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Published Version:
Ingrao C., Novelli V., Valenti F., Messineo A., Arcidiacono C., Huisingh D. (2021). Feasibility of usage of hemp as a feedstock for anaerobic digestion: Findings from a literature review of the relevant technological and energy dimensions. CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY, 51(11), 1129-1158 [10.1080/10643389.2020.1745036].

Availability:
This version is available at: https://hdl.handle.net/11585/933695 since: 2023-07-05

Published:

DOI: http://doi.org/10.1080/10643389.2020.1745036

Feasibility of usage of hemp as a feedstock for anaerobic digestion: Findings from a literature review of the relevant technological and energy dimensions

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Abstract

Renewable biomasses are used worldwide as inputs for energy production through processes, like Anaerobic Digestion (AD), which is a well-established technology to transform them into bio-gas and other by-products.

Maize, triticale, sunflower and sorghum are energy crops frequently used as feedstocks in AD applications, mainly because of their high biogas potential. However, their cultivation generates some negative environmental impacts due to the direct and indirect land use changes. Therefore, it is important to seek for alternative species to replace some of them with others with lower environmental impacts while producing comparable biogas and energy yields.

Industrial Hemp (IH) was documented in this literature review to be a suitable crop for AD applications with yields that are highly competitive with those of the energy crops being used now. Additionally, this literature review provided insight into the diversity of the methane yielding parts of the IH plants, with fresh leaves yielding the highest quantities.

Finally, the authors of this literature review highlighted the need for research and development designed to expand the usage of IH as green biomass in AD plants, for efficient production of biogas and organic nutrients, and thereby, contributing to transitioning towards low fossil-carbon footprint societies.

Keywords

Anaerobic digestion; industrial hemp; energy efficiency; environmental feasibility; energy crops; Fossil-carbon footprint reduction

Acronyms

AD: Anaerobic Digestion
BEY: Biomass Energy Yield
BMP: Biochemical Methane Potential (or BioMethane Potential)
CED: Cumulative Energy Demand
CF: Carbon Footprint
CHP: Combined Heat and Power
CSTR: Continuous Stirred Tank Reactor
DM: Dry Matter
FM: Fresh Matter
GHG: Greenhouse Gas
HHM: Hay Horse Manure
HHV: High Heating Value
IH: Industrial Hemp
LCA: Life Cycle Assessment
LCSA: Life Cycle Sustainability Assessment
MEY: Methane Energy Yield
NEY: Net Energy Yield
OLR: Organic Loading Rate
SHM: Silage Horse Manure
SSF: Simultaneous Saccharification and Fermentation
UASS: Upflow Anaerobic Solid-State
VS: Volatile Solid

Contents

1. Introduction

Energy is considered as one of the most important commodities of life in the present age and, for that, it is essential that it is produced and supplied in secure and sustainable ways, so that ecologically, economically and socially sound energy systems are ensured throughout all societies for the short and long-term future (Rehman et al., 2013). Fossil fuels continue to be important energy sources, due to their abundant availability, the monetary gains from their exploitation and the need to ensure a continuous supply of energy for a rapidly growing human population (Volpe et al., 2014; Sundaram et al., 2017; Ingrao et al., 2018a). Fossil carbon extraction from the earth and its combustion are responsible for multiple negative impacts, affecting the health of humans and the quality of the natural ecosystem. According to the World Health Organization (WHO), approximately seven million humans die prematurely each year, globally, due primarily to fossil-carbon-based pollutants. Additionally, as global temperatures are steadily increasing concentrations of carbon dioxide in the atmosphere, other human health impacts are occurring and are contributing to bio-diversity losses, which are causing vulnerabilities of global ecosystem sustainability (Collet et al., 2017, Sundaram et al., 2017): these are some of the major environmental concerns that need to be addressed and solved.

To this end, solutions and strategies are urgently needed to phase out the use of systems based upon fossil-carbon energy and to accelerate the global transition to those utilising renewable energy sources like solar, wind, hydro, geothermal, and biomass, that are promising alternatives (Böske et al., 2014; Schroyen et al., 2018). These are, indeed, delivering lower-environmental impacts (Prade et al., 2012; Schroyen et al., 2017), which is why they are being implemented globally. Valorisation of biomass usage is one of the alternatives that is useful and effective for socio-economic and environmental improvements. Chief among them are crop diversification, reforestation and more sustainable management of forests, and the creation of jobs, particularly in rural communities where large quantities of agricultural biomass and residues are produced (Valenti et al., 2016, 2018a).

Efficient and sustainable utilisation of biomass as an energy source is essential for reduction: of the current dependence upon consumption of fossil fuels in heat, power, and transportation related applications; and of the resulting emissions of GHGs (Kreuger et al., 2011a; Prade et al., 2012).

In this context, Anaerobic Digestion (AD) is a well-established technology to utilise that (organic-matter rich) biomass, so much so that it is gaining increasing interest from farmers, energy managers, company owners, academics and other stakeholders (Nges et al., 2012; Valenti et al., 2018b; Nag et al., 2019).

AD is a complex process, involving a diverse assemblage of bacteria and methanogenic species, and is developed through four steps, commencing with hydrolysis of the biomass, followed by acidogenesis, acetogenesis and methanogenesis (Schroyen et al., 2017; Nag et al., 2019).

Two products are produced within AD: biogas; and a nutrient-rich digestate. The former is a gaseous mixture which is mainly comprised of methane and carbon dioxide, while the digestate is a stabilised material that can be either utilised directly or as a solid and liquid fraction after centrifugation (Nayal et al., 2016; Evangelisti et al., 2017; Ingrao et al., 2018a).

