor (GLR), and a bubble column reactor (BCR) the CO conversion efficiency. From all reactors investigated, the continuous stirred tank reactor was a sustainable option because it showed high specific bioactivity and gas–liquid mass transfer rates [75]. In parallel, Schwede et al. [72] recently investigated the immobilization of methanogenic archaea onto biochar (from green waste pyrolysis) to improve biological methanation processes. Results demonstrated that biochar was a suitable carrier for methanogenic archaea and that the biochar was successfully inoculated. During the first 24h, the conversion of H_2 with CO_2 and CO to CH_4 was fast and achieved more than 50% of the syngas components were converted to methane. However, CO was in majority utilized for formate/acetate formation rather than for methanogenesis conversion. Then, due to inhibition of methanogenesis by CO, it was demonstrated that methane production declined with increasing CO partial pressure [72]. Finally, Figueras et al. [20] have recently investigated the biomethanation of syngas by enriched mixed anaerobic consortium in a 10 L continuous stirred tank reactor working at 4 bars and 55 °C [20]. Higher pressure reactor is a pathway to improve the gas-liquid transfer Syngas (40% CO, 40% H_2, 20% CO_2) biomethanation was performed successfully and methane productivity as high as 6.8 $mmol_{CH4}/L_{reactor}/h$ with almost full conversion of CO (97%) and H_2 (98%) was achieved [20].

3.3 Use of biochar to improve the performances of anaerobic digestion

3.3.1. As methane enhancer

In recent decades, several studies have investigated the supplementation of anaerobic digestion using specific materials to improve stability, performance, and microbial biofilm formation [23,78,79]. Activated carbon [80], zeolites [81], and more recently biochar [23,78] are among the materials tested. Due to their physicochemical properties, high porosity, and accessible surface area, biochar has been largely investigated recently to improve anaerobic digestion performance [23,82,83]. Carbonaceous material addition into anaerobic digestion systems was first investigated by Kumar et al. [80], who studied the effect of charcoal powder addition on mesophilic anaerobic digestion of cow slurry in continuous flow anaerobic digestion and batch anaerobic digestion. They demonstrated that adding 0.4 g g^{-1} fresh matter of charcoal corresponded to an increase in methane yield of 34.7% and 17.4% for continuous flow anaerobic digestion and batch anaerobic digestion, respectively. However, the high production cost of charcoal limited its use in anaerobic digestion because the observed energy gain cannot cover the price of charcoal [82]. For this purpose, the use of biochar and/or activated biochar supplementation in the anaerobic digestion process have been investigated as described in **Table 2** [17,23,78,84]. Biochar can improve the anaerobic digestion stability and performances by means of: 1) buffering the medium due to alkaline pH of biochar [59]; 2) adsorption potential anaerobic digestion inhibitors (ammonium, phenols, limonene) [17,23]; 3) accelerating the transformation of macromolecular substances to dissolved ones [85]; 4) providing high nutrients (Ca, Mg, P, K) supplies [86]; 5) acting as microbial biofilm for bacteria and methanogens due to its high porosity of biochar [23,87,88]; and 6) stimulating methanogens by promoting direct interspecies electron transfer among the bacteria and methanogens [88,89]. Acid-buffering issues represent a major reason for why anaerobic digestion is disruptive and generally occurs when the feedstock composition changes by total ammonia accumulation or by high organic loading rate (OLR) [23]. Biochar has proved its ability to adjust the alkalinity of the anaerobic digestion system. Linville et al. [59] found an improvement in alkalinity of $CaCO_3$ from 2800 mg L^{-1} to 4800 -6800 mg L^{-1} providing digestion better anaerobic digestion stability when walnut shell biochar was added inside the digester [59]. Promising results have been highlighted and biochar addition has been demonstrated to accelerate and improve the production of biomethane [17,23]. To date, several assays of biochar or activated biochars supplementation on anaerobic digestion have been tested: in wet anaerobic digestion [59,90], dry anaerobic digestion [88,89], and more recently in two stage hydrogen-methane production [87]. Li et al. [90] studied the effects of manganese oxide-modified biochar (corn straw, 600 °C), which is known for its high heavy metal content, on anaerobic digestion of sewage sludge. The results showed that the addition of 0.09 g g^{-1} DM of modified biochar enhanced methane production by increasing the cumulative methane yield to 127.4% compared to the control. However the high biochar dose (0.20 g g^{-1} DM) exhibited the lowest cumulative methane production (**Table 2**), suggesting that microbial activities could be inhibited by high biochar doses [90]. Li et al. [90] demonstrated that manganese oxide-modified biochar incorporation into the anaerobic digestion process could improve the performances by increasing the buffering capacity and promoting the degradation of intermediate acids [90]. Besides the effect of the biochar dose, biochar addition with different sizes also showed a significant impact on the maximum methane production rate (Qmax). A study conducted by Cheng et al. [84], showed that the highest increase in Qmax was observed by using granular biochar (2.2 g g^{-1} VS), which was 12 ± 6.1% higher than the control (without biochar addition). It was highlighted that a linear relationship between Qmax and biochar surface area did not exist, but in general, Qmax decreased with increasing surface area, suggesting that differences in adsorption capabilities of biochar may be one explanation for these observed discrepancies [84]. Pan et al. [85] investigated the impact of different biochar origins (wheat straw, fruitwood, chicken manure) produced at various pyrolysis temperatures (350, 450, and 550 °C) on the anaerobic digestion of chicken manure [85]. The best results were observed by addition of fruitwood biochar (550 °C), with an increase of 69% of the cumulative methane yield compared to the control, with a methane potential of 294 L CH_4 kg^{-1} VS_{added} compared to 174 L CH_4 kg^{-1} VS_{added} for the control. Interestingly, fruitwood biochar produced at 550 °C exhibited the larger surface area (202 m^2 g^{-1}) and the highest total ammonia nitrogen reduction capacity (TAN concentration of 3.34 g L^{-1} compared to 4.48 g L^{-1} for the control), which can explain the improvement in methane potential [85]. Finally, Wu et al. [91] investigated the effect of magnetic biochar addition prepared with different $FeCl_3$:rice straw ratios on anaerobic digestion organic fraction of municipal solid waste (OFMSW). The results showed that the methane production with magnetic biochar prepared with 3.2 g $FeCl_3$:100 g rice straw ratio increased by 11.69 % compared to control (without biochar addition); these findings were justified by the selective enrichment of microorganisms on magnetic biochar that participate in anaerobic digestion. However, high Fe content in magnetic biochar (33 g $FeCl_3$:100 g rice straw ratio) led to a decrease in methane production by 38.34% compared to the control due to iron oxide electron competition [91]. Jang et al. [86] studied the effect of adding biochar (derived from dairy manure) on methane production at different temperatures conditions (psychrophilic; mesophilic; thermophilic). In comparison with the anaerobic digestion without biochar addition, the methane yield with 10 g L^{-1} of biochar increased by 26.47% in psychrophilic, 24.90% in mesophilic, and 24.69% in thermophilic conditions. Furthermore, the addition of biochar lowered the concentration of total VFAs and propionic acid and shortened the lag phases of anaerobic digestion for all the temperatures investigated [86]. Mumme et al. [92] also investigated the effect of biochar addition on biogas production and ammonia inhibition.

Kinetic and microbiota analyses revealed that biochar can prevent mild ammonia inhibition (2.1 g TAN kg^{-1}). Stronger inhibitions (3.1–6.6 g TAN kg^{-1}) were not mitigated. Biochar addition to the anaerobic digestion process has also been investigated in continuous assays [93–96]. Shen et al. [93] investigated the biochar incorporation in anaerobic digestion process in a semi-continuous assay treating sewage sludge. Interestingly, substrate utilization, methane productivity, and process stability was improved by biochar addition in the anaerobic digestion process [93]. Corn stover biochar addition enhanced the methane production rate by up to 37% compared to the control [93]. Microbial communities were also investigated, and corn stover addition (3.4–3.6 g biochar g^{-1} VS added) promoted the abundance of Clostridia and Methanosarcina [93]. Similarly, Sun et al. [88] investigated the impact of biochar addition in microbial communities shift during mesophilic and thermophilic anaerobic digestion process. Interestingly, methanogen community distribution was more intensively influenced by the biochar supplement in mesophilic than thermophilic conditions. Segun-Giwa et al. [94] also investigated the addition of biochar (0.25 g day^{-1}) on long-run anaerobic digestion of food waste. At an OLR of 2 g VS L^{-1} day^{-1}, the reactor without biochar addition led to VFA accumulation and failed whereas the reactor fed with biochar remained stable up to an OLR of 5.4 g VS L^{-1} day^{-1} [94]. Wanbugu et al. [95] also investigated the addition of biochar (from waste wood pyrolysis at 600 °C) on the anaerobic digestion of food waste in up-flow anaerobic sludge blanket (UASB). The average COD removal efficiencies of the control and the biochar-amended reactor were 47% and 77% at an OLR of 6.9–7.8 g COD L^{-1} day^{-1}, respectively. Cumulative biogas production and methane composition were improved in the UASB fed with biochar and after 34 days the concentration of VFAs were, respectively, 1600 mg L^{-1} and 350 mg L^{-1} for UASB without and with biochar addition [95]. Future research should be led to better understand biochar–microbe interactions and the effects in continuously-fed anaerobic digesters.

Biochar addition to dry anaerobic digestion has also revealed positive results [82,88,89]. Sun et al. [88] studied on dry anaerobic digestion of beer lees the effect of biochar addition (2 g L^{-1}, 6 g L^{-1}, 10 g L^{-1}, and 14 g L^{-1}) at both mesophilic and thermophilic conditions. Cumulative methane production rate and yield with 10 g L^{-1} of biochar were improved by 82.9% and 82.6% at mesophilic conditions and 47.2% and 46.8% at thermophilic conditions in comparison with the control [88]. Nonetheless, high concentration of biochar (14 g L^{-1}) led to a decrease in methane production rate and yield. Similarly, Meyer-Kohlstock et al. [82] investigated the influence of biochar addition (wood residue at 650 °C) in a mesophilic solid-state (batch) fermentation with percolation. The results showed that methane production increased by 5% with a biochar addition of 5% (based on organic DM biochar to bio-waste), while an addition of 10% showed an increase of 3%, suggesting that high biochar concentration can reduce efficiency. Finally, Capson-Tojo et al. [89] recently investigated the impact of biochar and $FeCl_3$ addition on dry continuous pilot reactors. It was demonstrated that higher methane production rates (up to 1.75 L L^{-1} day^{-1}) and lower concentrations of acetate and propionate were achieved when biochar and trace elements ($FeCl_3$) were added [89]. Finally, biochar addition (biochar from pyrolysis of pine sawdust at 650 °C) was investigated recently in the performances of two stage hydrogen and methane production treating aqueous carbohydrates food wastes at mesophilic conditions (35 °C) using bench-scale bioreactors [87]. Interestingly, biochar addition improved hydrogen yield by 31.0% and methane by 10.0% and reduced the lag in the two phases by 36.0% and 41.0%, respectively. Biochar addition promoted the VFA generation during dark fermentation process and subsequent VFAs degradation in methane production [87]. These different studies have demonstrated the benefits of using biochar in anaerobic digestion even if certain concentrations should not be exceeded to avoid an opposite effect [87,88].

Table 2
Selected reported studies of in-situ addition of biochars in anaerobic digestion systems and their effects on biomethane production.

Anaerobic digestion substrate	**Anaerobic digestion process conditions**	**Biochar feedstock/ carbonaceous material**	**Pyrolysis conditions/ Activation**	**Biochar Dose**	**Cumulative / yield CH_4-control**	**Cumulative /yield CH_4-biochar**	**Improvement rate %**	**Ref.**
Cow slurry	Mesophilic batch at 35 °C	Powder charcoal (Darco G60)	-	0.4 g g^{-1} fresh matter	-	-	**+ 17.4**	[80]
	Semi continuous digesters at 35 °C		-		-	-	**+ 34.7**	
Swine sludge and wastewater	Glass serum bottles at 30 °C	Pine wood	Pyrolysis 980 °C	2.2 g g^{-1} VS (granular loading)	-	-	**+12 ± 6.1**	[84]
				9.6 g g^{-1} VS (powder loading)	-	-	**- 57 ± 3**	
Dewatered sewage sludge	Mesophilic batch wet anaerobic digestion at 35 °C	Corn straw	Pyrolysis 600 °C RT of 120 min HR of 25 K min^{-1} /Soaking in $KMnO_2$ MR of biochar: KMnO2=10:1	0.09 g g^{-1} DM	~53.3 L kg^{-1}VS	121.2 Lkg^{-1} VS	**+ 127.4**	[90]
				0.20 g g^{-1} DM		~37.0 L kg^{-1}VS	**- 30.6**	
Chicken manure	Mesophilic batch wet anaerobic digestion at 35 °C	Fruitwood biochar	Pyrolysis 550 °C RT of 2 h	5 g g^{-1} DM	174 L kg^{-1}VS	294 L kg^{-1}VS	**+43.1**	[85]
Citrus peel	-	coconut shell, wood, and rice husk	-	1 g g^{-1}	165.9 mL CH_4 g^{-1} VS	178.2 mL CH_4 g^{-1}VS	**+ 12.3**	[97]
				3 g g^{-1}		186.8 mL CH_4 g^{-1}VS	**+ 20.9**	
Dairy manure	Psychrophilic serum bottles at 20 °C	Dairy manure	Pyrolysis 350 °C RT of 3 h HR of 10 °C min^{-1}	10 g L^{-1}	-	368.2 mL CH_4 g^{-1} VS	**+ 26.5**	[86]
	Mesophilic serum bottles at 35 °C			10 g L^{-1}	-	474.6 mL CH_4 g^{-1}VS	**+24.9**	
	Thermophilic serum bottles at 55 °C			10 g L^{-1}	-	431.3 mL CH_4 g^{-1}VS	**+24.7**	
Beer lees	Mesophilic batch dry anaerobic digestion at 35 °C	Cow manure	Pyrolysis 500 °C RT of 4 h HR of 100 °C h^{-1}	10 g L^{-1}	220.1± 7.7 L kg^{-1}VS	401.8 ± 7.7 L kg^{-1}VS	**+82.6**	[88]
				14 g L^{-1}		358.1±4.2 L·kg^{-1} VS	**+62.7**	
	Thermophilic batch dry anaerobic digestion at 55 °C			10 g L^{-1}	310.4 ± 9.2 L kg^{-1}VS	456.8 ± 7.7 L kg^{-1}VS	**+47.2**	
				14 g L^{-1}		416.9±8.9 L·kg^{-1} VS	**+34.3**	
Aqueous carbohydrates food waste stimulated from white bread	Bach wet two-phase anaerobic digestion (H_2 and CH_4 production) at 35 °C	Pine sawdust	Pyrolysis 650 °C RT of 20 min	8.3 g L^{-1}	1070.0 ± 3 mL/L	1136.6 ± 7.0 mL/L	**+6.2**	[87]

Organic fraction of municipal solid waste (OFMSW)	Mesophilic batch wet AD	Rice straw	Pyrolysis 500 °C RT of 2 h / the substrate was suspended in $FeCl_3$ solution	0.5 % (w/w) of 3.2g FeCl3:100g rice straw biochar	174.2 L kg^{-1}VS	194.6 L kg^{-1}VS	**+11.7**	[91]
				0.5 % (w/w) of 33 g FeCl3:100 g rice straw biochar		107.5 L kg^{-1}VS	**-38.3**	
Bio-waste (OFMSW)	Mesophilic solid-state batch at 40 °C	Clean forestry wood residue (Holm Oak)	Pyrolysis 650 °C	5% VS	245 N L kg^{-1} VS	257.4 N Lkg^{-1} VS	**+5.1**	[82]
				10% VS		252.3 N Lkg^{-1} VS	**+3**	
Food wastes	Continuous pilot scale reactors at 37 °C	Slow-pyrolyzed wood biochar	-	From 10 to 50 g L^{-1} with 100 mg Fe L^{-1}	~ 200 mL CH_4 g^{-1} VS	350 m L CH_4 g^{-1} VS	**+ 75**	[89]
N-rich substrates	Mesophilic batch, glass syringes at 42 °C	Mixture of paper sludge and wheat husks	Pyrolysis 550 °C RT of 20 min	-	-	-	**-8.5**	[92]
		Wheat straw DG	Hydrothermal carbonization 230 °C RT of 6 h		-	-	**+31.7**	
wastewater sludge	Mesophilic Batch glass bottles at 38 °C	waste forest industry wood (a mix of pine, spruce, and cedar)	Pyrolysis 450–550 °C	0.8-3.7 g g^{-1}VS	-	-	**+ 192–461**	[98]
Sewage sludge	Yearlong semi-continuous thermophilic two stage anaerobic digestion at 55 °C	Corn stover	Pyrolysis & gasification 500–850 °C	0.25-1 g day^{-1}	-	-	**+ 36.9**	[93]
		Pine	-		-	-	**+ 16.6**	
Chicken manure	Semi-continuous stirred tank reactors at 35 ± 1 °C	Orchard waste wood	Pyrolysis 550 ± 50 °C	4.97 % TS	-	-	**+33** (OLR of 0.625 g VS L^{-1} day^{-1}) **+ 36** (OLR of 3.125 g VS L^{-1} day^{-1}) **+ 32** (OLR of 6.25 g VS L^{-1} day^{-1})	[96]

RT: Residence Time; HR: Heating rate

3.3.2. As a tool for AD inhibitors removal

Biochar represents an exceptional sustainable product for remediation and adsorption; it has been investigated as a low-cost sorbent for various organic molecules and inhibitors as summarized in **Table 3**. Ahmad et al. [99], reported that the adsorption performances of biochar depends mainly on some physicochemical proprieties such as surface area, porosity, alkalinity, ion-exchange capacity, and surface functional groups. To deal with the high adsorption capacity of commercial activated carbon, activation processes represent a promising strategy to improve biochar adsorption performances [99,100].

Adsorption or inhibitors mitigation can be done ex-situ or directly in-situ of the anaerobic digestion process. Phenol and furan derivatives are potential anaerobic digestion inhibitors and has been carried out in many adsorption studies using biochar as sorbent. A study showed that biochar produced from pistachio shells removed 51% of phenols through hydrophobic sorption from an aqueous solution of 200 mg L^{-1} [101]. Mohammed et al. [102] reported that pine fruit shell biochar removed more than 26.74 mg phenols g^{-1}. Li et al. [103] reported a high adsorption capacity of 169.0 mg phenols g^{-1} through chemical interactions and pore expansion using chemically activated biochar (with $KHCO_3$ and urea) produced from bamboo. Monlau et al. [71] studied the adsorption of furfural and 5-HMF from lignocellulosic hydrolysates with a concentration of 1 g L^{-1} using biochar derived from anaerobic digestion residues.

Table 3.

Selected reported studies of *ex-situ* addition of biochars as adsorbent for inorganic and organic contaminants.

Inhibitor group	Name/origin	Biochar feedstock	Inhibitor concentration	Removal performance	Removal mechanisms	Ref.
Polyphenol	Phenol	Pistachio shells	100 mg L^{-1}	51%	Hydrophobic sorption	[101]
	Phenol	Pine fruit shells	20–100 mg L^{-1}	26.7 mg g^{-1}	Physisorption mechanisms	[102]
	Phenol	Oil palm frond chips	40-260 mg L^{-1}	62.9 mg g^{-1}	Surface adsorption and pore-filling	[104]
	Phenol	Bamboo/ activated with $KHCO_3$ and urea	1000 mg L^{-1}	169.0 mg g^{-1}	chemical adsorption and physical adsorption through pore expansion	[103]
Ammonium	NH_4^+ from biogas slurry	Biogas residue	0–855 mg L^{-1}	48.9 mg g^{-1}	Ion exchange mechanism	[105]
	NH_4^+ from NH_4Cl	HNO_3 $^-$impregnated corncob	10–100 mg L^{-1}	22.6 mg NH_4^+-N g^{-1}	Sharing or exchange electrons	[106]
	NH_4^+ from NH_4Cl	Orange peel	10–100 mg L^{-1}	4.7 mg g^{-1}	surface complexation, cation exchange and electrostatic attraction	[107]
	NH_4^+ from NH_4Cl	Pineapple peel	10–100 mg L^{-1}	5.6 mg g^{-1}	surface complexation, cation exchange and electrostatic attraction	[107]
	NH_4^+ from NH_4Cl	Caragana korshinskii biomass/ ultrasonic activation	0–100 mg L^{-1}	26.3 mg g^{-1}	Specific surface area and electrostatic adsorption	[108]
	NH_4^+ from NH_4Cl	Oil palm shells/chemical activation with K_2CO_3	100 mg L^{-1}	1.49 mg g^{-1}	surface complexation and electrostatic interaction	[109]
Furan derivatives	Furfural	Solid digestate	1 g L^{-1}	99%	π–π stacking interaction	[71]
	HMF	Solid digestate	1 g L^{-1}	94%	π–π stacking interaction	
	HMF	cotton and linen residues/steam activated	1 g L^{-1}	99%	-	[110]
	Furfural	Bamboo/heat treated (800°C)	10 g L^{-1}	100 %	Pore filling due to high specific surface area	[111]

The authors reported that more than 94% and 99% of 5-HMF and furfural were removed respectively [71]. Same results were founded in the studies conducted by Klasson. K et al. [110] and Li et al. [111]. Biochar has also exhibited great abilities in adsorbing ammonium

[112]. Ammonium (NH_4^+) in groundwater and surface water can caused severe environmental pollution and health issues among people [113] and represents one of the anaerobic digestion inhibitor, which the threshold inhibition level was reported to be varied between 1.5 to 2.5 g/L [114–116]. Recent studies confirmed that the adsorption method using biochar and activated carbon is considered to be an economic and effective strategy for removing NH_4^+ [117–119]. T.M. Vu et al. [106] have used a modified corncob-biochar with HNO_3 and NaOH for removing NH_4^+ from a synthetic water (ammonium concentration from 10 to 100 mg L^{-1}). The highest adsorption capacity of 22.6 mg NH_4^+-N g^{-1} was obtained using modified biochar with NaOH 0.3M and HNO_3 6M [106]. The authors reported that the ammonium adsorption depended strongly on the pH [106]. Yu et al. [105] investigated the efficiency of biochar derived from biogas plant digestate as adsorbent for ammonium removal on artificial wastewater solution and the highest adsorption capacity of 48.89 mg NH_4^+-N g^{-1} biochar was achieved [105]. It was highlighted that the ash content in biochar played an important role in ammonium adsorption due to the significant role that SiO_2 compounds played as adsorption sites in the process [105]. Moreover, a recent study of Wang et al. [108] evaluated the potential adsorption of an activated biochar by ultrasonic activation produced from *Caragana korshinskii* biomass at different temperatures (450, 500 and 650 °C), for removing ammonium from a synthetic solution (concentration from 0-100 mg L^{-1}). The results showed that the highest adsorption capacity of 26.3 mg NH_4^+-N g^{-1} was obtained using the ultrasonic (time was 480 min, the frequency was 45 kHz, and the power was 700W) activated biochar produced at 500 °C. They reported that the ultrasonic activation induced the pore formation, which increase the specific surface area through cavitation corrosion and micro-acoustic flow mechanism [108]. Inhibitor mitigation can also be performed directly in-situ of the anaerobic digestion process. Biochar addition has also been reported as efficient in-situ adsorption of potential inhibitors to the anaerobic digestion process such as D-limonene present citrus peel [97]. In the experiment, three different kinds of biochars were used: coconut shell, wood, and

rice husk. The cumulative methane production in incubations containing biochar and citrus peel ranged from 178.2 (ratio 1:1 citrus peel/biochar) to 186.8 mL CH_4 g^{-1}VS (ratio 1:3 citrus peel/biochar), while citrus peel only produced 165.9 mL CH_4 g^{-1}VS. Furthermore, the authors noted high methanogenic activity within the digester due to the biochar ability to absorb limonene [97]. Finally, Torri and Fabbri [29] demonstrated that biochar addition in situ enables anaerobic digestion of aqueous phase (APL) and mitigation of inhibitors compounds. Batch tests exhibited poor performance in anaerobic digestion of APL, which underlined the inhibition of biological process. Biochar addition increased yield of methane (60 ± 15% of theoretical) with respect to pure APL (34 ± 6% of theoretical) and improved the reaction rate [29]. The adsorption and removal of anaerobic digestion inhibitors such as polyphenol, furans, and ammonium has become a key area of research interest these last decades. It appears that using biochar from renewable biomasses and wastes to adsorb various contaminants and molecules has emerged as a potential cost-effective alternative of conventional activated carbon. Indeed, the price of biochar was estimated at 246 \$ US t^{-1}, corresponding to about 1/6 of commercially activated carbon (~US \$1500 t-1) [99].

4. Agronomic benefits of dual use of biochar and digestate

4.1 Nomination and history of using biochar in agriculture

Biochar origin was first discovered in the Amazon region and known as Terra Preta de Indio, where it was created through the use of slash and burn techniques [99,120,121]. Nowadays, around 10% of the Amazon is occupied by this soil typology, characterized by its high fertility in comparison to others soils [122]. The International Biochar Initiative (IBI) defines biochar as a "solid material obtained from biomass in an oxygen limited environment" [123]. On another hand, the European Biochar Certificate (EBC) defines biochar as "a heterogeneous substance rich in aromatic carbon and minerals produced from sustainable biomass under controlled conditions with clean technology and used for any purpose that does not involve rapid mineralization of biochar to CO_2" [124]. Therefore, the term biochar is generally associated with high stable carbon content contributing to carbon sequestration [125] and improving soil properties due to it physicochemical properties [126–128]. Until yet, biochar exhibited several advantages, among other 1) improving soil nutrient dynamic and exchange with the soil environment [126], 2) enhancing water retention and soil micro-organisms biofilm formation [126,127], 3) retaining organic and inorganic contaminants in soil [129,130], 4) improving the physicochemical properties of soil [127], 5) reducing GHG especially CO_2 emissions [131,132], 6) improving plant growth and quality [132,133], and enhancing carbon sequestration due to its high stable carbon content [128,133,134].

4.2 Effects of combining biochar and digestate on plant nutrition and productivity.

Co-application of biochar and digestate has been tested on plant growth performances under both controlled (growth chambers and greenhouses) and field conditions on different crops such as maize [135–137], winter rye [138], winter wheat [139], taro [140], geranium [141], Chinese melon [142], and radish [143] (**Table 4**). Rhizosphere biological modifications, notably the microbial communities and functions, also occurred in response to dual application of biochar and digestate and the co-application resulted in reduced microbial respiration along with increased soil carbon sequestration [144–147] and reduced GHG emissions [147,148]. In **Fig. 3**, several positive effects on coupling biochar and digestate illustrate the likely benefits of combining them for agronomic purposes. Biochar could not be considered as a nutrient-supplying source, but its potential in crop fertilization has been demonstrated combined with mineral fertilizers or other types of organo-fertilizers like compost [149,150] and digestate [3,139,145] (**Fig. 3**). Indeed, both digestate and biochar can have significant beneficial effects when co-applied, owing to their complementary agronomic and biostimulant properties [3,139,145] with positive consequences on soil fertility and nutrient availability, which presumably would stimulate both plant and microbial functional traits responsible for enhanced fertilizer use efficiency [151]. In addition, liquid digestates are characterized as nutrient-rich (ammonium, potassium, etc.), whereas solid digestates usually contain high phosphorus and fibers [142]. Thus, combining both solid and liquid digestate would provide adequate nutrient elements and may, in some cases, improve soil properties and replace/minimize use of mineral nutrients fertilizers [145,146]. For N supply, which is the most important macronutrient for crop productivity, most digestates are brought to the soil at N concentrations varying from 80 to 275 kg N ha^{-1} [152]. Regardless of the soil nature and plant species, a rate up to 170 kg N ha^{-1} is generally applied, which corresponds to the maximum amount initially allowed by the EU Nitrate Directive for spreading in vulnerable zones [153].

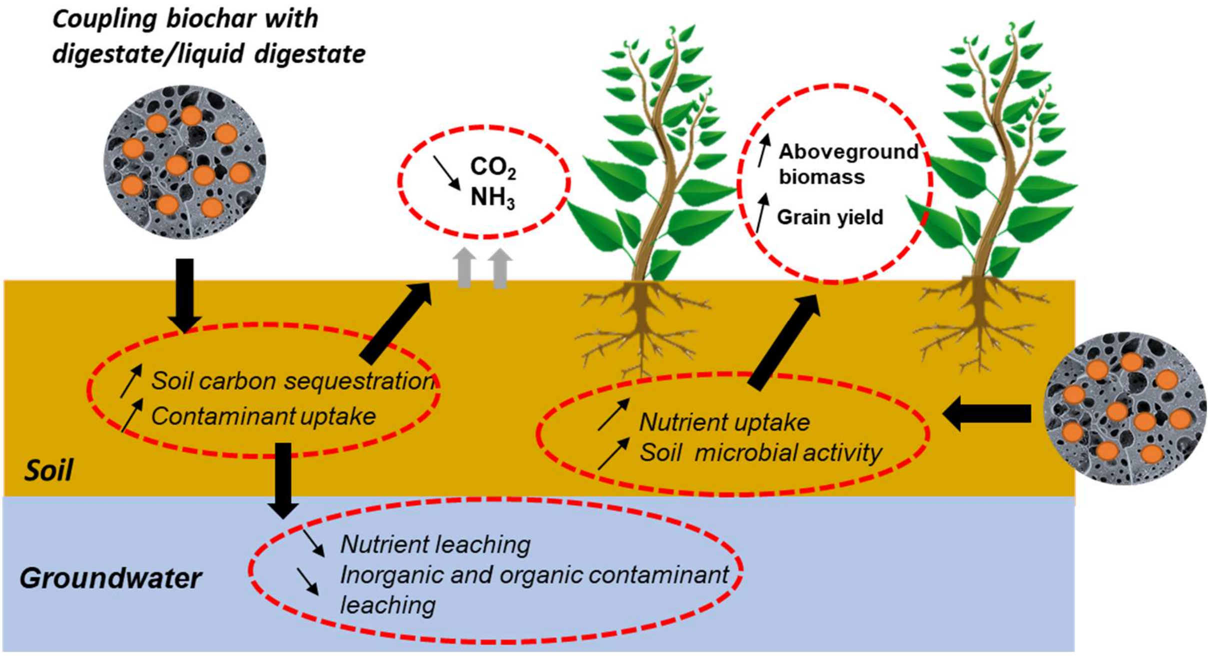

Fig. 3. Illustration of advantages of combining biochar and digestate for agronomic purposes. Downward arrows indicate an increase and upward arrows indicate a decrease.