Generally, while 70-80% of the output digestate is recirculated within the plant to feed the digester, the remaining 20-30% is used in agriculture as a valuable soil amendment (Nayal et al., 2016; Rana et al., 2016). Usage of organic fertilisers from digestate instead of synthetic fertilisers contributes to enhance sustainability of agricultural systems, by reducing costs and associated GHGs (Yasar et al., 2017; Ingrao et al., 2018a; Selvaggi et al., 2018).

Yields in biogas production and energy performances of AD systems are dependent upon the type and the quality of the biomass utilised which, in turn, are affected by the way it is harvested, stored and processed in the AD systems (Bacenetti et al., 2015; Ingrao et al., 2018a; Valenti et al., 2018c).

There are abundant sources of biodegradable organic waste including animal waste (sewage and manure) from pigs, cattle, poultry, and horses (Yusuf et al., 2011; Böske et al., 2014; Lamnatou et al., 2019).

To optimise biogas yield, those biomass materials are often co-digested with '*energy crops*' such as maize, triticale, sunflower and sorghum, which are cultivated with the main objective of producing energy for application in a wide range of sectors (Nges et al., 2012; Schroyen et al., 2018; Valenti et al., 2019).

In this regard, a mixture of feedstocks of different types and quantities helps to enhance digestion performance and energy yields, and application of the digestate produced will provide a better balance of macro- and micro-nutrients (Nges et al., 2012; Valenti et al., 2018d).

Energy crops are generally ensilaged, so they can be stored for a period of time before their energy content is extracted via AD. This makes it possible to use the organic matter when needed, and when the selling price of the methane produced is higher (Pakarinen et al., 2008; Nges et al., 2012).

Although energy-crop biomass yields large quantities of biogas, it is responsible for a set of environmental burdens mainly deriving from cultivation of the invested lands and from the extensive extraction of ground water for irrigation of those lands. Furthermore, energy crops compete for high quality land that needs to be used for production of human food and animal feeds. (Rana et al., 2016; Selvaggi et al., 2018; Ingrao et al., 2019). In contrast, as one great advantage over energy crops, Industrial Hemp (IH) (*Cannabis Sativa* L.) can be produced on marginal lands and, at the same time, enables production of a diversified biomass that includes hurds, fibres and seeds (Kreuger et al., 2011a; Kumar et al., 2017). Hence, these materials are treated as co-products of IH cultivation systems in a wide range of downstream systems, mainly including production of foods and feeds, generation of bioenergy and biofuels, and construction of green buildings. Such applications can be pursued simultaneously, and so contribute to maximising yields while significantly reducing land use change and other relevant environmental impacts as overall associated with production of those materials.

With regard to bioenergy and biofuel, IH is generally harvested and ensilaged for later usage as a green feedstock in AD plants for biogas production (Prade et al., 2012). However, according to this author team, it would be desirable to find and test alternative solutions that enable energy generation while preserving diversification of the aforementioned output biomass materials and of the possible application paths.

In this context, this literature review was designed to build upon research findings on this topic, as the starting point to identify and to fill the knowledge and application gaps in this content area, namely the use of AD to convert IH biomass into value-added, sustainable energy sources and nutrients. In particular, the authors sought to:

1. Develop insights into the current status of research performed on the environmental, technical, energetic and economic dimensions of IH as a feedstock in AD-based systems for producing bio-gas;
2. Contribute to enhancing the knowledge and literature on IH in AD applications;
3. Foster research and wide-spread usage of IH in AD systems to contribute to accelerating the transition to equitable, sustainable, liveable, post-fossil carbon societies (Ingrao et al., 2018b).

To the authors' knowledge, this type of literature review has not been published and, so, according to the authors, it synthetises valuable insights that can be of interest and utility to readers worldwide.

Two related literature reviews by Ingrao et al. (2018a) and Ingrao et al. (2019), reviewed AD systems sourced with food and agricultural-waste biomass respectively, highlighted the key technical, energetic, and environmental issues.

Additionally, Schluttenhofer and Yuan (2017) highlighted ways to deepen the knowledge of hemp biology based upon domesticating and maximising the agronomic potential of IH.

No previous literature reviews specifically, addressed usage of IH as a feedstock in AD, thus highlighting its scientific relevance, novelty features and the growing interest about potential uses of IH in AD.

The article by Rehman et al. (2013), reviewed potential energy paths for hemp biomass usage, as a gaseous and as a solid biofuel for use in Pakistan. Their publication deepened the knowledge on IH production, by documenting the feasibility of its usage as a bioenergy source.

Their findings can be useful in stimulating interest for usage of IH in Italy and in other Mediterranean regions, because these countries have similar soil and climatic conditions to those of Pakistan.

In contrast with the paper by Rehman et al. (2013), this literature review is more focussed upon addressing aspects of IH such as biomass and energy yields, land availability, energy mix, environmental performance and economic returns. The authors hope that it will deepen the knowledge for relevant stakeholders to help them to make further improvements for enhanced sustainability of AD systems that use IH for production of biogas and other biofuels as well as digestates to be used as agricultural soil amendments.

2. Paper search methodology and presentation of the studies selected

The authors of this paper reviewed the findings from relevant articles on the use of IH biomass in AD plants for production of biogas. A ten-year time span was chosen to develop projections of technical, energy and environmental issues and to draw conclusions and make recommendations based upon the articles found and reviewed.

The bibliographical search in Scopus was conducted using the following combinations of key-words or phrases: ‘*industrial hemp*’; ‘*energy crops*’; ‘*biogas production*’; and ‘*anaerobic digestion*’. Articles were selected if they addressed hemp being used as a suitable biomass feedstock for AD-plants, with the main focus of producing methane, thermal and electrical energy.