Although biochar and digestate are known to be agronomically beneficial, effects of coupling biochar and digestate on crop yields are still inconsistent among different studies (Table 4). Positive results of such a coupling were highlighted many times in maize, Taro (*Colocasia esculenta*), chinese Melon (*Cucumis melo L.*), tomato (*Solanum lycopersicum L.*) and marigold (*Tagetes erecta L.*) plants [135,140,142,154]. For instance, Glaser et al. [135] demonstrated that application of biochar and digestate (at rate of 1 and 40 t ha^{-1} and digestate at 200 kg N ha^{-1}) on maize produced better yields (yields and plant nutrition) compared to pure digestate. At a concentration of 40 t ha^{-1} of biochar, the co-application of digestate improved maize yield by 42% compared to untreated plants without biochar addition [135]. Similarly, Bouaravong et al. [140] also demonstrated the positive effect of coupling biochar (2 kg m^{-2}) with different digestate doses (0 to 100 kg N ha^{-1}) on taro plant growth [140] with the observation that co-application of digestate at levels up to 100 kg N ha^{-1} with biochar resulted in linear increase in biomass yield, higher crude leaf protein content, and improved soil fertility as measured by pH, water-holding capacity, and N content. For instance, at a digestate dose of 100 kg N ha^{-1}, biomass yield exhibited 1027 g m^{-2} compared to 609 g m^{-2} obtained with biochar alone [140]. Similarly, Elbashier et al. [142] make a comparison of industrial fertilizers, biochar and digestate amendments on photosynthesis rate and growth parameters of the Chinese melon (*Cucumis melo* L.) under saline and no saline water conditions. This study found that combination of biochar and digestate resulted in a more productive fertilization specifically under saline irrigation conditions compared to mineral fertilizer. Under saline water irrigation, combination of biochar and digestate improved plant height by 36, 22, and 54% compared to biochar, digestate, and unfertilized soil, respectively [142]. Finally, Tayibi et al. [155] have investigated the effect of coupling biochar produce from solid digestate at 500 °C (50 and 100 t ha^{-1}) with liquid digestate (170 Kg N ha^{-1}) on nutrient leaching (NH_4^+, NO_3^-, PO_4^{3-}, K^+, and Na^+) and wheat plants growth. This study found that the coupling of biochar and liquid digestate have only decrease the leaching of NO_3^- by 82% and 91%, at 50 and 100 t ha^{-1} respectively, compared to soil treated only with liquid digestate [155]. In addition, this combination demonstrated that biochar application at 50 t ha^{-1} did not exhibit a negative impact on the relative seed germination of wheat plants and improved aerial dry biomass production up to 27.5%, compared to soil with only liquid digestate addition. In another study, same tendency was noticed on the aerial dry biomass of tomato plants growth, which was improved by 25% under biochar application at 25 t ha^{-1} with liquid digestate (170 kg N ha^{-1}), compared to the treatment with liquid digestate alone [156].

In addition to digestate role in improving soil and plant N status, adding biochar to anaerobic digestate has also been demonstrated to improve soil biological activity, antioxidant capacity, and carbon sequestration [141,142], and that both may be considered suitable fertilizing substrates or soil conditioners, especially for acidic soils [3,143,148]. Another study by Marchetti et al. [145] revealed the benefit of coupling biochar from animal manure (10 t ha^{-1}) with digestate (170 kg N ha^{-1}) demonstrating an improved organic matter stock and available P for crops, without modifying N availability.

Table 4.

Selected publications studied the potential effect of combining biochar with digestate on plant nutrition and productivity.

Biochar rate	**Fertilizer rate**	**Plant choice**	**Impact on plant nutrition availability and yield**	**Ref.**
40 t ha^{-1}	Digestate at 200 kg N ha^{-1}	Maize	• Improvement of maize yield by 42 %	[135]
20 t ha^{-1}	Digestate doses 100 kg N ha^{-1}	Taro	• Improvement of crude leaf and protein content, water holding capacity and N content. • Improvement of biomass yield by 1027 g m^{-2} compared to 609 g m^{-2} obtained with biochar alone.	[140]
180 t ha^{-1}	Digestate at 500 mL/pot equivalent to NPK: 120-150-150 kg ha^{-1}	Chinese melon (Cucumis melo L.)	• Improvement of the plant height by 36, 22, and 54% compared to biochar, digestate, and unfertilized soil, respectively, under saline water irrigation	[142]
50-100 t ha^{-1}	Liquid digestate at 170 kg N ha^{-1}	Wheat	• Decrease of nitrate leaching (NO_3^-) by 82% and 91%, at 50 and 100 t ha^{-1} respectively, compared to soil treated only with liquid digestate. • Improvement of aerial dry biomass production up to 27.5%, at biochar application of 50 t ha^{-1}, compared to soil with only liquid digestate addition.	[155]
25-50 t ha^{-1}	Liquid digestate at 170 kg N ha^{-1}	Tomato	• Improvement of aerial dry biomass production up to 25%, at biochar application of 25 t ha^{-1}, compared to	[156]

			soil with only liquid digestate addition.	
10 t ha^{-1}	Digestate at 170 kg N ha^{-1}	-	• Improvement of the available P for crops and the organic matter stock: the organic matter (C_{org}) decreased from 0.5 to 7.4 g C kg^{-1} using different type of biochars.	[145]
30 t ha^{-1}	Digestate	Radish (*Raphanus Sativus* L.)	• No effect of co-application of biochar and digestate on dry biomass compared to digestate alone	[143]
20 t ha^{-1}	Digestate at 250 kg N ha^{-1}	Wheat	• No effect on wheat growth and grain yields, compared to soil with digestate alone.	[139]

Although no negative impact has been reported yet about coupling digestate and biochar on crop performances, few studies have reported no significant effect under this combination [138,139,143]. For example, Sekar et al. [143] investigated radish cultivation (*Raphanus Sativus* L.) in response to co-application of biochar and digestate in a fifteen month field experiment (**Table 4**). It was found that adding digestate alone significantly improved radish dry biomass (413 g compared to 31 g in soil alone) and that the effect of biochar (30 t ha^{-1}) was not significant as compared to digestate alone [143]. Likewise, Udall et al. [139] reported no effect on wheat growth and grain yields in response to the combination of biochar (20 t ha^{-1}) and digestate (250 kg N ha^{-1}) compared to digestate alone.

4.3 Effects of combining biochar and digestate on soil microbial activity.

Reduced microbial respiration in soil along with improved soil carbon sequestration was measured due to the addition of biochar to digestate [144–147]. Either applied alone or combined with digestate, biochar tended to enrich the C sink of the soil through a reduction in soil respiration due to a reduction in dissolved organic carbon owing to a lower accessibility of microbes to dissolved organic carbon [144]. It seems that the addition of biochar to digestate reduced soluble compounds due to the presence of residual phenol compounds in biochar that exhibit antioxidant capacity in soil microbial communities, and other activities (CO_2 production and dehydrogenase activity) [146]. Similarly, Mukherjee et al. [144]

investigated microbial respiration under a mixture biochar and digestate with the conclusion that addition of digestate to soil led to a significant increase in CO_2 evolution compared to untreated soil. This may be due to a higher proportion of easily degradable C in digestate as opposed to a lower CO_2 release (up to 11-fold difference) observed in soil added with a mixture of digestate and biochar [144]. Interestingly, this effect was also observed when only 1% (w/w) of biochar was mixed with digestate in soil, suggesting that even a low concentration biochar lowered the microbial accessible dissolved organic carbon [144]. Conversely, other findings by Marchetti et al. [145] found no significant effects when biochar (from wood chips and swine manure solids) was added to soils previously amended with slurry digestate. In this study, the digestate-amended soils had an important CO_2 emission rate (1188 mg CO_2 kg^{-1} dry soil) compared to 874 mg measured in untreated soils. In parallel the addition of biochar did not significantly reduce CO_2 emission, with values of 1059 and 959 mg $CO_{2\ \mathrm{released}}$ kg^{-1} in dry soil for both wood chips and swine manure solid biochar [145]. These finding were also in accordance with the results of the study conducted by Tayibi et al. [156], which demonstrated that adding biochar (25 t ha^{-1}) with liquid digestate (170 Kg N ha^{-1}) did not impact the CO_2 emission rate compared to the application of liquid digestate alone [156].

4.4 Effects of combining biochar and digestate on GHG and soil contaminants reduction emissions.

In parallel with carbon sequestration, recent publications have also investigated the effect of co-addition of biochar/digestate in soil on N_2O emissions [147,148]. To date, few studies have examined the effects of biochar on nitrogen transformations within soil amended with digestate [147]. Nitrous oxide (N_2O) is an important GHG, representing around 8% (in 2004) of the global GHG emissions (as CO_2 equivalent), and the global warming potential of N_2O is 298 times higher than CO_2 over a 100-year period [157,158]. One of the major sector contributing to N_2O emissions is agriculture especially due to nitrification and denitrification processes in soil [158]. Martin et al. [147] investigated the GHG nitrous oxide (N_2O) fluxes from soil amended with a combination of digestate and biochar incorporated at several concentrations (0%, 1%, and 3% w/w soil). For this purpose, three digestates of different origin coming from 1) cattle dung and potato waste, 2) cattle slurry and maize silage, and 3) maize silage, have been tested [147]. Important nitrous oxide emissions were quantified from soil amended with digestate originating from a maize feedstock. In parallel, biochar amendment reduced N_2O emissions from all digestate tested, and the higher effect was observed in the treatments with a maximum load of biochar [147]. Similarly, Bruun et al. [148] investigated N_2O and carbon dioxide (CO_2) emissions over a period of 55 days by combining biochar at two concentrations (1% and 3% by mass) with anaerobically digested slurry [148]. When biochar (3% w/w soil) was applied with digestate, N_2O emissions was reduced by 47% compared to biochar at concentration of 1%. Interestingly, N_2O emissions reduction was concomitant with microbial activity improvement, creating anoxic conditions and immobilization of soil nitrogen [148]. Besides improving the soil physicochemical properties, biochar addition to soil, either with or without digestate, has been shown to be effective in reducing the leaching of organic and inorganic contaminants [129,130,144]. Interesting synergies have been shown when combining digestate and biochar for simultaneous sorption/sequestration and mineralization of pesticides [144,159]. In laboratory incubation experiments, Mukherjee et al. [159] investigated the mineralization of three pesticides (*i.e* bentazone, boscalid, and pyrimethanil) when biochar from pine woodchips was mixed with digestate in a sandy soil [159]. It was demonstrated that digestate increased pesticide mineralization mainly by improving soil microbial activities due to the available of carbon source. Among all the biochar-digestate mixtures investigated, co-application of digestate and biochar (both at 5%) positively influenced mineralization and simultaneous sorption of the three pesticides [159]. Coupling biochar and digestate has demonstrated promising results in the literature but such an approach is still in its infancy. Furthermore, the performances appear to be multifactorial and several parameters can influence biochar properties and efficiency for agronomic issues. Biochar properties will be mainly influenced by biomass origin and pyrolysis condition, soil origin (sandy, loamy), climatic conditions, and plant types tested.

4.6. Potential risks of using biochar in agriculture

Beside the environmental and agronomic benefits of using biochar, some studies noticed the potential environmental risks related to biochar applications [160–164]. This knowledges are of importance for biochar utilization in an effective and safe manner, as well as for predicting its environmental behavior [163]. Some risks associated with the addition of biochar such as release of toxic substances, retention of heavy metals, suppression of the effectiveness of applied pesticides due to retention, and ecotoxicological effects on soil microbes has been identified [160–164]. Biochar can be the source of various hazardous compounds such as heavy metals (Cd, Cu, Cr, Ni, Zn), polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), and other toxins such as volatile organic compounds, xylenols, cresols, acrolein and formaldehyde [163,165,166]. In particular, PAHs are very harmful to many plants and others living ecosystems [167,168]. These toxic compounds are produced during pyrolysis process and their concentrations and compositions are highly dependent on biomass feedstock and pyrolysis operation conditions (i.e temperature, residence time, ramp time) [163,169]. In addition to organic compounds, biochar may also contain metal contaminants (e.g., Cu, Cd, and Pb), which are mainly derived from feedstocks containing heavy metals, such as sewage sludge [170] and residues from some biogas plants [169]. Stefuniuk et al. [169] have evaluated the chemical and the ecotoxicological of biochars produced at three temperatures of pyrolysis (400, 600 and 800 °C) using biogas residues (taken in three different agricultural biogas plants operating in mesophilic or thermophilic). The analyses highlighted that with an increased pyrolysis temperature, there was an increase in the contents of PAHs and of certain heavy metals (Cr, Cu, Cd, Pb and Mn).

Due to the specific properties of biochar [171], the sorption of pesticides and herbicides by biochar has been studied with promising results [165]. For instance, Taha et al. [172] studied the adsorption of a mixture of 15 different pesticides (with individual pesticide concentrations of 400µg/l) from water by untreated and treated (using phosphoric acid) biochars and charcoal. The authors reported that treated rice straw biochar reduced the pesticide concentration in water (pH 7) by 99 % in only 2 hours [172]. These results show that biochar can be considered as a double-edged product if the amount of pesticide used to treat plant diseases has not been calculated considering the adsorption efficiency of biochar, making plant disease treatment complicated and poorly managed. Nonetheless, pesticides have been generally used with a higher amount than what plant diseases require for treatment, in this case, the management of bioavailability of herbicides and pesticides using biochar is more likely to be favorable, which helps to improve environmental health and food safety as leading to a more rapid development of weed resistance, reduce crop uptake and leaching of these substances [165,172].

Although biochar has many positive effects for agronomic issues, few works on the literature reported the potential negative effect of biochar on terrestrial ecosystems even though most of the biochar have acceptable content of contaminants (e.g., PAHs and heavy metals), which raised question-related to the risk associated with the application of biochar for soil amendments [173–175]. For instance, Busch et al. [176] reported a reduction in shoot and radical length in maize with the addition of biochar generated at high pyrolysis temperature but not for that produced at low temperature. They concluded that the decline in radical and shoot length was due to higher PAHs content, mainly naphthalene, in the biochar extract at high temperature pyrolysis [176]. Same effect was also reported by Rogovska et al. [177] that investigated the impact of different biochars extracts on Zea mays. Biochars were produced from agricultural residues using several thermochemical processes at various temperatures (slow, fast, and gasification pyrolysis processes). The results showed that all produced biochars from corn hindered shoot length, which was associated with PAHs presence. Naphthalene and Phenanthrene delayed germination by 24 h, but after 5 days, the germination rate of the affected seeds was like the control [177].

Nzanza et al. [178] have reported a microbial inhibition after the use of biochar produced from eucalyptus which conducted to negatively impact the crop yield and leaf nutrient as a reduction of tomato dry weight by 13 % and phosphorus in leave by 26 % [178]. Similarly, Liu et al. [179] have also reported a negative impact of biochar application at rate of 60 t ha^{-1} (produced from wheat straw), which also lead to a microbial inhibition, conducted to reduce plant beneficial fauna population [179]. Stefaniuk et al. [169] also investigated the potential toxicity of biochars produced from various digestates of agricultural biogas plants on various living organisms (springtails, *Lepidium sativum* plants, V. fischeri). In the ecotoxicological tests, the most negative effect on the test organisms was characteristic of biochar produced from non-separated mesophilic digestate. This study shows that the main factors determining the level of toxicity of biochars produced from digestate towards various living organisms (springtails and *Lepidium sativum* plants, V. fischeri) are both the feedstock origin and the temperature at which the pyrolysis process is conducted [169]. Finally, the suggested biochar quality guidelines, including the International Biochar Initiative [123], and the European Biochar Certificate [124], focus mainly on the total concentrations of PAHs, PCBs and heavy metals in biochar. Even if, the IBI also required to perform a germination inhibition tests using three plants test species, these analyses cannot fully reflect the potential ecotoxicity of contaminants on overall terrestrial and aquatic ecosystems. Thus, further research should be conducted in detail on the bioavailability of contaminants in biochar and their risks on the various ecosystems to ensure the reliability of biochar application.