The scope of the review included research on co-digestion of hemp biomass with other biomass types; and AD/co-digestion facilities as part of integrated energy systems and/or in comparison with other biomass treatments. Attention was focussed upon AD, because it is a proven technology for transforming bio-based materials into valued-added energy, fuels and nutrients, with relatively low energy consumption rates and environmental impacts (Böske et al., 2014). In addition to this, IH is known to be one versatile crop for a wide range of applications (Ingrao et al., 2015), which is the main reason why the authors of this paper wanted to explore its application as fresh biomass for biogas production in AD plants.

The literature review helped the authors of this paper, to document that IH has been increasingly investigated during the period 2009-2019. As a matter of fact, by searching *'industrial hemp'* in Scopus, in the indexed article-titles, abstracts, and key-words, 352 articles were found. By reviewing the results and limiting them to *'buildings'*, 95 papers were found. When the search was limited to bioenergy and biofuels, 59 and 50 papers were found respectively. By searching for papers on '*biogas production*' and *'anaerobic digestion'*, 16-19 papers were found. Therefore, it is understood that the authors made several literatures searches with different search word combinations before a significant number of papers was found to represent this research area.

Papers dealing with IH-derived biogas production were extrapolated from Rehman et al. (2013) and, additionally, the following ones were reviewed: Barta et al. (2013); Böske et al. (2014); Adamovičs et al. (2014); Gissén et al. (2014); and Schroyen et al. (2015, 2107, and 2018). A total of fifteen papers, published during 2009-2019, were selected for in-depth review, based upon selection criteria presented above in this section.

The number of publications per year is depicted in Fig. 1. It is clear that the greatest number of articles were published in 2011 and, later, in 2014, while a decrease in articles was recorded between 2014 to 2018.

Based upon the review conducted, IH AD appeared to be an emerging technology, mainly because relevant but relatively little research has been developed thus far in this content area. However, the authors of this paper believe that many other studies are expected in the future, because considerable potentials for improvement and innovation can still be found.

The 15 papers selected for this literature review were the result of the joint work and commitment of 71 authors (15 of whom were the corresponding authors), mainly from six countries distributed in Northern and Southern Europe: in Fig. 1, the number of papers reviewed and of the related-authors were distributed by country and publication year. Sweden covered 40% of the 15 papers selected for this review with a total of 34 authors, representing almost 50% of the contributing authors. This could be due to the availability of green IH biomass, as well as to the interest and attention to research on IH usage for AD installations, in that part of Europe, in particular, in Sweden.

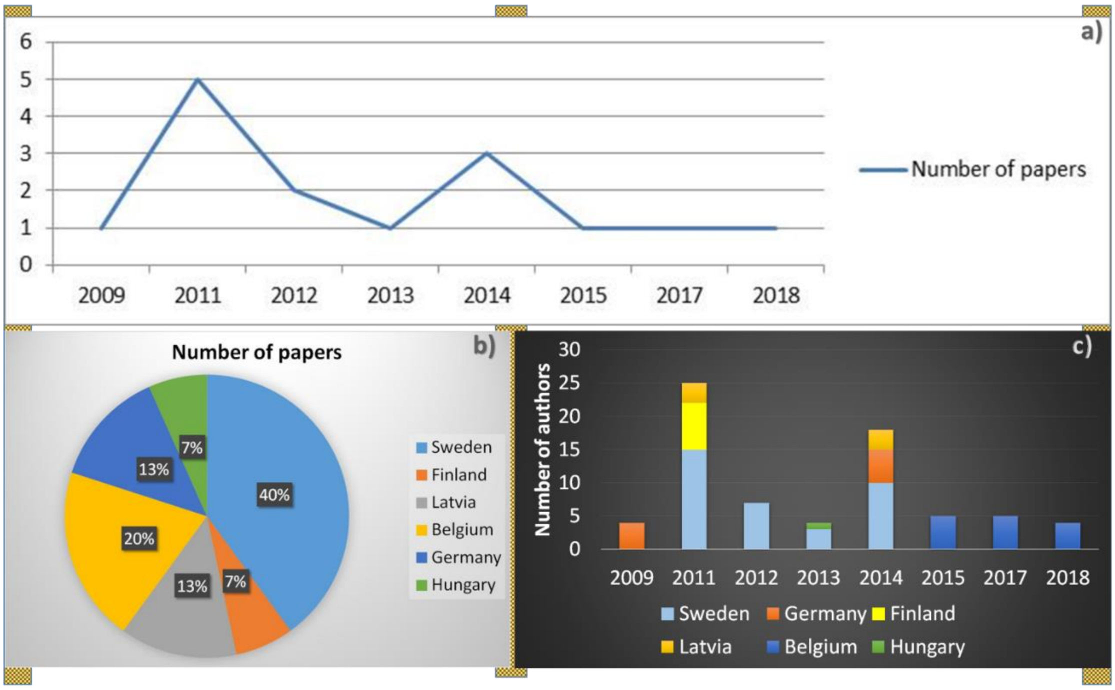

Fig. 1. Overview of the reviewed papers: a) Number of yearly publications[1]; b) Distribution of the papers considered, based upon affiliations of the corresponding authors; and c) Distribution of contributing authors (71) per affiliation country and publication year.

Many of the selected papers were authored by team members from different institutions in the same country. This suggested that this area's complexity requires that the systems must be investigated from a multidisciplinary perspective. Each of these papers were discussed in Section 4 by highlighting objectives and key findings. *For additional information, the reader is referred to the original papers.*

3. Reviewing objectives and the primary findings of the literature review

Anaerobic digestion has become the major technology for sustainable treatment of a wide range of biomasses, by optimising the valorisation and exploitation of those biomasses, to produce added-value energy sources and nutrients. Another benefit of processing the bio-based materials via AD, is that it reduces contamination of air, land and aquatic areas that would be impacted if these materials are not properly utilised.