5. Economic, environmental, and societal consideration

To assess the benefit of coupling anaerobic digestion with pyrolysis, it is important to take into consideration the three pillars of the sustainability evaluation: economic, environmental, and societal [180]. To characterize a product or a process in terms of sustainability, a suite of different indicators that cover environmental, economic, and social issues, needs to be adopted. Indicators are quantitative or qualitative factors that provide means to measure a degree of achievement, to reflect changes, or to assess performance or compliance [180]. Multicriteria decision analysis based on the different indicators can be further applied to assess the sustainability of the overall approach [181,182]. First, it is important to consider economical balances when considering the development of innovative processes such as the dual approach coupling anaerobic digestion and pyrolysis process [46,183]. Anaerobic digestion is a well-known technology with wide application in the treatment of high-strength organic wastes. The economic feasibility of this type of installation is usually attained thanks to the availability of fiscal incentives [184]. For this purpose, coupling anaerobic digestion and pyrolysis process can represent an interesting option to improve the economic benefits [184,185]. The techno-economic analysis involves evaluation of a process/technology through process simulation approach often using software such as Aspen Plus and Intelligen Superpro Designer [186]. The economic benefits is generally assess by the use of several indicators such as: capital expenditures (CAPEX), operational expenditure (OPEX), net present value (NPV), payback period (PBP), internal rate of return (IRR), return on investment (ROI) [186,187]. The NPV indicates whether the project is profitable, considering the time value of the cash flows, i.e., revenue streams, capital investments and operational costs. The IRR is the discount rate that produces a zero NPV. The payback period refers to the number of years it takes to generate enough revenues to pay the investment back, without considering the time value of money [187]. Up to date, very few studies have investigated the economical balances of coupling anaerobic digestion with thermo-chemical processes like pyrolysis [188–190]. Mills et al. [190] have investigated the economical assessment of various energy technologies for the conversion of sewage sludge. In their study several scenarios were compared and among them 1) conventional anaerobic digestion with CHP, 2) Thermal Hydrolysis Process (THP) anaerobic digestion with CHP, 3) THP anaerobic digestion followed by drying, pyrolysis of the digested sludge and use of the both the biogas and the pyrolysis gas in a CHP [190]. Interestingly, the scenario 3 coupling anaerobic digestion with pyrolysis process exhibited higher IRR of 7.64% in comparison of 4.05 % and 5.98 % respectively for scenario 1 and 2. When incentives where considered the IRR of the scenario 3 increase until 17.46 % [190]. Gonzalez et al. [189] have also considered the economical balances of coupling anaerobic digestion of agricultural wastes with subsequent solid digestate pyrolysis [189]. If the energetic interest of coupling the two processes was highlighted, it was clearly demonstrated that the economic aspects were clearly discouraging in absence of important subsidies [189]. If the syngas and bio-oil are generally used as energy carriers, biochar can be used for various applications such as energy, as additive in AD process and agricultural issues. To our knowledge, specific studies on the economic assessment of biochar used as additive in AD process (as enhancer, stabilizer, or biogas treatment) has not been reported. As concerns agricultural sector, biochar can have price varying from 100 to 550 \$ t^{-1} [135,191]. It is also important to consider that such project can also benefit of government incentives such as Feed-in-Tariffs, Renewable Obligation Certificates, carbon credits that can significantly improve the project viability [187,191,192]. Nonetheless, a lack of data is available among the scientific communities and further research are needed on the coupling of anaerobic digestion and pyrolysis at higher TRL to provide relevant data for assessing economic analysis.

The environmental pillar is generally assessed by means of LCA (Life Cycle Assessment) analysis. The LCA is an established method, both technically and scientifically and is standardized by the International Organization for Standardization ISO 14040 [186,193,194]. Some recent studies have evaluated the environmental benefits or not of coupling anaerobic digestion and pyrolysis on sludge [195], municipal solid wastes [196], food wastes [194] or other industrial wastes [197]. Li and Feng [195] have compared the integrated approach with anaerobic digestion and pyrolysis alone from the points of view of life cycle assessment. It was demonstrated that the integrated approach had better environmental performance and energy efficiency than single pyrolysis because prepositive anaerobic digestion enhanced the conversion of sludge organic matter to energy [195]. Similarly, Wang et al. [196] have investigated the LCA of the integration of anaerobic digestion and pyrolysis for treatment of municipal solid waste. Coupling anaerobic digestion and pyrolysis is more environmentally friendly (-11.53 of total environmental impact /kg OFMSW) than single anaerobic digestion or pyrolysis [196]. Opatokum et al. [194] have also investigated the LCA of energy production from food waste through anaerobic digestion, pyrolysis and integrated energy system [194]. The integrated treatment system indicated similar environmental benefits to anaerobic digestion with the highest benefits in climate change and water depletion in addition to the increased energy generation potential and the production of valuable products (biochar and bio-oil) [194]. In parallel, Opatokum et al. [194] demonstrated that the three treatment options of food waste management are environmentally more favorable than the conventional landfilling of the wastes [194]. Finally, in the development of new technologies, it is important to consider the social acceptance among the various stakeholders (farmers, industrials, policy bodies…). To date and to our knowledge, the social benefits of coupling anaerobic digestion with pyrolysis have not been investigated, although each technology has demonstrated its ability to improve the social sustainability, although impact is highly dependent on site location the location [182,198–200]. Furthermore, anaerobic digestion is a well-developed industry, while pyrolysis is under development [200]. Key sustainability issues for anaerobic digestion/pyrolysis can involve providing energy services to rural and remote areas, agricultural and agro-industrial development, improve agricultural practices, reduce fertilizers and fossil energy dependency, new job creation, restructuring of energetic and agricultural policy, carbon sequestration and environmental benefits. However, it will be important to also take into account the potential disadvantages that can be generated by the development of this innovative wastes and/or biomasses valorization routes (location near inhabited area, increase of transport, odour problems, risk of real estate depreciation…). For these purposes, it is of prime importance during the project development to consult the local residents' interests but also, more generally, coordination between all of the stakeholders. It will be also important to define or harmonize some standards for the use of digestate and biochar as agriculture purposes including some specific tests to evaluate their potential toxicity on aquatic and terrestrial organisms [201].

6. Perspective: an integrated circular cascading approach

Based on available data, the complementarity between anaerobic digestion and pyrolysis process can be extended in future works beyond the classical framework of anaerobic digestion, as shown in **Fig. 4.**

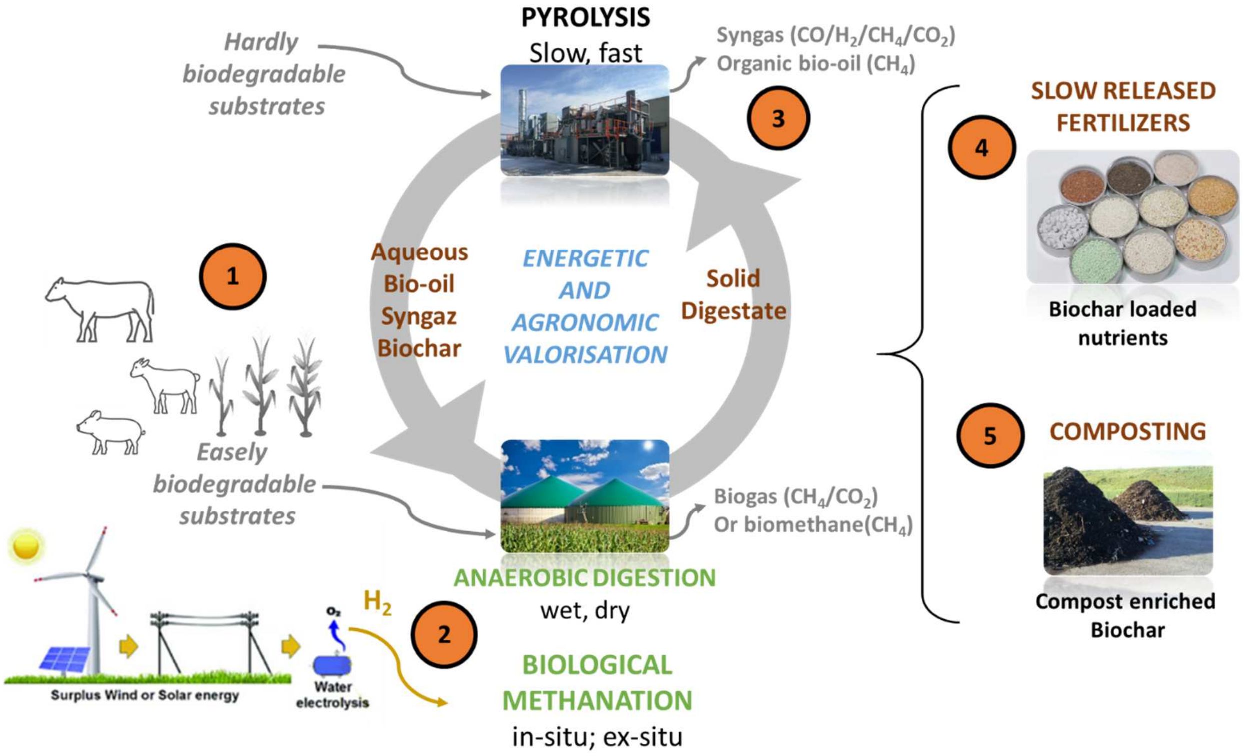

Fig. 4. Mean scheme of perspectives of integrating circular cascading approach by coupling anaerobic digestion and pyrolysis process.

1) Biochar can be added before the anaerobic digestion process directly as animal feed additives or in liquid manure storage to reduce gaseous emissions but also in the silage process for the juice recovery. Biochar as animal feed additive has attracted interest recently and has shown positive effects [13,202]. For instance, adding infeed additive biochar resulting in improving animal health, feed efficiency as well as reduce nutrient losses and GHG emissions [202]. Biochar can also be added to uncovered manure storage to reduce odorous emissions of ammonium, ammonia, and other odorous substances, while simultaneously absorbing nutrients in the liquid manure [203,204]. Biochar addition in crops silage dedicated to the anaerobic digestion process can also be interesting because biochar can promote lactic acid fermentation in silage, prevent faulty fermentation, reduce fungus formation and the risk of clostridia infections due to less acetic, and especially butyric, production during silage [203]. Furthermore,

thanks to biochar, there is little or no formation of fermentation juices, reducing environmental burdens due to juice lixiviation to groundwater [203].

2) The use of biochar in anaerobic digestion and biological methanation as demonstrated its interest recently to improve the performances [17,72,205]. It seems that biochar addition can stimulate the direct interspecies electron transfer and promote anaerobic digestion and/or in situ biological methanation performance [205]. In parallel, the biological methanation can be done by using the syngas produce during the pyrolysis process [20,72]. Syngas biological methanation is still in its infancy and the implementation of a higher technology readiness level scale is a prerequisite for validation of laboratory-scale results along with the influence of biochar addition that should also be extended. Similarly, research should be reinforced on the APL valorization through the anaerobic digestion process (**Fig. 2**). Indeed, the characteristics of APL, high quantity of COD, numerous complex organic compounds (furans and polyphenols), and ammonia content give them the opportunity to be used as co substrate in anaerobic digestion units [32,206]. Until now, most of the research investigations on the APL valorization through anaerobic digestion has been performed at the batch scale; meanwhile, less is known about continuous pilot-scale trials that deserve to be considered given the influence of APL origin but also its impact on anaerobic digestion stability/performance on microbial communities' diversity. Few information are also available on the APL potential toxicity on anaerobic digestion performances [32] and it seems that biochar addition can attenuate the potential toxicity of some organic compounds on the anaerobic digestion process [29].

3) Pyrolysis of solid digestate has attracted the attention of the scientific communities these last decades [50,155]. Several bridges must be studied in the future to better understand the potential of solid digestate in pyrolysis process. First of all, most of the

study has been done until yet with slow pyrolysis process and the impact of fast pyrolysis should be addressed in the future as the products distribution (i.e. biochar, bio-oil, syngas) will not be the same [207]. The typologies (wet vs dry anaerobic digestion process) and solid digestate origin (agricultural, biowastes, sludge…) should be also investigated in the future as the physico-chemical properties of biochar and bio-oil is largely influenced by its pyrolysis conditions and feedstock [208]. Finally, it will be also pertinent to test the pyrolysis of solid digestate in mixture with other co-substrates.

4) Another interesting opportunity is to use biochar for the production of slow-release fertilizers and/or organo-mineral fertilizers by absorbing the nutrient content of the liquid digestate creating new markets, and reducing the required land for the liquid digestate [136]. Such an approach can be performed by directly introducing the biochar in digestate before solid/liquid separation using a filter press, screw press, or centrifugal system. This would allow concentrating the available nutrients from the liquid phase in the solid phase and thus producing an "enriched nutrients solid digestate". Another option is to mix the liquid digestate with biochar for the recovery of "biochar-enriched nutrients". These two strategies deal with the fact that biochar is able to adsorb available nutrients present in the liquid phase, such as ammonium, potassium, and phosphorous [136,209]. Currently, there are only a few studies on nutrient recovery from the liquid fraction of digestate [112,209]. Kizito et al. [112] have studied the influence of two kinds of biochars (from wood and rice husk) to recover ammonium nitrogen from agricultural digestate through adsorption process. The maximum NH_4 (+)-N adsorption from digestate at an initial concentration of 1400 mg N L^{-1} was 44.64 mg g^{-1} and 39.8 mg g^{-1} for wood and rice husk biochar, respectively. Kizito et al. [209] investigated the performances of phosphate recovery from the liquid fraction of digestate by using four biochars (from wood, corncobs, rice

husks, sawdust pyrolysis). It was demonstrated that biochar can be effectively used to recover P-PO_4^{3-} from digestate and at an initial load of 150 mg P-PO_4^{3-} L^{-1}, adsorptions varying from 5.41 to 7.67 mg P-PO_4^{3-} g^{-1} biochar were recorded [209]. Kizito et al. [136] evaluated the addition of digestate-enriched biochar as soil amendment during maize growth. The addition of digestate-enriched biochars resulted in soil organic matter improvement (232%–514%), macronutrients increase (110%–230%). Furthermore, significant increase in biomass yield compared to soil control without biochar enrichment (165% versus 91%, respectively) was reported [136]. Finally, for mineral fertilizer, biochar has been used as a precursor for coating material or in the manufacture of mineral fertilizers with a slow-release properties [210,211]. For instance, Chen et al. [210] investigated an innovative slow-release nitrogen fertilizer based on the coating of urea granules with biochar-based waterborne copolymers. They are tested some biochar produced from different biomasses (maize straw, rice straw, and forest litter) on the fertilizer properties including water resistance, degradability in soil, and leaching behavior of nutrient. Interestingly, the urea particles coated with rice biochar-based copolymer exhibited a better release behavior with 65.28% of nutrient leaching compared to more than 90% from the pure urea [210]. Similarly, biochar (eucalyptus wood, 400 °C) granulation with additives (22% bentonite and 5% pregelatinized maize flour) and urea using a granulator dish was investigated by Peregrina et al. [211]. To evaluate the performance of these fertilizers on maize yield, a one-year field experiment with tropical soil was performed. The best results were obtained using biochar-based fertilizers composed of 51% biochar and 10% urea, resulting an increase in nitrogen use efficiency (NUE) and crop yield of 12% and 21%, respectively, compared to pure urea fertilizer [211].

5) In addition to producing organo/mineral fertilizers or biochar enriched nutrients, biochar can be incorporated to improve the performances, stability, and agronomic

quality of solid digestate compost if a composting process is applied [149,212,213]. Biochar incorporation inside composting process can improve this latter by several ways:1) modifying the main physico-chemical properties of compost, 2) enhancing organic matter decomposition through better microbial activities, 3) reducing GHG and ammonia emissions; 4) upgrading compost nutrient quality and maturity through a better stability of the organic matter and 5) improve plant and crops production when compost is used in agronomic issues [214,215].

7. Concluding remarks

While anaerobic digestion and pyrolysis as single processes have been widely studied, their combination in the field of waste management is still in its infancy. Co-application of anaerobic digestion and pyrolysis has proven advantages and benefits in energy recovery, as well as improvement in stability and performance of anaerobic digestion itself along with positive consequences on soil fertility and crop eco-production that could be gained from the combination. This review provided clear evidence showcasing the “energy recovery and efficiency” advantage that could be gained from the combined use of both anaerobic digestion and pyrolysis processes. Notably, through several cascade integrations such as 1) solid digestate valorization during pyrolysis, 2) reuse of bio-oil APL in the anaerobic digestion process, 3) use of the produced syngas in biological methanation, 4) use of biochar in AD process and 5) combination of liquid digestate and biochar for agronomic issues. Biochar has been shown to be a central element in anaerobic digestion and pyrolysis coupling, notably by improving the anaerobic digestion stability/performances and applicability of the “biochar and digestate” combination for agronomic purposes. Nevertheless, the use of biochar in anaerobic digestion or for agronomic issues in combination with digestate is still in its infancy and several avenues are worth exploring. If the energetic benefits have been demonstrated, few data are available on technico-economic analysis of coupling anaerobic digestion and pyrolysis. To state on the clear benefit of such dual approach it is important to validate the process at higher Technology Readiness Level to have relevant mass and energy flow to be modeled. Future implementation of the dual anaerobic digestion– pyrolysis process does not depend solely on technical constraints. A multidisciplinary approach integrating technical, social, environmental, and economic sciences is worth implementing.

Credit Author Statement

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Declaration of interest

None.

References

[1] Qambrani NA, Rahman MM, Won S, Shim S, Ra C. Biochar properties and eco-friendly applications for climate change mitigation, waste management, and wastewater treatment: A review. Renew Sustain Energy Rev 2017;79:255–73. https://doi.org/10.1016/j.rser.2017.05.057.

[2] Xu F, Li Y, Ge X, Yang L, Li Y. Anaerobic digestion of food waste – Challenges and opportunities. Bioresour Technol 2018;247:1047–58. https://doi.org/10.1016/j.biortech.2017.09.020.

[3] Monlau F, Francavilla M, Sambusiti C, Antoniou N, Solhy A, Libutti A, et al. 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. Appl Energy 2016;169:652–62. https://doi.org/10.1016/j.apenergy.2016.02.084.

[4] Pecchi M, Baratieri M. Coupling anaerobic digestion with gasification, pyrolysis or hydrothermal carbonization: A review. Renew Sustain Energy Rev 2019;105:462–75. https://doi.org/10.1016/j.rser.2019.02.003.

[5] Aghbashlo M, Tabatabaei M, Soltanian S, Ghanavati H. Biopower and biofertilizer

production from organic municipal solid waste : An exergoenvironmental analysis. Renew Energy 2019;143:64–76. https://doi.org/10.1016/j.renene.2019.04.109.

[6] Panuccio MR, Attinà E, Basile C, Mallamaci C, Muscolo A. Use of Recalcitrant Agriculture Wastes to Produce Biogas and Feasible Biofertilizer. Waste and Biomass Valorization 2016;7:267–80. https://doi.org/10.1007/s12649-015-9445-5.

[7] Aboulkas A, Hammani H, El Achaby M, Bilal E, Barakat A, El harfi K. Valorization of algal waste via pyrolysis in a fixed-bed reactor: Production and characterization of bio-oil and bio-char. Bioresour Technol 2017;243:400–8. https://doi.org/10.1016/j.biortech.2017.06.098.

[8] Fabbri D, Torri C. Linking pyrolysis and anaerobic digestion (Py-AD) for the conversion of lignocellulosic biomass. Curr Opin Biotechnol 2016;38:167–73. https://doi.org/10.1016/j.copbio.2016.02.004.

[9] Feng Q, Lin Y. Integrated processes of anaerobic digestion and pyrolysis for higher bioenergy recovery from lignocellulosic biomass: A brief review. Renew Sustain Energy Rev 2017;77:1272–87. https://doi.org/10.1016/j.rser.2017.03.022.

[10] Chiappero M, Norouzi O, Hu M, Demichelis F, Berruti F, Di Maria F, et al. Review of biochar role as additive in anaerobic digestion processes. Renew Sustain Energy Rev 2020;131. https://doi.org/10.1016/j.rser.2020.110037.

[11] Caoa Y, Pawłowski A. Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: Brief overview and energy efficiency assessment. Renew Sustain Energy Rev 2012;16:1657–65. https://doi.org/10.1016/j.rser.2011.12.014.

[12] Salman CA, Schwede S, Thorin E, Yan J. Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes. Appl Energy 2017;204:1074–83. https://doi.org/10.1016/j.apenergy.2017.05.006.

[13] Nizami AS, Rehan M, Waqas M, Naqvi M, Ouda OKM, Shahzad K, et al. Waste biorefineries: Enabling circular economies in developing countries. Bioresour Technol 2017;241:1101–17. https://doi.org/10.1016/j.biortech.2017.05.097.

[14] Hood-Nowotny R, Watzinger A, Wawra A, Soja G. The Impact of Biochar Incorporation on Inorganic Nitrogen Fertilizer Plant Uptake; An Opportunity for Carbon Sequestration in Temperate Agriculture. Geosciences 2018;8:420. https://doi.org/10.3390/geosciences8110420.

[15] Peiris C, Gunatilake SR, Mlsna TE, Mohan D, Vithanage M. Biochar based removal of antibiotic sulfonamides and tetracyclines in aquatic environments: A critical review. Bioresour Technol 2017;246:150–9. https://doi.org/10.1016/j.biortech.2017.07.150.

[16] Xu X, Cao X, Zhao L, Sun T. Comparison of sewage sludge- and pig manure-derived biochars for hydrogen sulfide removal. Chemosphere 2014;111:296–303. https://doi.org/10.1016/j.chemosphere.2014.04.014.

[17] Fagbohungbe MO, Herbert BMJ, Hurst L, Ibeto CN, Li H, Usmani SQ, et al. The challenges of anaerobic digestion and the role of biochar in optimizing anaerobic digestion. Waste Manag 2017;61:236–49. https://doi.org/10.1016/j.wasman.2016.11.028.

[18] Kanjanarong J, Giri BS, Jaisi DP, Oliveira FR, Boonsawang P, Chaiprapat S, et al. Removal of hydrogen sulfide generated during anaerobic treatment of sulfate-laden

wastewater using biochar: Evaluation of efficiency and mechanisms. Bioresour Technol 2017;234:115–21. https://doi.org/10.1016/j.biortech.2017.03.009.

[19] Shen Z, Jin F, Wang F, McMillan O, Al-Tabbaa A. Sorption of lead by Salisbury biochar produced from British broadleaf hardwood. Bioresour Technol 2015;193:553–6. https://doi.org/10.1016/j.biortech.2015.06.111.

[20] Figueras J, Benbelkacem H, Dumas C, Buffiere P. " Biomethanation of syngas by enriched mixed anaerobic consortium in pressurized agitated column ." Bioresour Technol 2021;338:125548. https://doi.org/10.1016/j.biortech.2021.125548.

[21] Liaw S-S, Perez VH, Westerhof RJM, David GF, Frear C, Garcia-Perez M. Biomethane Production from Pyrolytic Aqueous Phase: Biomass Acid Washing and Condensation Temperature Effect on the Bio-oil and Aqueous Phase Composition. BioEnergy Res 2020;13:878–886.

[22] Monlau F, Sambusiti C, Ficara E, Aboulkas A, Barakat A, Carrère H. New opportunities for agricultural digestate valorization: Current situation and perspectives. Energy Environ Sci 2015;8:2600–21. https://doi.org/10.1039/c5ee01633a.

[23] Masebinu SO, Akinlabi ET, Muzenda E, Aboyade AO. A review of biochar properties and their roles in mitigating challenges with anaerobic digestion. Renew Sustain Energy Rev 2019;103:291–307. https://doi.org/10.1016/j.rser.2018.12.048.

[24] Tang S, Wang Z, Liu Z, Zhang Y, Si B. The role of biochar to enhance anaerobic digestion: A review. J Renew Mater 2020;8:1033–52. https://doi.org/10.32604/jrm.2020.011887.

[25] Sikarwar VS, Pohořelý M, Meers E, Skoblia S, Moško J, Jeremiáš M. Potential of coupling anaerobic digestion with thermochemical technologies for waste valorization. Fuel 2021;294. https://doi.org/10.1016/j.fuel.2021.120533.

[26] Kumar M, Dutta S, You S, Luo G, Zhang S, Show PL, et al. A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. J Clean Prod 2021;305:127143. https://doi.org/10.1016/j.jclepro.2021.127143.

[27] Kan T, Strezov V, Evans TJ. Lignocellulosic biomass pyrolysis: A review of product properties and effects of pyrolysis parameters. Renew Sustain Energy Rev 2016;57:126–1140. https://doi.org/10.1016/j.rser.2015.12.185.

[28] Tripathi M, Sahu JN, Ganesan P. Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. Renew Sustain Energy Rev 2016;55:467–81. https://doi.org/10.1016/j.rser.2015.10.122.

[29] Torri C, Fabbri D. Biochar enables anaerobic digestion of aqueous phase from intermediate pyrolysis of biomass. Bioresour Technol 2014;172:335–41. https://doi.org/10.1016/j.biortech.2014.09.021.

[30] Oliveira FR, Patel AK, Jaisi DP, Adhikari S, Lu H, Khanal SK. Environmental application of biochar: Current status and perspectives. Bioresour Technol 2017;246:110–22. https://doi.org/10.1016/j.biortech.2017.08.122.

[31] Xia C, Cai L, Zhang H, Zuo L, Shi SQ, Lam SS. A review on the modeling and validation of biomass pyrolysis with a focus on product yield and composition. Biofuel Res J 2021;29:1296–315. https://doi.org/10.18331/BRJ2021.8.1.2.

[32] Seyedi S, Venkiteshwaran K, Zitomer D. Toxicity of various pyrolysis liquids from

biosolids on methane production yield. Front Energy Res 2019;7:1–12. https://doi.org/10.3389/fenrg.2019.00005.

[33] Huber GW, Iborra S, Corma A. Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering. Chem Rev 2006;106:4044–98. https://doi.org/10.1021/cr068360d.

[34] Manara P, Zabaniotou A. Towards sewage sludge based biofuels via thermochemical conversion - A review. Renew Sustain Energy Rev 2012;16:2566–82. https://doi.org/10.1016/j.rser.2012.01.074.

[35] Tang J, Zhu W, Kookana R, Katayama A. Characteristics of biochar and its application in remediation of contaminated soil. J Biosci Bioeng 2013;116:653–9. https://doi.org/10.1016/j.jbiosc.2013.05.035.

[36] Nanda S, Dalai AK, Berruti F, Kozinski JA. Biochar as an Exceptional Bioresource for Energy, Agronomy, Carbon Sequestration, Activated Carbon and Specialty Materials. Waste and Biomass Valorization 2016;7:201–35. https://doi.org/10.1007/s12649-015-9459-z.

[37] Tan X fei, Liu S bo, Liu Y guo, Gu Y ling, Zeng G ming, Hu X jiang, et al. Biochar as potential sustainable precursors for activated carbon production: Multiple applications in environmental protection and energy storage. Bioresour Technol 2017;227:359–72. https://doi.org/10.1016/j.biortech.2016.12.083.

[38] Ioannidou O, Zabaniotou A. Agricultural residues as precursors for activated carbon production-A review. Renew Sustain Energy Rev 2007;11:1966–2005. https://doi.org/10.1016/j.rser.2006.03.013.

[39] Arnold S, Moss K, Henkel M, Hausmann R. Biotechnological Perspectives of Pyrolysis Oil for a Bio-Based Economy. Trends Biotechnol 2017;35:925–36. https://doi.org/10.1016/j.tibtech.2017.06.003.

[40] Krishania M, Kumar V, Vijay VK, Malik A. Analysis of different techniques used for improvement of biomethanation process : A review. Fuel 2013;106:1–9. https://doi.org/10.1016/j.fuel.2012.12.007.

[41] Huttunen S, Rintala JA. Laboratory investigations on co-digestion of energy crops and crop residues with cow manure for methane production : Effect of crop to manure ratio 2007;51:591–609. https://doi.org/10.1016/j.resconrec.2006.11.004.

[42] Monlau F, Sambusiti C, Barakat A, Quéméneur M, Trably E, Steyer JP, et al. Do furanic and phenolic compounds of lignocellulosic and algae biomass hydrolyzate inhibit anaerobic mixed cultures? A comprehensive review. Biotechnol Adv 2014;32:934–51. https://doi.org/10.1016/j.biotechadv.2014.04.007.

[43] Ferrer P, Cambra-López M, Cerisuelo A, Peñaranda DS, Moset V. The use of agricultural substrates to improve methane yield in anaerobic co-digestion with pig slurry: Effect of substrate type and inclusion level. Waste Manag 2014;34:196–203. https://doi.org/10.1016/j.wasman.2013.10.010.

[44] Li Y, Li Y, Zhang D, Li G, Lu J, Li S. Solid state anaerobic co-digestion of tomato residues with dairy manure and corn stover for biogas production. Bioresour Technol 2016;217:50–5. https://doi.org/10.1016/j.biortech.2016.01.111.

[45] Tabatabaei M, Aghbashlo M, Valijanian E. A comprehensive review on recent

biological innovations to improve biogas production , Part 2 : Mainstream and downstream strategies. Renew Energy 2020;146:1392–407. https://doi.org/10.1016/j.renene.2019.07.047.

[46] Reza Barati M, Aghbashlo M, Ghanavati H, Tabatabaei M, Sharifi M, Javadirad G, et al. Comprehensive exergy analysis of a gas engine-equipped anaerobic digestion plant producing electricity and biofertilizer from organic fraction of municipal solid waste. Energy Convers Manag 2017;151:753–63. https://doi.org/10.1016/j.enconman.2017.09.017.

[47] Sawatdeenarunat C, Nguyen D, Surendra KC, Shrestha S, Rajendran K, Oechsner H, et al. Anaerobic biorefinery: Current status, challenges, and opportunities. Bioresour Technol 2016;215:304–13. https://doi.org/10.1016/j.biortech.2016.03.074.

[48] Guilayn F, Jimenez J, Martel JL, Rouez M, Crest M, Patureau D. First fertilizing-value typology of digestates: A decision-making tool for regulation. Waste Manag 2019;86:67–79. https://doi.org/10.1016/j.wasman.2019.01.032.

[49] Akhiar A, Battimelli A, Torrijos M, Carrere H. Comprehensive characterization of the liquid fraction of digestates from full-scale anaerobic co-digestion. Waste Manag 2017;59:118–28. https://doi.org/10.1016/j.wasman.2016.11.005.

[50] Monlau F, Sambusiti C, Antoniou N, Barakat A, Zabaniotou A. A new concept for enhancing energy recovery from agricultural residues by coupling anaerobic digestion and pyrolysis process. Appl Energy 2015;148:32–8. https://doi.org/10.1016/j.apenergy.2015.03.024.

[51] Salman CA, Schwede S, Naqvi M, Thorin E, Yan J. Synergistic combination of pyrolysis, anaerobic digestion, and CHP plants. Energy Procedia 2019;158:1323–9. https://doi.org/10.1016/j.egypro.2019.01.326.

[52] Sambusiti C, Monlau F, Ficara E, Carrère H, Malpei F. A comparison of different pre-treatments to increase methane production from two agricultural substrates. Appl Energy 2013;104:62–70. https://doi.org/10.1016/j.apenergy.2012.10.060.

[53] Miltner M, Makaruk A, Harasek M. Review on available biogas upgrading technologies and innovations towards advanced solutions. J Clean Prod 2017;161:1329–37. https://doi.org/10.1016/j.jclepro.2017.06.045.

[54] Sun C, Cao W, Banks CJ, Heaven S, Liu R. Biogas production from undiluted chicken manure and maize silage: A study of ammonia inhibition in high solids anaerobic digestion. Bioresour Technol 2016;218:1215–23. https://doi.org/10.1016/j.biortech.2016.07.082.

[55] Shanmugam SR, Adhikari S, Nam H, Kar Sajib S. Effect of bio-char on methane generation from glucose and aqueous phase of algae liquefaction using mixed anaerobic cultures. Biomass and Bioenergy 2018;108:479–86. https://doi.org/10.1016/j.biombioe.2017.10.034.