In this context, **Prade et al. (2011)** investigated the optimal biomass and Biomass Energy Yield (BEY) for biogas and solid fuel production from IH grown in a cold climate at latitudes of approximately 55°N (Southern Sweden). In their study, the authors:

1. Compared the energy yield from IH with the yields from alternative energy crops commonly grown in the study region;

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[1] Years 2010, 2016, and 2019 are not included in the graph, because no papers were found based upon the criteria set for this review, as discussed in section 2.

2. Obtained information about suitable harvesting periods of IH for optimised production of biogas and solid fuel;
3. Highlighted the influence of different N-fertilisation regimes on the IH yield on a dry matter (DM) basis.

Prade et al. (2011) found that IH is highly competitive with the majority of the energy crops cultivated in the study area, in terms of biomass yield and in relation to the BEY for production of biogas and solid fuel.

Padre's team found that the per unit of DM yields are more affected by planting dates and weather conditions than by N-fertilisation rates; and that the optimal harvesting period is autumn (September - November) whether the IH is used as a feedstock for biogas production, and spring (February - April) if it is used for production of a solid biofuel (in the form of briquettes, straw bales, or pellets) to be used for heat generation.

The total energy in the biomass per ha/yr. of cultivated field (BEY) was determined, based upon the Higher Heating Value (HHV), which was documented to average of 296 GJ/ha/yr. (when used as feedstock for AD), while the combustion energy yield averaged to 201 GJ/ha/yr. (when used as solid fuel for heating.)

Solid biofuel production was found to be the major application for IH in Sweden, according to **Kreuger et al. (2011a).** Their research estimated the Methane Energy Yield (MEY) of IH (GJ/ha) based upon pre-determined values of biomass yield (t_{DM}/ha) and specific methane yield. A three-year period (2006-2008) of IH cultivation was used for the assessment. In agreement with Prade's et al. (2011) findings, Kreuger et al. (2011a) documented that the highest biomass yields per ha were found when harvesting was performed in the September and October. In that period, the average BEY was equal to 286±27 GJ/ha. Their results were similar to those reported by Prade et al. (2011), while the energy related to the methane content in the biogas (MEY) was 136±24 GJ/ha, which was higher than the production of transportation fuels from domestically grown crops like cereals and rapeseeds.

Methane production in AD plants was confirmed to be a reliable way of producing renewable transportation fuel.

Kreuger et al. (2011b) investigated several scenarios for separate and joint production of ethanol and methane, by utilising autumn harvested dry hemp as the biomass to estimate and compare the energy outputs per unit of hemp biomass used. In particular, ethanol was produced from hexoses derived from pre-treated hemp stems through 'Simultaneous Saccharification and Fermentation' (SSF).

Methane was produced using different biomass types for the different scenarios considered, namely: crushed leaves; chopped stems; ground stems; steam pre-treated stems; pre-hydrolysed steam pre-treated stems; and residues from the ethanol production line.

The Kreuger et al, documented that steam pre-treatment resulted in a higher methane production than mechanical grinding. Additionally, they found that co-production of methane and ethanol from hemp when the latter is first subjected to a steam treatment doubled the energy yields compared to that obtained when ethanol was produced from hexoses alone.

Following this research path, **Barta et al. (2013)** analysed energy and techno-economic issues in three macro-scenarios focussed on co-production, for district application purposes, of: biogas and CHP (for two of the scenarios); and ethanol, biogas, and CHP (for the third scenario).

The scenarios were implemented based upon a cascade, system's efficiency optimisation approach, that included:

1. AD of chopped hemp alone;
2. Steam pre-treatment of chopped hemp that produced a slurry to be treated in AD, with subsequent upgrading of the output biogas and conversion of the solid fraction of the AD output effluent into CHP;
3. Chopped-hemp, steam pre-treated to develop a slurry, with the solid fraction used for SSF for production of broth for fermentation into ethanol and then distilled and dehydrate.

Anaerobic digestion was integral to the third scenario to treat the volatiles from the flash steam treatment, the liquid slurry, and the stillage from the combined distillation and dehydration phase. Similar to the two previous scenarios, both biogas and CHP were produced. The authors documented that the energy yielded by the biogas, ethanol, heat and CHP, was lower than the energy input associated with the scenarios analysed. The authors concluded that none of the scenarios were economically viable, since the biogas selling price was not high enough to generate a net economic benefit.

Although, the costs for ethanol production were higher than for biogas production, that was compensated by the relatively higher market price of ethanol. The authors found that the highest cost aspect was the production and supply of the hemp biomass feedstock, but the authors highlighted the uncertainty because at the time of that study, hemp was cultivated for purposes other than for energy uses.

As a future dimension for research, Barta et al. (2013) emphasised the need for utilisation of feedstock biomasses that are cheaper than hemp as a potential solution to give higher outputs of ethanol and biogas, or primarily combined production with higher value products, in a cascade approach. However, considering the uncertainty in hemp prices, according to Barta, et al. (2013), it would be valuable to repeat the study under conditions of increased interest in energy application of hemp and to document the changes in economic results.

In a study in Latvia by **Balodis et al. (2011)** compared biomass yields of different plant-species for methane production. Hemp produced an average DM yield of 12.63 tons per ha, which was competitive with traditional energy crops like maize, sunflower and rape.

The range of MEY was 122 to 111 GJ/ha, with an average of 116.5 GJ/ha. Those values referred to September-October harvests which, in agreement with studies previously reviewed in this paper, show that hemp biomass can be profitably used as an AD feedstock.

Those values were lower than the 136±24 GJ/ha, obtained by Kreuger et al. (2011a): this could be attributed to different soil and climate conditions (Sweden vs. Latvia) as well as to different cultivation practices and harvesting time.