[56] Sethupathi S, Zhang M, Rajapaksha AU, Lee SR, Nor NM, Mohamed AR, et al. Biochars as potential adsorbers of CH4, CO2 and H2S. Sustain 2017;9:1–10. https://doi.org/10.3390/su9010121.

[57] Pelaez-Samaniego MR, Smith MW, Zhao Q, Garcia-Perez T, Frear C, Garcia-Perez M. Charcoal from anaerobically digested dairy fiber for removal of hydrogen sulfide within biogas. Waste Manag 2018;76:374–82.

https://doi.org/10.1016/j.wasman.2018.03.011.

[58] Shen Y, Linville JL, Urgun-Demirtas M, Schoene RP, Snyder SW. Producing pipeline-quality biomethane via anaerobic digestion of sludge amended with corn stover biochar with in-situ CO2 removal. Appl Energy 2015;158:300–9. https://doi.org/10.1016/j.apenergy.2015.08.016.

[59] Linville JL, Shen Y, Ignacio-de Leon PA, Schoene RP, Urgun-Demirtas M. In-situ biogas upgrading during anaerobic digestion of food waste amended with walnut shell biochar at bench scale. Waste Manag Res 2017;35:669–79. https://doi.org/10.1177/0734242X17704716.

[60] Farooq M, Almustapha MN, Imran M, Saeed MA, Andresen JM. In-situ regeneration of activated carbon with electric potential swing desorption (EPSD) for the H2S removal from biogas. Bioresour Technol 2018;249:125–31. https://doi.org/10.1016/j.biortech.2017.09.198.

[61] Plaza MG, González AS, Pis JJ, Rubiera F, Pevida C. Production of microporous biochars by single-step oxidation: Effect of activation conditions on CO2 capture. Appl Energy 2014;114:551–62. https://doi.org/10.1016/j.apenergy.2013.09.058.

[62] Tan X, Liu Y, Zeng G, Wang X, Hu X, Gu Y, et al. Application of biochar for the removal of pollutants from aqueous solutions. Chemosphere 2015;125:70–85. https://doi.org/10.1016/j.chemosphere.2014.12.058.

[63] Zhang H, Voroney RP, Price GW, White AJ. Sulfur-enriched biochar as a potential soil amendment and fertiliser. Soil Res 2017;55:93–9. https://doi.org/10.1071/SR15256.

[64] Álvarez-chávez BJ, Godbout S, Le Roux E, Palacios JH, Raghavan V. Bio-oil yield and quality enhancement through fast pyrolysis and fractional condensation concepts. Biofuel Res J 2019;24:1054–64. https://doi.org/10.18331/BRJ2019.6.4.2.

[65] Oasmaa A, Kuoppala E. Solvent fractionation method with Brix for rapid characterization of wood fast pyrolysis liquids. Energy and Fuels 2008;22:4245–8. https://doi.org/10.1021/ef800407d.

[66] Abnisa F, Wan Daud WMA. A review on co-pyrolysis of biomass: An optional technique to obtain a high-grade pyrolysis oil. Energy Convers Manag 2014;87:71–85. https://doi.org/10.1016/j.enconman.2014.07.007.

[67] Hübner T, Mumme J. Integration of pyrolysis and anaerobic digestion - Use of aqueous liquor from digestate pyrolysis for biogas production. Bioresour Technol 2015;183:86–92. https://doi.org/10.1016/j.biortech.2015.02.037.

[68] Seyedi S, Venkiteshwaran K, Zitomer D. Anaerobic Co-Digestion of Condensate from Biosolids Pyrolysis. 2018. https://doi.org/10.2175/193864718824828678.

[69] Chen H, Zhang C, Rao Y, Jing Y, Luo G, Zhang S. Methane potentials of wastewater generated from hydrothermal liquefaction of rice straw: Focusing on the wastewater characteristics and microbial community compositions. Biotechnol Biofuels 2017;10:1–16. https://doi.org/10.1186/s13068-017-0830-0.

[70] Barakat A, Monlau F, Steyer JP, Carrere H. Effect of lignin-derived and furan compounds found in lignocellulosic hydrolysates on biomethane production. Bioresour Technol 2012;104:90–9. https://doi.org/10.1016/j.biortech.2011.10.060.

[71] Monlau F, Sambusiti C, Antoniou N, Zabaniotou A, Solhy A, Barakat A. Pyrochars

from bioenergy residue as novel bio-adsorbents for lignocellulosic hydrolysate detoxification. Bioresour Technol 2015;187:379–86. https://doi.org/10.1016/j.biortech.2015.03.137.

[72] Schwede S, Bruchmann F, Thorin E, Gerber M. Biological Syngas Methanation via Immobilized Methanogenic Archaea on Biochar. Energy Procedia 2017;105:823–9. https://doi.org/10.1016/j.egypro.2017.03.396.

[73] Grimalt-alemany A, Skiadas I V., Gavala HN. Syngas biomethanation: state-of-the-art review and perspectives. Biofuels, Bioprod Biorefining 2017;12:139–58. https://doi.org/10.1002/bbb.1826.

[74] Götz M, Lefebvre J, Mörs F, McDaniel Koch A, Graf F, Bajohr S, et al. Renewable Power-to-Gas: A technological and economic review. Renew Energy 2016;85:1371–90. https://doi.org/10.1016/j.renene.2015.07.066.

[75] Guiot SR, Cimpoia R, Carayon G. Potential of wastewater-treating anaerobic granules for biomethanation of synthesis gas. Environ Sci Technol 2011;45:2006–12. https://doi.org/10.1021/es102728m.

[76] Shah S, Bergland WH, Bakke R. Methane from Syngas by Anaerobic Digestion. Proc 58th Conf Simul Model (SIMS 58) Reykjavik, Iceland, Sept 25th – 27th, 2017 2017;138:114–20. https://doi.org/10.3384/ecp17138114.

[77] Thema M, Weidlich T, Hörl M, Bellack A, Mörs F, Hackl F, et al. Biological CO 2 - Methanation : An Approach. Energies 2019;12:1–32.

[78] Codignole Luz F, Cordiner S, Manni A, Mulone V, Rocco V. Biochar characteristics and early applications in anaerobic digestion-a review. J Environ Chem Eng 2018;6:2892–909. https://doi.org/10.1016/j.jece.2018.04.015.

[79] Dehhaghi M, Meisam T, Aghbashlo M, Panahia HKS, Nizami A-S. A state-of-the-art review on the application of nanomaterials for enhancing biogas production. J Environ Manage 2019;251. https://doi.org/10.1016/j.jenvman.2019.109597.

[80] Kumar S, Jain MC, Chhonkar PK. A note on stimulation of biogas production from cattle dung by addition of charcoal. Biol Wastes 1987;20:209–15. https://doi.org/10.1016/0269-7483(87)90155-8.

[81] Montalvo S, Guerrero L, Borja R, Sánchez E, Milán Z, Cortés I, et al. Application of natural zeolites in anaerobic digestion processes: A review. Appl Clay Sci 2012;58:125–33. https://doi.org/10.1016/j.clay.2012.01.013.

[82] Meyer-Kohlstock D, Haupt T, Heldt E, Heldt N, Kraft E. Biochar as additive in biogas-production from bio-waste. Energies 2016;9. https://doi.org/10.3390/en9040247.

[83] Cai J, He P, Wang Y, Shao L, Lü F. Effects and optimization of the use of biochar in anaerobic digestion of food wastes. Waste Manag Res 2016;34:409–16. https://doi.org/10.1177/0734242X16634196.

[84] Cheng Q, De Los Reyes FL, Call DF. Amending anaerobic bioreactors with pyrogenic carbonaceous materials: the influence of material properties on methane generation. Environ Sci Water Res Technol 2018;4:1794–806. https://doi.org/10.1039/c8ew00447a.

[85] Pan J, Ma J, Liu X, Zhai L, Ouyang X, Liu H. Effects of different types of biochar on the anaerobic digestion of chicken manure. Bioresour Technol 2019;275:258–65.

https://doi.org/10.1016/j.biortech.2018.12.068.

[86] Jang HM, Choi YK, Kan E. Effects of dairy manure-derived biochar on psychrophilic, mesophilic and thermophilic anaerobic digestions of dairy manure. Bioresour Technol 2018;250:927–31. https://doi.org/10.1016/j.biortech.2017.11.074.

[87] Sunyoto NMS, Zhu M, Zhang Z, Zhang D. Effect of biochar addition on hydrogen and methane production in two-phase anaerobic digestion of aqueous carbohydrates food waste. Bioresour Technol 2016;219:29–36. https://doi.org/10.1016/j.biortech.2016.07.089.

[88] Sun C, Liu F, Song Z, Wang J, Li Y, Pan Y, et al. Feasibility of dry anaerobic digestion of beer lees for methane production and biochar enhanced performance at mesophilic and thermophilic temperature. Bioresour Technol 2018. https://doi.org/10.1016/j.biortech.2018.12.105.

[89] Capson-Tojo G, Girard C, Rouez M, Crest M, Steyer JP, Bernet N, et al. Addition of biochar and trace elements in the form of industrial FeCl3 to stabilize anaerobic digestion of food waste: dosage optimization and long-term study. J Chem Technol Biotechnol 2019;94:505–15. https://doi.org/10.1002/jctb.5797.

[90] Li J, Zhang M, Ye Z, Yang C. Effect of manganese oxide-modified biochar addition on methane production and heavy metal speciation during the anaerobic digestion of sewage sludge. J Environ Sci (China) 2018:1–11. https://doi.org/10.1016/j.jes.2018.05.009.

[91] Wu W, Qin Y, Cheng JJ, Li X, Wang H. Improving methane yield from organic fraction of municipal solid waste (OFMSW) with magnetic rice-straw biochar. Bioresour Technol 2017;245:1058–66. https://doi.org/10.1016/j.biortech.2017.09.047.

[92] Mumme J, Srocke F, Heeg K, Werner M. Use of biochars in anaerobic digestion. Bioresour Technol 2014;164:189–97. https://doi.org/10.1016/j.biortech.2014.05.008.

[93] Shen Y, Forrester S, Koval J, Urgun-Demirtas M. Yearlong semi-continuous operation of thermophilic two-stage anaerobic digesters amended with biochar for enhanced biomethane production. J Clean Prod 2018;167:863–74. https://doi.org/10.1016/j.jclepro.2017.05.135.

[94] Giwa AS, Xu H, Chang F, Wu J, Li Y, Ali N, et al. Effect of biochar on reactor performance and methane generation during the anaerobic digestion of food waste treatment at long-run operations. J Environ Chem Eng 2019;7:103067. https://doi.org/10.1016/j.jece.2019.103067.

[95] Wambugu CW, Rene ER, van de Vossenberg J, Dupont C, van Hullebusch ED. Role of biochar in anaerobic digestion based biorefinery for food waste. Front Energy Res 2019;7:1–13. https://doi.org/10.3389/fenrg.2019.00014.

[96] Pan J, Ma J, Zhai L, Liu H. Enhanced methane production and syntrophic connection between microorganisms during semi-continuous anaerobic digestion of chicken manure by adding biochar. J Clean Prod 2019;240:118178. https://doi.org/10.1016/j.jclepro.2019.118178.

[97] Fagbohungbe MO, Herbert BMJ, Hurst L, Li H, Usmani SQ, Semple KT. Impact of biochar on the anaerobic digestion of citrus peel waste. Bioresour Technol 2016;216:142–9. https://doi.org/10.1016/j.biortech.2016.04.106.

[98] Cimon C, Kadota P, Eskicioglu C. Effect of biochar and wood ash amendment on biochemical methane production of wastewater sludge from a temperature phase anaerobic. Bioresour Technol 2019:122440. https://doi.org/10.1016/j.biortech.2019.122440.

[99] Ahmad M, Rajapaksha AU, Jung Eun Lim a MZ, Bolan N, Mohan D, Vithanage M, et al. Biochar as a sorbent for contaminant management in soil and water: A review. Chemosphere 2014;99:19–23. https://doi.org/10.1016/j.chemosphere.2013.10.071.

[100] Souza LS, Cazetta AL, Martins AC, Santos Júnior OO, Almeida VC, Bedin KC, et al. NaOH-activated carbon of high surface area produced from guava seeds as a high-efficiency adsorbent for amoxicillin removal: Kinetic, isotherm and thermodynamic studies. Chem Eng J 2015;288:778–88. https://doi.org/10.1016/j.cej.2015.12.042.

[101] Inyang M, Dickenson E. The potential role of biochar in the removal of organic and microbial contaminants from potable and reuse water: A review. Chemosphere 2015;134:232–40. https://doi.org/10.1016/j.chemosphere.2015.03.072.

[102] Mohammed NASS, Abu-zurayk RA, Hamadneh I, Al-Dujaili AH. Phenol adsorption on biochar prepared from the pine fruit shells : Equilibrium, kinetic and thermodynamics studies. J Environ Manage 2018;226:377–85. https://doi.org/10.1016/j.jenvman.2018.08.033.

[103] Li Z, Xing B, Ding Y, Li Y, Wang S. A high-performance biochar produced from bamboo pyrolysis with in-situ nitrogen doping and activation for adsorption of phenol and methylene blue. Chinese J Chem Eng 2020;28:2872–80. https://doi.org/10.1016/j.cjche.2020.03.031.

[104] Lawal AA, Hassan MA, Abdillah M, Farid A, Yasim-anuar TAT, Zulkhairi M, et al. Adsorption mechanism and effectiveness of phenol and tannic acid removal by biochar produced from oil palm frond using steam pyrolysis. Environ Pollut 2021;269. https://doi.org/10.1016/j.envpol.2020.116197.

[105] Yu Q, Xia D, Li H, Ke L, Wang Y, Wang H, et al. Effectiveness and mechanisms of ammonium adsorption on biochars derived from biogas residues. RSC Adv 2016;6:88373–81. https://doi.org/10.1039/c6ra16913a.

[106] Vu TM, Trinh VT, Doan DP, Van HT, Nguyen TV, Vigneswaran S, et al. Removing ammonium from water using modified corncob-biochar. Sci Total Environ 2017;579:612–9. https://doi.org/10.1016/j.scitotenv.2016.11.050.

[107] Hu X, Zhang X, Hao H, Guo W, Wen H, Li C. Comparison study on the ammonium adsorption of the biochars derived from different kinds of fruit peel. Sci Total Environ 2020;707:135544. https://doi.org/10.1016/j.scitotenv.2019.135544.

[108] Wang T, Li G, Yang K, Zhang X, Wang K, Cai J, et al. Enhanced ammonium removal on biochar from a new forestry waste by ultrasonic activation : Characteristics , mechanisms and evaluation. Sci Total Environ 2021;778:146295. https://doi.org/10.1016/j.scitotenv.2021.146295.

[109] Munar-florez DA, Varón-cardenas DA, Ramírez-contreras NE, García-núñez JA. Adsorption of ammonium and phosphates by biochar produced from oil palm shells : Effects of production conditions. Results Chem 2021;3:100119. https://doi.org/10.1016/j.rechem.2021.100119.

[110] Klasson KT, Uchimiya M, Lima IM, Larry L. Boihem J. Feasability of removing

furfurals from sugar solutions using activated biochars made from agricultural residues. Bioresources 2011;6:3242–51.

[111] Li Y, Shao J, Wang X, Deng Y, Yang H, Chen H. Characterization of modified biochars derived from bamboo pyrolysis and their utilization for target component (furfural) adsorption. Energy and Fuels 2014;28:5119–27. https://doi.org/10.1021/ef500725c.

[112] Kizito S, Wu S, Kipkemoi Kirui W, Lei M, Lu Q, Bah H, et al. Evaluation of slow pyrolyzed wood and rice husks biochar for adsorption of ammonium nitrogen from piggery manure anaerobic digestate slurry. Sci Total Environ 2015;505:102–12. https://doi.org/10.1016/j.scitotenv.2014.09.096.