This study and others documented that IH is a high biomass yielding crop for production of biogas and biofuels. The authors highlighted that biomass yields differed according to the variety. The varietal yield differences ranged from 10.70 t/ha from the variety *'Benico'*, to 14.20 t/ha form the variety *'Futura75'*.

In another study, **Pakarinen et al. (2011)** investigated the suitability of the fibrous parts of autumn-harvested, chopped IH for biogas production, in comparison with maize and fava bean. They found that all three crops provided good biomass yields, with maize producing the highest quantity (15 t_{DM}/ha), followed by hemp (14 t_{DM}/ha) and fava (10 t_{DM}/ha).

With regard to MEYs, hemp was highly competitive to the other crops (maize, in particular) with a 108GJ/ha value, while IH yielded as much as 137 GJ/ha when it was milled into fine particles.

Authors of the reviewed articles found that energy crops are often compared in terms of resource-efficiency related issues, like arable land usage, environmental impact of the whole supply chain, the energy and economic efficiency of the solid, liquid and gaseous energy carriers (Börjesson and Tufvesson, 2011; Prade et al., 2012).

However, the energy balances were often overlooked, but they can be calculated by subtracting the direct and indirect energy inputs of cultivation, harvest, transport and energy conversion data (Prade et al., 2012).

In this context, **Prade et al. (2012)** compared energy balances of four scenarios based upon different pathways for harvest timing and utilisation of hemp biomass. In accordance with published findings, those pathways were the following: hemp harvested in autumn, thereby, producing green (fresh) biomass for usage as feedstock to biogas production; and dry biomass obtained from spring-harvested IH for production of different forms of solid fuels (Prade et al., 2012). Accordingly, the following scenarios were considered by the authors:

a. Combined Heat and Power (CHP) from spring-harvested hemp in the form of bales;
b. Heat from spring harvested hemp as briquettes and bales; and
c. Both CHP and vehicle fuel from autumn-harvested, chopped ensiled IH biomass as feedstock in AD plants.

The researchers highlighted that alternative routes for usage of IH for energy production can be followed, and that differences among the scenarios were related to conversion efficiency, energy output and Net Energy Yield (NEY).

Scenarios providing CHP from dry hemp bales had the greatest NEY (approximately 100 GJ/ha), compared to other dry hemp biomass utilisation options such as heat production from briquettes and bales. The whole chain, based on generation of biogas from AD of green biomass and utilisation of it to produce CHP, was found to have the lowest conversion efficiency and the lowest NEY.

In contrast, the highest biomass yield and the highest NEY was from the fresh biomass (harvested in autumn) with 10.2 t_{DM}/ha that yielded 200-250 GJ/ha., which was in agreement with previous findings.

The researchers found that the biogas-derived CHP option performed worst due to demands for higher energy inputs and having lower conversion efficiencies.

Prade et al. (2012) concluded that, overall, hemp produced high quantities of biomass DM and good NEY/ha. They found that IH provided good energy output-to-input ratios, which significantly contributed to making it an above-average energy crop.

Based upon these findings, the authors of this literature review concluded that hemp can compete effectively with most of the common energy crops, in a number of applications.

Industrial hemp is a reliable alternative when energy crops like maize cannot be cultivated economically or when annual crops are preferable. According to Kreuger et al. (2011b) and Ingrao et al. (2015), its use as a predecessor in crop rotation systems and its minimal pesticide requirements help to make IH a valuable crop in organic farming.

The AD methane productivity is reduced as if inadequate proportions and quantities of nitrogen, phosphorus and sulphur, are present in the biomass being fermented (Hinken et al., 2008; Pobeheim et al., 2010; Nges et al., 2012).

In addition to this, the carbon-nitrogen (C:N) ratio is an important parameter for optimal management of AD-based supply chains: A C:N ratio in the range of 16-20 was recommended for the stability of the AD process (Mshandete et al., 2004; Álvarez et al., 2010; Nges et al., 2012).

Such conditions can be achieved by treating a properly-designed mix of substrates, as indicated by **Nges et al. (2012)**, who investigated the benefits of co-digestion of waste biomasses and energy crops. For this purpose, Nges et al. (2012) based their assessment upon a full-scale Swedish AD plant, where there was intense competition for waste biomass streams suitable for AD. In particular, they documented benefits from adding energy crops like maize, hemp and triticale to a base feedstock comprised of pig and poultry manure along with waste from slaughterhouses and food processing activities. Those benefits were related to the possibility of using existing infrastructure, better efficiency, increased biodegradation, dilution of inhibitory compounds, improved nutrient balance, and increased biogas production (Nges et al., 2012).

Nges et al. (2012) documented that co-digestion of those biomasses improved the C:N ratio and reduced the free-ammonia content, which resulted in improved process performance and stability of the AD.

Co-digestion of energy crops with waste biomass streams were documented to help to eliminate the need to add micronutrients normally required when energy crops were digested alone. Furthermore, addition of those energy crops to the basic feedstock (only consisting of industrial waste made of pig manure, slaughterhouse waste, food processing and poultry waste) resulted in generating a 30% increase in methane yield (Nges et al., 2012).

The authors of this paper emphasise that it is important, on one side that energy crops have multiple positive effects for the successful operation of AD plants and on the other side, their production implies use of land otherwise used to produce food or feed, thereby competing for land needed to produce human food and animal feed vs energy and biofuels. Therefore, it is important to investigate the consequences and impacts of the trade-offs such as:

a. Limiting the amount of energy crops produced in a region;
b. Producing food on high quality land using best organic agricultural practices and using some of the straw and other organic materials from agriculture in the AD-based systems;
c. Replacing energy crops with second and third generation biomass crops, especially when planted on land that is marginal for agricultural production. Thereby, there can be improvements in land use efficiency, which should help to minimise the negative indirect land use changes due to increased land devoted to production of energy crops (Gissén et al., 2014).
d. Additionally, energy crop cultivation in combination with utilisation of agricultural residues was suggested by Pakarinen et al. (2011) as useful for providing new opportunities for sustainable growth and for positively influencing the global market for agricultural and energy products.