[113] Vocciante M, De Folly D'Auris A, Finocchi A, Tagliabue M, Bellettato M, Ferrucci A, et al. Adsorption of ammonium on clinoptilolite in presence of competing cations: Investigation on groundwater remediation. J Clean Prod 2018;198:480–7. https://doi.org/10.1016/j.jclepro.2018.07.025.

[114] Sambusiti C, Ficara E, Malpei F, Steyer JP, Carrère H. Benefit of sodium hydroxide pretreatment of ensiled sorghum forage on the anaerobic reactor stability and methane production. Bioresour Technol 2013;144:149–55. https://doi.org/10.1016/j.biortech.2013.06.095.

[115] Jiang Y, Mcadam E, Zhang Y, Heaven S, Banks C, Longhurst P. Ammonia inhibition and toxicity in anaerobic digestion : A critical review. J Water Process Eng 2019;32:100899. https://doi.org/10.1016/j.jwpe.2019.100899.

[116] Yenigün O, Demirel B. Ammonia inhibition in anaerobic digestion : A review. Process Biochem 2013;48:901–11. https://doi.org/10.1016/j.procbio.2013.04.012.

[117] Moreno-Castilla C, López-Ramón M V., Carrasco-Marín F. Changes in surface chemistry of activated carbons by wet oxidation. Carbon N Y 2000;38:1995–2001. https://doi.org/10.1016/S0008-6223(00)00048-8.

[118] Shang L, Xu H, Huang S, Zhang Y. Adsorption of Ammonium in Aqueous Solutions by the Modified Biochar and its Application as an Effective N-Fertilizer. Water Air Soil Pollut 2018;229. https://doi.org/10.1007/s11270-018-3956-1.

[119] Tang Y, Alam MS, Konhauser KO, Alessi DS, Xu S, Tian WJ, et al. Influence of pyrolysis temperature on production of digested sludge biochar and its application for ammonium removal from municipal wastewater. J Clean Prod 2019;209:927–36. https://doi.org/10.1016/j.jclepro.2018.10.268.

[120] Sohi SP, Krull E, Lopez-Capel E, Bol R. A review of biochar and its use and function in soil. Adv Agron 2010. https://doi.org/10.1016/S0065-2113(10)05002-9.

[121] Gul S, Whalen JK, Thomas BW, Sachdeva V, Deng H. Physico-chemical properties and microbial responses in biochar-amended soils: Mechanisms and future directions. Agric Ecosyst Environ 2015;206:46–59. https://doi.org/10.1016/j.agee.2015.03.015.

[122] Manyà JJ. Pyrolysis for biochar purposes: A review to establish current knowledge gaps and research needs. Environ Sci Technol 2012;46:7939–54. https://doi.org/10.1021/es301029g.

[123] IBI. Standardized product definition and product testing guidelines for biochar that is used in soil, v. 1.1. Int Biochar Initiat 2015:1–47. https://doi.org/http://www.biochar-

international.org/characterizationstandard. 22.

[124] EBC (2012). European Biochar Certificate - Guidelines for a Sustainable Production of Biochar'. Eur Biochar Found (EBC), Arbaz, Switzerland Version 61 19th June, 2016:1–22. https://doi.org/10.13140/RG.2.1.4658.7043.

[125] Ronsse F. Report on biochar production techniques 2013:1–12.

[126] Rajakumar R, Sankar J. Biochar for Sustainable Agriculture-A review. Int J Appl Pure Sci 2016;02:211–24. https://doi.org/10.1016/b978-0-12-811729-3.00011-x.

[127] Laird DA, Fleming P, Davis DD, Horton R, Wang B, Karlen DL. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 2010;158:443–9. https://doi.org/10.1016/j.geoderma.2010.05.013.

[128] Ding Y, Liu Y, Liu S, Li Z, Tan X. Biochar to improve soil fertility . A review. Agron Sustain Dev 2016. https://doi.org/10.1007/s13593-016-0372-z.

[129] Uchimiya M, Klasson KT, Wartelle LH, Lima IM. Chemosphere Influence of soil properties on heavy metal sequestration by biochar amendment : Chemosphere 2011;82:1438–47. https://doi.org/10.1016/j.chemosphere.2010.11.078.

[130] Khorram MS, Zhang Q, Lin D, Zheng Y, Fang H, Yu Y. ScienceDirect Biochar : A review of its impact on pesticide behavior in soil environments and its potential applications. JES 2016;44:269–79. https://doi.org/10.1016/j.jes.2015.12.027.

[131] Nelissen V, Kumar B, Ruysschaert G, Boeckx P. Soil Biology & Biochemistry Effect of different biochar and fertilizer types on N 2 O and NO emissions. Soil Biol Biochem 2014;70:244–55. https://doi.org/10.1016/j.soilbio.2013.12.026.

[132] Jiang Z, Lian F, Wang Z, Xing B. The role of biochars in sustainable crop production and soil resiliency. J Exp Bot 2019;71:520–42. https://doi.org/10.1093/jxb/erz301.

[133] Spokas KA, Novak JM, Stewart CE, Cantrell KB, Uchimiya M, Dusaire MG, et al. Chemosphere Qualitative analysis of volatile organic compounds on biochar. Chemosphere 2011;85:869–82. https://doi.org/10.1016/j.chemosphere.2011.06.108.

[134] Purakayastha TJ, Kumari S, Pathak H. Characterisation, stability, and microbial effects of four biochars produced from crop residues. Geoderma 2015;239–240:293–303. https://doi.org/10.1016/j.geoderma.2014.11.009.

[135] Glaser B, Wiedner K, Seelig S, Schmidt HP, Glaser B, Wiedner K, et al. Biochar organic fertilizers from natural resources as substitute for mineral fertilizers. Agron Sustain Dev 2014;35:667–78. https://doi.org/10.1007/s13593-014-0251-4.

[136] Kizito S, Luo H, Lu J, Bah H, Dong R, Wu S. Role of nutrient-enriched biochar as a soil amendment during maize growth: Exploring practical alternatives to recycle agricultural residuals and to reduce chemical fertilizer demand. Sustain 2019;11:3211. https://doi.org/10.3390/su11113211.

[137] Rodriguez L. Integrated Farming Systems for Food and Energy in a Warming , Resource-depleting World. n.d.

[138] Greenberg I, Kaiser M, Gunina A, Ledesma P, Polifka S, Wiedner K, et al. Substitution of mineral fertilizers with biogas digestate plus biochar increases physically stabilized soil carbon but not crop biomass in a field trial. Sci Total Environ 2019;680:181–9. https://doi.org/10.1016/j.scitotenv.2019.05.051.

[139] Udall D, Rayns F, Charlesworth S. The Potential of Biochar and Anaerobic Digestate use in a Temperate Conventional Wheat Production System 2017;4:44–9.

[140] Bouaravong B, Dung NNX, Preston TR. Effect of biochar and biodigester effluent on yield of Taro (Colocasia esculenta) foliage. Livest Res Rural Dev 2017;29.

[141] Calamai A, Palchetti E, Masoni A, Marini L, Chiaramonti D, Dibari C, et al. The Influence of Biochar and Solid Digestate on Rose-Scented Geranium (Pelargonium graveolens L'Hér.) Productivity and Essential Oil Quality. Agronomy 2019;9:260. https://doi.org/10.3390/agronomy9050260.

[142] Elbashier M, Xiaohou S, Ali A, Mohmmed A. Effect of Digestate and Biochar Amendments on Photosynthesis Rate, Growth Parameters, Water Use Efficiency and Yield of Chinese Melon (Cucumis melo L.) under Saline Irrigation. Agronomy 2018;8:22. https://doi.org/10.3390/agronomy8020022.

[143] Sekar S, Hottle RD, Lal R. Effects of Biochar and Anaerobic Digester Effluent on Soil Quality and Crop Growth in Karnataka, India. Agric Res 2014;3:137–47. https://doi.org/10.1007/s40003-014-0104-z.

[144] Mukherjee S, Weihermueller L, Tappe W, Vereecken H, Burauel P. Microbial respiration of biochar- and digestate-based mixtures. Biol Fertil Soils 2016;52:151–64. https://doi.org/10.1007/s00374-015-1060-x.

[145] Marchetti R, Castelli F, Orsi A, Sghedoni L, Bochicchio D. Biochar from swine manure solids: Influence on carbon sequestration and Olsen phosphorus and mineral nitrogen dynamics in soil with and without digestate incorporation. Ital J Agron 2012;7:189–95. https://doi.org/10.4081/ija.2012.e26.

[146] Cardelli R, Giussani G, Marchini F, Saviozzi A. Short-term effects on soil of biogas digestate, biochar and their combinations. Soil Res 2018;56:623. https://doi.org/10.1071/sr18017.

[147] Martin SL, Clarke ML, Othman M, Ramsden SJ, West HM. Biochar-mediated reductions in greenhouse gas emissions from soil amended with anaerobic digestates. Biomass and Bioenergy 2015;79:39–49. https://doi.org/10.1016/j.biombioe.2015.04.030.

[148] Bruun EW, Müller-Stöver D, Ambus P, Hauggaard-Nielsen H. Application of biochar to soil and N2O emissions: Potential effects of blending fast-pyrolysis biochar with anaerobically digested slurry. Eur J Soil Sci 2011;62:581–9. https://doi.org/10.1111/j.1365-2389.2011.01377.x.

[149] Sánchez-Monedero MA, Sánchez-García M, Alburquerque JA, Cayuela ML. Biochar reduces volatile organic compounds generated during chicken manure composting. Bioresour Technol 2019;288:121584. https://doi.org/10.1016/j.biortech.2019.121584.

[150] Somerville PD, Farrell C, May PB, Livesley SJ. Biochar and compost equally improve urban soil physical and biological properties and tree growth, with no added benefit in combination. Sci Total Environ 2019:135736. https://doi.org/10.1016/j.scitotenv.2019.135736.

[151] Kookana RS, Sarmah AK, Zwieten L Van, Krull E. Biochar Application to Soil : Agronomic and Environmental Benefits and Unintended Consequences. vol. 112. 1st ed. Elsevier Inc.; 2011. https://doi.org/10.1016/B978-0-12-385538-1.00003-2.

[152] Gell K, van Groenigen JW, Cayuela ML. Residues of bioenergy production chains as soil amendments: Immediate and temporal phytotoxicity. J Hazard Mater 2011;186:2017–25. https://doi.org/10.1016/j.jhazmat.2010.12.105.

[153] EU.C. Council Directive 91/676/EEC of 12 December 1991 concerning the protection of waters against pollution caused by nitrates from agricultural sources. vol. L 375. 1991.

[154] Vaughn SF, Eller FJ, Evangelista RL, Moser BR, Lee E, Wagner RE, et al. Evaluation of biochar-anaerobic potato digestate mixtures as renewable components of horticultural potting media. Ind Crops Prod 2014;65:467–71. https://doi.org/10.1016/j.indcrop.2014.10.040.

[155] Tayibi S, Monlau F, Mariase F, Cazaudehore G, Fayoud N-E, Oukarroum A, et al. Coupling anaerobic digestion and pyrolysis processes for maximizing energy recovery and soil preservation according to the circular economy concept. J Environ Manage 2021. https://doi.org/10.1016/j.jenvman.2020.111632.

[156] Tayibi S, Monlau F, Marias F, Thevenin N, Jimenez R, Oukarroum A, et al. Industrial symbiosis of anaerobic digestion and pyrolysis: Performances and agricultural interest of coupling biochar and liquid digestate. Sci Total Environ 2021;793:148461. https://doi.org/10.1016/j.scitotenv.2021.148461.

[157] Denman, K.L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P.M., Dickinson RE et al. Couplings between changes in the climate system and biogeochemistry. Clim Chang 2007 Phys Sci Basis, S Solomon Al, Eds, Cambridge Univ Press 2007:499–587.

[158] Smith P, Martino D, Cai Z, Gwary D, Janzen H, Kumar P, et al. Agriculture. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA editors. Climate change: mitigation. Contribution of working group III to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge Cambridge Univ Press 2007:497–540.

[159] Mukherjee S, Weihermüller L, Tappe W, Hofmann D, Köppchen S, Laabs V, et al. Sorption-desorption behaviour of bentazone, boscalid and pyrimethanil in biochar and digestate based soil mixtures for biopurification systems. Sci Total Environ 2016;559:63–73. https://doi.org/10.1016/j.scitotenv.2016.03.145.

[160] Sun Z, Sänger A, Rebensburg P, Lentzsch P, Wirth S, Kaupenjohann M, et al. Contrasting effects of biochar on N2O emission and N uptake at different N fertilizer levels on a temperate sandy loam. Sci Total Environ 2017;578:557–65. https://doi.org/10.1016/j.scitotenv.2016.10.230.

[161] Wang J, Xia K, Waigi MG, Gao Y, Odinga ES, Ling W, et al. Application of biochar to soils may result in plant contamination and human cancer risk due to exposure of polycyclic aromatic hydrocarbons. Environ Int 2018;121:169–77. https://doi.org/10.1016/j.envint.2018.09.010.

[162] Zhu Q, Peng X, Huang T. Contrasted effects of biochar on maize growth and N use efficiency depending on soil conditions. Int Agrophysics 2015;29:257–66. https://doi.org/10.1515/intag-2015-0023.

[163] Lian F, Xing B. Black Carbon (Biochar) in Water/Soil Environments: Molecular Structure, Sorption, Stability, and Potential Risk. vol. 51. 2017. https://doi.org/10.1021/acs.est.7b02528.

[164] Xu G, Zhang Y, Sun J, Shao H. Negative interactive effects between biochar and phosphorus fertilization on phosphorus availability and plant yield in saline sodic soil. Sci Total Environ 2016;568:910–5. https://doi.org/10.1016/j.scitotenv.2016.06.079.

[165] Hussain M, Farooq M, Nawaz A, Al-Sadi AM, Solaiman ZM, Alghamdi SS, et al. Biochar for crop production: potential benefits and risks. vol. 17. 2017. https://doi.org/10.1007/s11368-016-1360-2.

[166] Kim HS, Kim KR, Kim HJ, Yoon JH, Yang JE, Ok YS, et al. Effect of biochar on heavy metal immobilization and uptake by lettuce (Lactuca sativa L.) in agricultural soil. Environ Earth Sci 2015;74:1249–59. https://doi.org/10.1007/s12665-015-4116-1.

[167] Sushkova S, Minkina T, Tarigholizadeh S, Rajput V, Fedorenko A, Antonenko E, et al. Soil PAHs contamination effect on the cellular and subcellular organelle changes of Phragmites australis Cav. Environ Geochem Health 2021;43:2407–21. https://doi.org/10.1007/s10653-020-00735-8.

[168] Odinga ES, Gudda FO, Waigi MG, Wang J, Gao Y. Occurrence, formation and environmental fate of polycyclic aromatic hydrocarbons in biochars. Fundam Res 2021;1:296–305. https://doi.org/10.1016/j.fmre.2021.03.003.

[169] Stefaniuk M, Oleszczuk P, Bartmiński P. Chemical and ecotoxicological evaluation of biochar produced from residues of biogas production. J Hazard Mater 2016;318:417–24. https://doi.org/10.1016/j.jhazmat.2016.06.013.

[170] Devi P, Saroha AK. Risk analysis of pyrolyzed biochar made from paper mill effluent treatment plant sludge for bioavailability and eco-toxicity of heavy metals. Bioresour Technol 2014;162:308–15. https://doi.org/10.1016/j.biortech.2014.03.093.

[171] Wang D, Jiang P, Zhang H, Yuan W. Biochar production and applications in agro and forestry systems: A review. Sci Total Environ 2020;723:137775. https://doi.org/10.1016/j.scitotenv.2020.137775.

[172] Taha SM, Amer ME, Elmarsafy AE, Elkady MY. Adsorption of 15 different pesticides on untreated and phosphoric acid treated biochar and charcoal from water. J Environ Chem Eng 2014;2:2013–25. https://doi.org/10.1016/j.jece.2014.09.001.