Similarly, **Böske et al. (2014)** focussed upon different feedstock mixtures obtained by adding animal bedding materials, such as wheat straw, spruce wood chips, hemp and flax, to a base substrate characterised by Hay Horse Manure (HHM) or Silage Horse Manure (SHM).

Those materials were added to cover an average of 50% of the dung-based feedstock, with different organic loading rates based upon a VS-related ratio ranging from 1.6:1 to 2.8:1 (bedding material to dung).

The study was conducted at the lab scale using an Upflow Anaerobic Solid-State (UASS) reactor equipped with liquor recirculation, to compare a single-stage with a two-stage UASS system integrated with an anaerobic filter; and to determine the Biochemical Methane Potential (BMP) of those mixtures.

The authors documented that horse manure digestion by a mesophilic UASS process is a good way to perform AD on that organic residue. When adding alternative bedding materials to that basic feedstock, wheat straw was found to generate the highest BMP (230 $L_{methane}/kg_{VS}$). Hemp showed a BMP equal to 168 $L_{methane}/kg_{VS}$ and was found to be competitive with other feedstocks. It was documented to produce more methane than flax and far more methane than spruce wood chips.

Böske et al. (2014) confirmed that the organic loading rate influences the solid retention time, and is a key factor for process performance, whereas, the anaerobic digestion filter did not provide a significant advantage.

Böske et. al. (2014) highlighted the benefit of using thermophilic instead of mesophilic temperatures and optimisation of the retention times, independently of the organic loading rates. They found that with mesophilic temperatures 58.1% of methane was produced, but 59.8% was produced using thermophilic temperatures (Böske et al., 2014). In addition to this, in line with their previous study (Böske et al.,2014), by expanding BMP tests to two types of horse manure and four different bedding materials, they found the combination of manure+wheat straw to be the one with the highest BMP. In the light of the above, they concluded that thermophilic UASS process can be key for efficient energy recovery from straw-based manures.

Adamovičs et al. (2014) investigated the feasibility of using IH in Latvia for production of biogas to be used in CHP or as methane for other purposes. They evaluated ten IH varieties in two trial years (2011, 2012), including *'Futura 75*' and *'Uso 31'*, which were tested by the authors for application in AD installations. '*Future 75'* was documented to produce 21.27 t_{DM}/ha while '*Uso 31*' produced 15.01 t_{DM}/h.

Hemp varieties varied in productivity due to varietal differences and due to differences in the soil, climatic conditions, cultivation practices and NPK fertiliser usage. Average yields were found to be 12.63 t_{DM}/ha in the study by Balodis et al. (2011) and 17.62 t_{DM}/ha in the study by Adamovičs et al. (2014).

Adamovičs et al. (2014) documented that all investigated IH varieties (i.e., *'Bialobrzeskie'*, *'Futura 75'*, *'Fedora 17'*, *'Santhica 27'*, *'Beniko'*, *'Ferimon'*, *'Epsilon 68'*, *'Tygra'*, *'Wojko'*, and *'Uso 31'*) are suitable for biogas production, but that '*Futura75*' was the best performing variety among those tested.,

In agreement with Pakarinen et als' (2011) findings, Adamovičs et al. (2014) documented that both the biomass and the biogas yields are affected by particle size. Methane yield from *'Futura 75'* was reported by Adamovičs et al. (2014) to be equal to 50.92% in the first case (fine size), and 48.11% in the second case (coarse size).

Methane yield was documented to be approximately 50% by Adamovičs et al. (2014) that was in agreement with the findings of Böske et al. (2014).

By using those percentages to the biogas yield values calculated by Adamovičs et al. (2014), and multiplying them by the HHV of methane and by the average dry biomass yield, the MEY was calculated to be: 208.09 GJ/ha (finely ground IH) vs. 148.15 GJ/ha (coarsely ground IH).

Adamovičs et al. (2014) documented that leaves of IH in the *'Uso 31'* variety, are valuable parts of the hemp plant that are most suited for treatment in AD plants, because leaves contain less cellulose and lignin and have more juice than the stems (Adamovičs et al., 2014).

Biogas yields from leaves averaged 0.586 L_{biogas}/gDM, with a 62.28% methane content: MEY was equal to 214.36 GJ/ha. However, to make it profitable at the industrial scale, proper mechanisation and processing systems must be developed and tested, to compare methane yields of foliar and stems separately. That would help to enhance potential interest in IH as a crop, to provide multiple products such as: food production (seeds); buildings (fibres and hurds); and biogas-derived energy (leaves). This could reduce competition for land-use for energy crops and for food and feed crops. This could help to reduce the net environmental impacts from production of IH.

'Futura 75' was the hemp variety used by **Gissén et al. (2014)** in their study designed to compare life cycle inventory data of supply chains of crops for usage as milled feedstock for biogas-derived energy systems in southern Sweden. Autumn-harvested hemp was compared with sugar beet, maize, triticale, winter wheat, and ley. The cultivars of each crop were selected with the focus of high biomass yields rather than on the quality of foods and feeds; they were '*Test type*', '*Arabica*', *'Tulus'*, '*Mixing'*, and '*Opus*', respectively. For that research, a sugar beet cultivar with low sugar content and high biomass production was tested by Gissén's team for biogas production from the whole plant (beet and tops). The ley was a mix developed at the experimental farm, and consisted of 25% white and red clover, 50% hybrid ryegrass, and the remainder was a mixture of two ryegrasses (Gissén et al., 2014).