[173] Pathy A, Ray J, Paramasivan B. Biochar amendments and its impact on soil biota for sustainable agriculture. Biochar 2020;2:287–305. https://doi.org/10.1007/s42773-020-00063-1.

[174] He M, Xiong X, Wang L, Hou D, Bolan NS, Ok YS, et al. A critical review on performance indicators for evaluating soil biota and soil health of biochar-amended soils. J Hazard Mater 2021;414. https://doi.org/10.1016/j.jhazmat.2021.125378.

[175] Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. Biochar effects on soil biota - A review. Soil Biol Biochem 2011;43:1812–36. https://doi.org/10.1016/j.soilbio.2011.04.022.

[176] Busch D, Kammann C, Grünhage L, Müller C. Simple Biotoxicity Tests for Evaluation of Carbonaceous Soil Additives: Establishment and Reproducibility of Four Test Procedures. J Environ Qual 2012;41:1023–32. https://doi.org/10.2134/jeq2011.0122.

[177] Rogovska N, Laird D, Cruse RM, Trabue S HE. Germination tests for assessing biochar quality. J Environ Qual 2012;41(4):1014. https://doi.org/10.2134/jeq2011.0103. PMID: 22751043.

[178] Nzanza B, Marais D, Soundy P. Effect of arbuscular mycorrhizal fungal inoculation and biochar amendment on growth and yield of tomato. Int J Agric Biol 2012;14:965–9.

[179] Liu J, Ding Y, Ji Y, Gao G, Wang Y. Effect of Maize Straw Biochar on Bacterial Communities in Agricultural Soil. Bull Environ Contam Toxicol 2020;104:333–8. https://doi.org/10.1007/s00128-020-02793-1.

[180] Manara P, Zabaniotou A. Indicator-based economic, environmental, and social sustainability assessment of a small gasification bioenergy system fuelled with food processing residues from the Mediterranean agro-industrial sector. Sustain Energy Technol Assessments 2014;8:159–71. https://doi.org/10.1016/j.seta.2014.08.007.

[181] Haase M, Babenhauserheide N, Rösch C. Multi criteria decision analysis for sustainability assessment of 2nd generation biofuels. Procedia CIRP 2020;90:226–31. https://doi.org/10.1016/j.procir.2020.02.124.

[182] Rolewicz-Kalińska A, Oniszk-Popławska A, Wesołowska J, Ryńska ED. Conditions for the development of anaerobic digestion technologies using the organic fraction of municipal solid waste: perspectives for Poland. Environ Dev Sustain 2016;18:1279–96. https://doi.org/10.1007/s10668-016-9808-5.

[183] Aghbashlo M, Tabatabaei M, Soltanian S, Ghanavati H, Dadak A. Comprehensive exergoeconomic analysis of a municipal solid waste digestion plant equipped with a biogas genset. Waste Manag 2019;87:485–98. https://doi.org/10.1016/j.wasman.2019.02.029.

[184] Sevillano CA, Pesantes AA, Carpio EP, Martínez EJ, And, Gómez X. Anaerobic Digestion for Producing Renewable Energy — The Evolution of This Technology in a New Uncertain Scenario. Entropy 2021;23:1–23. https://doi.org/https://doi.org/10.3390/e23020145.

[185] Cathcart A, Smyth BM, Lyons G, Murray ST, Rooney D, Johnston CR. An economic analysis of anaerobic digestate fuel pellet production: can digestate fuel pellets add value to existing operations? Clean Eng Technol 2021;3:100098. https://doi.org/10.1016/j.clet.2021.100098.

[186] Rajendran K, Murthy GS. Techno-economic and life cycle assessments of anaerobic digestion – A review. Biocatal Agric Biotechnol 2019;20:101207. https://doi.org/10.1016/j.bcab.2019.101207.

[187] Zamalloa C, Vulsteke E, Albrecht J, Verstraete W. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. Bioresour Technol 2011;102:1149–58. https://doi.org/10.1016/j.biortech.2010.09.017.

[188] González R, González J, Rosas JG, Smith R, Gómez X. Biochar and Energy Production : Valorizing Swine Manure through Coupling Co-Digestion and Pyrolysis. C-Journal Carbon Res 2020;6. https://doi.org/10.3390/c6020043.

[189] Mabalane PN, Oboirien BO, Sadiku ER, Masukume M. A Techno-economic Analysis of Anaerobic Digestion and Gasification Hybrid System : Energy Recovery from Municipal Solid Waste in South Africa. Waste and Biomass Valorization 2021;12:1167–84. https://doi.org/10.1007/s12649-020-01043-z.

[190] Mills N, Pearce P, Farrow J, Thorpe RB, Kirkby NF. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. Waste

Manag 2014;34:185–95. https://doi.org/10.1016/j.wasman.2013.08.024.

[191] Dickinson D, Balduccio L, Buysse J, Ronsse F, van Huylenbroeck G, Prins W. Cost-benefit analysis of using biochar to improve cereals agriculture. GCB Bioenergy 2015;7:850–64. https://doi.org/10.1111/gcbb.12180.

[192] Dave A, Huang Y, Rezvani S, Mcilveen-wright D, Novaes M, Hewitt N. Techno-economic assessment of biofuel development by anaerobic digestion of European marine cold-water seaweeds. Bioresour Technol 2013;135:120–7. https://doi.org/10.1016/j.biortech.2013.01.005.

[193] Rosen MA. Environmental sustainability tools in the biofuel industry. Biofuel Res J 2018;17:751–2. https://doi.org/10.18331/BRJ2018.5.1.2.

[194] Opatokun SA, Lopez-Sabiron AM, Ferreira G, Strezov V. Life cycle analysis of energy production from food waste through anaerobic digestion, pyrolysis and integrated energy system. Sustainability 2017;9:1–15. https://doi.org/10.3390/su9101804.

[178] Nzanza B, Marais D, Soundy P. Effect of arbuscular mycorrhizal fungal inoculation and biochar amendment on growth and yield of tomato. Int J Agric Biol 2012;14:965–9.

[179] Liu J, Ding Y, Ji Y, Gao G, Wang Y. Effect of Maize Straw Biochar on Bacterial Communities in Agricultural Soil. Bull Environ Contam Toxicol 2020;104:333–8. https://doi.org/10.1007/s00128-020-02793-1.

[180] Manara P, Zabaniotou A. Indicator-based economic, environmental, and social sustainability assessment of a small gasification bioenergy system fuelled with food processing residues from the Mediterranean agro-industrial sector. Sustain Energy Technol Assessments 2014;8:159–71. https://doi.org/10.1016/j.seta.2014.08.007.

[181] Haase M, Babenhauserheide N, Rösch C. Multi criteria decision analysis for sustainability assessment of 2nd generation biofuels. Procedia CIRP 2020;90:226–31. https://doi.org/10.1016/j.procir.2020.02.124.

[182] Rolewicz-Kalińska A, Oniszk-Popławska A, Wesołowska J, Ryńska ED. Conditions for the development of anaerobic digestion technologies using the organic fraction of municipal solid waste: perspectives for Poland. Environ Dev Sustain 2016;18:1279–96. https://doi.org/10.1007/s10668-016-9808-5.

[183] Aghbashlo M, Tabatabaei M, Soltanian S, Ghanavati H, Dadak A. Comprehensive exergoeconomic analysis of a municipal solid waste digestion plant equipped with a biogas genset. Waste Manag 2019;87:485–98. https://doi.org/10.1016/j.wasman.2019.02.029.

[184] Sevillano CA, Pesantes AA, Carpio EP, Martínez EJ, And, Gómez X. Anaerobic Digestion for Producing Renewable Energy — The Evolution of This Technology in a New Uncertain Scenario. Entropy 2021;23:1–23. https://doi.org/https://doi.org/10.3390/e23020145.

[185] Cathcart A, Smyth BM, Lyons G, Murray ST, Rooney D, Johnston CR. An economic analysis of anaerobic digestate fuel pellet production: can digestate fuel pellets add value to existing operations? Clean Eng Technol 2021;3:100098. https://doi.org/10.1016/j.clet.2021.100098.

[186] Rajendran K, Murthy GS. Techno-economic and life cycle assessments of anaerobic

digestion – A review. Biocatal Agric Biotechnol 2019;20:101207. https://doi.org/10.1016/j.bcab.2019.101207.

[187] Zamalloa C, Vulsteke E, Albrecht J, Verstraete W. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. Bioresour Technol 2011;102:1149–58. https://doi.org/10.1016/j.biortech.2010.09.017.

[188] González R, González J, Rosas JG, Smith R, Gómez X. Biochar and Energy Production : Valorizing Swine Manure through Coupling Co-Digestion and Pyrolysis. C-Journal Carbon Res 2020;6. https://doi.org/10.3390/c6020043.

[189] Mabalane PN, Oboirien BO, Sadiku ER, Masukume M. A Techno-economic Analysis of Anaerobic Digestion and Gasification Hybrid System : Energy Recovery from Municipal Solid Waste in South Africa. Waste and Biomass Valorization 2021;12:1167–84. https://doi.org/10.1007/s12649-020-01043-z.

[190] Mills N, Pearce P, Farrow J, Thorpe RB, Kirkby NF. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. Waste Manag 2014;34:185–95. https://doi.org/10.1016/j.wasman.2013.08.024.

[191] Dickinson D, Balduccio L, Buysse J, Ronsse F, van Huylenbroeck G, Prins W. Cost-benefit analysis of using biochar to improve cereals agriculture. GCB Bioenergy 2015;7:850–64. https://doi.org/10.1111/gcbb.12180.

[192] Dave A, Huang Y, Rezvani S, Mcilveen-wright D, Novaes M, Hewitt N. Techno-economic assessment of biofuel development by anaerobic digestion of European marine cold-water seaweeds. Bioresour Technol 2013;135:120–7. https://doi.org/10.1016/j.biortech.2013.01.005.

[193] Rosen MA. Environmental sustainability tools in the biofuel industry. Biofuel Res J 2018;17:751–2. https://doi.org/10.18331/BRJ2018.5.1.2.

[194] Opatokun SA, Lopez-Sabiron AM, Ferreira G, Strezov V. Life cycle analysis of energy production from food waste through anaerobic digestion, pyrolysis and integrated energy system. Sustainability 2017;9:1–15. https://doi.org/10.3390/su9101804.

[195] Li H, Feng K. Life cycle assessment of the environmental impacts and energy efficiency of an integration of sludge anaerobic digestion and pyrolysis. J Clean Prod 2018;195:476–85. https://doi.org/10.1016/j.jclepro.2018.05.259.

[196] Wang J, Inalegwu S, Ma H, Wang M, Chen R, Tian W, et al. Life cycle assessment of the integration of anaerobic digestion and pyrolysis for treatment of municipal solid waste. Bioresour Technol 2021;338:125486. https://doi.org/10.1016/j.biortech.2021.125486.

[197] Mohammadi A, Venkatesh G, Sandberg M, Eskandari S, Granström K. Life cycle assessment of combination of anaerobic digestion and pyrolysis : focusing on different options for biogas use. Adv Geosci 2019;49:57–66.

[198] Martin S, Cowell R, Navr J. Rich or poor? Who actually lives in proximity to AD plants in Wales? Biomass and Bioenergy 2020;143:105799. https://doi.org/10.1016/j.biombioe.2020.105799.

[199] Vaneeckhaute C, Styles D, Prade T, Adams P, Thelin G, Rodhe L, et al. Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions : A multi-dimensional sustainability assessment. Resour Conserv

Recycl 2018;136:110–7. https://doi.org/10.1016/j.resconrec.2018.03.027.

[200] Zabaniotou A, Antoniou N, Bruton G. Analysis of good practices, barriers and drivers for ELTs pyrolysis industrial application. Waste Manag 2014;34:2335–46. https://doi.org/10.1016/j.wasman.2014.08.002.

[201] Tigini V, Franchino M, Bona F, Cristina G. Is digestate safe ? A study on its ecotoxicity and environmental risk on a pig manure. Sci Total Environ 2016;551–552:127–32. https://doi.org/10.1016/j.scitotenv.2016.02.004.

[202] Schmidt HP, Hagemann N, Draper K, Kammann C. The use of biochar in animal feeding. PeerJ 2019:1–54. https://doi.org/10.7717/peerj.7373.

[203] Schmidt H-P. Treating liquid manure with biochar. Ithaka J 2012:273–276.

[204] Dougherty B, Gray M, Johnson MG, Kleber M. Can biochar covers reduce emissions from manure lagoons while capturing nutrients? J Environ Qual 2017;46:659–66. https://doi.org/10.2134/jeq2016.12.0478.

[205] Wu B, Lin R, Shea RO, Deng C, Rajendran K, Murphy JD. Production of advanced fuels through integration of biological , thermo-chemical and power to gas technologies in a circular cascading bio-based system. Renew Sustain Energy Rev 2021;135:110371. https://doi.org/10.1016/j.rser.2020.110371.

[206] Dumas C, Ditlev L, Ottosen M, Escudié R, Jensen P. Editorial : Biological Methanation or (Bio / Syn) -Gas Upgrading. Front Energy Res 2020;8:30. https://doi.org/10.3389/fenrg.2020.00030.

[207] Laird DA, Brown RC, Amonette JE, Lehmann J. Review of the pyrolysis platform for coproducing bio-oil and biochar. Biofuels, Bioprod Biorefining 2009;3:547–62. https://doi.org/10.1002/bbb.169.

[208] Ghysels S, Acosta N, Estrada A, Pala M, Vrieze J De, Ronsse F, et al. Integrating anaerobic digestion and slow pyrolysis improves the product portfolio of a cocoa waste biorefinery. Sustain Energy Fuels 2020;4:3712–25. https://doi.org/10.1039/d0se00689k.

[209] Kizito S, Luo H, Wu S, Ajmal Z, Lv T, Dong R. Phosphate recovery from liquid fraction of anaerobic digestate using four slow pyrolyzed biochars: Dynamics of adsorption, desorption and regeneration. J Environ Manage 2017;201:260–7. https://doi.org/10.1016/j.jenvman.2017.06.057.

[210] Chen S, Yang M, Ba C, Yu S, Jiang Y, Zou H, et al. Preparation and characterization of slow-release fertilizer encapsulated by biochar-based waterborne copolymers. Sci Total Environ 2018;615:431–7. https://doi.org/10.1016/j.scitotenv.2017.09.209.

[211] Peregrina A, Grutzmacher P, Eduardo C, Cerri P, Sanches V, Alberto C, et al. Biochar-based nitrogen fertilizers : Greenhouse gas emissions , use efficiency , and maize yield in tropical soils. Sci Total Environ 2019:135375. https://doi.org/10.1016/j.scitotenv.2019.135375.

[212] Alburquerque JA, de la Fuente C, Campoy M, Carrasco L, Nájera I, Baixauli C, et al. Agricultural use of digestate for horticultural crop production and improvement of soil properties. Eur J Agron 2012;43:119–28. https://doi.org/10.1016/j.eja.2012.06.001.

[213] Casini D, Barsali T, Rizzo AM, Chiaramonti D. Production and characterization of co-composted biochar and digestate from biomass anaerobic digestion. Biomass Convers

Biorefinery 2019. https://doi.org/10.1007/s13399-019-00482-6.

[214] Agegnehu G, Srivastava AK, Bird MI. The role of biochar and biochar-compost in improving soil quality and crop performance: A review. Appl Soil Ecol 2017;119:156–70. https://doi.org/10.1016/j.apsoil.2017.06.008.

[215] Xiao R, Awasthi MK, Li R, Park J, Pensky SM, Wang Q, et al. Recent developments in biochar utilization as an additive in organic solid waste composting: A review. Bioresour Technol 2017;246:203–13. https://doi.org/10.1016/j.biortech.2017.07.090.

Graphical Abstract