All of those crops were chosen with the objective of achieving sustainable cultivation for energy generation purposes through adoption of well-planned crop rotation systems to minimise energy inputs and to optimise land use efficiency.

Biomass yields of IH, in the period 2007-2010, were found by Gissén et al. (2014) to range between 6.6 and 7.7 t_{DM}/ha (giving an average of 7.15 t_{DM}/ha) which was lower than previously published values, and lower than the other crops investigated by them.

In particular, the highest yielding crop was found to be sugar beet followed by triticale, with average values of 21.8 t_{DM}/ha and 15.7 t_{DM}/ha.(Gissén et al. (2014). Similar to hemp, maize showed lower productivity than the regional averages with values between 9-15 t_{DM}/ha. Ley showed biomass yields that averaged 9 t_{DM}/ha, while winter wheat's values ranged 6.2-7.7 t_{DM}/ha and averaged 6.95 tDM/ha, which were comparable to data recorded by Gissén et al. (2014) in the case of hemp.

Gissén et al. (2014) concluded that IH, although generally regarded as a reliable producer of biomass, was not found, in their research, to be as good a biomass producer as expected.

Energy output expressed as MEY was found by Gissén et al. (2014) to be nearly 75 GJ/ha for hemp, which was just slightly under half the MEY of the whole sugar beet (160 GJ/ha; the methane yield from maize was found to be close to 100 GJ/ha. Triticale and wheat grain had comparable values in the range 85-90 GJ/ha, while a l value of (80 GJ/ha) was document for ley.

The overall energy input associated with the IH supply chain (cultivation and harvesting, storage, and transport) was 14.6 GJ/ha, with cultivation and harvesting contributing approximately 70% of that input (Gissén et al., 2014). However, by allocating the energy inputs of fertilisers, diesel and machinery, Gissén et al. (2014) found fertilisers contributing 48% of the input costs, thereby, explaining why hemp had the highest feedstock costs (21.9 €/$GJ_{methane}$) among the crops investigated by the authors, which similar to the findings of Barta et al. (2013).

Similarly, **Plöchl et al. (2009)** assessed the environmental impacts associated with the supply chains of crops usable in AD for biogas production, by focussing upon energy balance and GHG emissions. The energy balance was expressed through the Cumulative Energy Demand (CED) indicator, while the Carbon Footprint (CF) was calculated for computation of GHG-emissions in a 100-year temporal horizon (expressed as kg CO_2 eq). The authors considered a set of biogas crop silages, including maize and hemp, the cultivation of which was conducted through application of different N-fertiliser amounts (0, 75, and 150 kg N/ha).

The authors found that hemp biomass yields decreased from 10.7 to 8.8 t_{DM}/ha when the amount of applied N-fertiliser was reduced from 150 kg/ha to 0, with an intermediate value of 10 t_{DM}/ha in case of a 75kg/ha of fertilizer applied. Thus, increased DM/ha resulted from increases in quantities of fertiliser, at least within this range of 0 to 150 kg/ha/year. This finding is in agreement with the findings of Prade et al. (2011), Adamovičs et al. (2014), and Gissén et al. (2014). However, other conditions like soil type, the timing and quantity of precipitation and other factors also play crucial roles.

Additionally, from a methane yield perspective, hemp produced about 50% as much methane as maize silage: 0.207 vs. 0.406 $m^3_{methane}/kg_{DM}$. By elaborating those values using methane HHV (39.13 MJ/ $m^3_{methane}$) and the DM hemp yield (as average of the values associated with the three different fertilisation regimes), the MEY was calculated in both cases, and resulted in: 79.62 GJ/ha (hemp) vs. 138.21 GJ/ha (maize). The MEY results of hemp were similar to those reported by Gissén et al. (2014), who found a value of 80 GJ/ha.

As the main result of their study, Plöchl et al. (2009) documented that the hemp supply chain is one of the most energy demanding chains, especially in case of application of the highest N-fertiliser rates.

Additionally, Plöchl et al. (2009) found that, reduced N-fertilisation rates reduces biomass and methane-energy yield but, it significantly reduces the CED and CF, thus highlighting the importance of trade-offs. They found a decrease: of CED, from 12 GJ/ha to slightly more than 4 GJ/ha; and of CF, from around 1.4 to 0.3 t CO_2 eq.

Energy production results were similar to those obtained by Gissén et al. (2014), who documented that energy input for producing hemp were reduced by 40%, from 14.6 to 8.76 GJ/ha, when fertiliser was partly replaced with digestate.

Results from Kreuger et al. (2011b) and Adamovičs et al. (2014) in terms of lignin content influencing biogas and methane yield, agreed with findings of **Schroyen et al. (2015)** who investigated the effects of enzymatic pre-treatments using laccase and peroxidase on diverse plant biomasses. The authors determined the relations between lignin content and bio-methane production. They found that crops such as miscanthus and willow, which contain high lignin contents, usually result in low MEYs (8.8–141.7 L/kg$_{VS}$).

In contrast, biomass such as corn stalks, wheat straw, hemp straw, and flax straw had higher MEYs (241 and 288 L/kg$_{VS}$), as the consequence of lower lignin content. In this regard, Schroyen et al. (2015) reported lignin content IH to be 92 g/kg$_{FM}$, while methane yield ranged between 184-248 L/kg$_{VS}$, depending upon whether samples were or were not enzymatically pre-treated for 6 and 24 h.

Schroyen et al. (2017) documented the effects of different concentrations (up to 2000 mg/L) of a series of selected phenolic compounds on the activity of lignin degrading enzymes like laccase and peroxidase, and how they affect biogas production in AD. They confirmed that phenolic compounds, especially if in high concentrations, are toxic for the bacteria performing the AD, thus inhibiting the AD processes. For example, they found that by increasing the phenolic concentration from 100 to 2000 mg/L, an increased inhibition of production of methane resulted. In agreement with those findings, Schroyen et al. (2017) found that IH produced more methane than miscanthus, mainly due to its lower lignin content: 92 vs. 120 g/kg$_{FM}$ (Schroyen et al., 2015, 2017): additionally, a decrease in biogas was observed in samples with a 2000mg/L concentration of phenolic compounds (Schroyen et al., 2017). During the AD, the composition of biogas was measured three times (after 11, 21 and 30 days): no differences in methane yield were observed. According to Schroyen et. al. (2017), this indicates that the phenolic compounds have an impact on the amount of biogas produced.

Furthermore, to measure the detoxifying potential of laccase enzymes, biogas production associated with biomass samples (IH vs. miscanthus) supplemented with different phenolic-compound concentrations was measured with and without addition of those enzymes.

The research confirmed the detoxification effects of the enzymes, as they removed almost 80% of the added phenolic compounds, thereby, documenting the benefits of their usage in incubation treatments to remove the toxic effects of the phenolic compounds.

Overall, the impact on the total biogas production over 30 days of testing was not significant, as the microbial community adapted to the new environment and overcame the initial phenolic compound-based inhibition (Schroyen et al., 2017). Both Schroyen et al. (2015) and Schroyen et al. (2017) highlighted the importance of optimising enzymatic pre-treatments to have a greater impact on the lignin degradation and on increasing the methane generation by better fulfilling the needed substrate features of the substrate such as the lignin concentration, which has a large negative impact on methane yield, that is dependent upon the types and quantities of phenolic compounds released (Schroyen et al., 2015). In this regard, Schroyen et al. (2015) suggested to break down the lignin barrier and diminish the lignin concentration, to improve BMP and related production rate. Schroyen et al. (2015) state that enzymatic pre-treatment can help to degrade the matrix, but they suggest to optimise it as much as possible to have greater, positive impacts on lignin degradation and BMP.

Schroyen et al. (2018) developed an AD model where those and related issues were addressed by treating a set of seven different biomass substrates.

They found that ensilaged maize is the substrate with the highest BMP values (413.9 L/kg$_{VS}$) while a value of 237.8 L/kg$_{VS}$ was found for IH and so was between wheat straw (247.1 L/kg$_{VS}$) and flax straw

(233.1 L/kg$_{VS}$), with corn stove exhibiting a good performance which was estimated by the authors in 242.4 L/kg$_{VS}$.

In contrast, miscanthus exhibited a lower BMP (144.5 L/kg$_{VS}$), mainly due to the higher inhibition in AD compared to IH. The model showed that a good prediction of BMP can be achieved without excessive characterisation of the substrate, as only the lignin content is crucial. Therefore, it is essential that the lignin content is considered in the implementation, testing and analysis of AD systems.

4. Discussion of findings from the scientific articles reviewed

This section is dedicated to reporting the main information derived from the selected papers, though it should be underscored that just AD-plants related results were extrapolated from those papers, to be consistent with the objective of this literature review (Table 1).

From Table 1, the authors of this literature review found that most of the authors focussed upon IH biomass as the sole feedstock, in comparison with other energy crop biomasses, like maize, sugar beet, and wheat.

Overall, the authors of the studies reviewed highlighted that IH is a slender and annual herbaceous crop producing biogas-yielding biomass competitively with energy crops but, on average, with a lower environmental impact. This is mainly because, as Barta et al. (2013) stated, it presents several advantages over those crops like the possibility of being cultivated with relatively low quantities of nitrogen and no pesticides. However, with regard to this point, it is worth underscoring that Plöchl et al. (2009) highlighted IH biomass yield as decreasing with the decrease in N-fertiliser application, thereby emphasising upon the need to find viable, sustainable trade-offs between production rates and application demands. Another advantage was highlighted by Kreuger et al. (2011b) and Prade et al. (2012) and is about IH being characterised by a low susceptibility to pests and diseases, which makes it a suitable candidate in rotation with food and feed crops, especially under organic farming conditions. In addition to this, increased IH cultivation was documented as enhancing bio-diversity of crops and thus, can help to develop integrated bio-economies, in which ecosystem services other than feedstock supply are important (Barta et al., 2013). This agrees with findings from Troiano et al. (2019) who underscored the need to focus upon the multifunctional roles of agriculture and horticulture for helping to ensure provision of a broad array of valuable services, such as: landscape maintenance; soil conservation; sustainable management of renewable environmental resources; preservation of biodiversity; and contributions to rural, socio-economic development. In this regard, another important advantage was emphasised by Burczyk et al. (2008) and Kumar et al. (2017) and regards IH helping to remediate soils contaminated by heavy metals, while delivering the biomass products reported above. This is because it acts as a phyto-remedial agent that extracts and accumulates large amounts of heavy metals, like cadmium, lead, copper, and mercury, thereby, helping to restore agricultural productivity of those soils and reducing the negative impacts of the heavy metals in the animal and human food chain.

Among the studies reviewed, Nges's et al. (2012) and Böske's et al. (2014) were the only authors who addressed relevant issues associated with co-digestion of a waste-biomass feedstock with alternative bedding materials or energy crops. Most of the studies focussed upon AD as the sole treatment for IH biomass, both in lab- and industrial-scale conditions, while Kreuger et al. (2011b) and Barta et al. (2013) investigated and compared complex systems thereby, providing an intermediate step of AD, to highlight the benefits of: steam pre-treatment of the biomass; co-production of methane and ethanol, and biogas, ethanol and electricity and heat; and recycling of the liquid fraction within the AD plant.

Yield values were found as to be affected by soil and climate conditions of the area where the hemp was grown. The N-fertilisation rates, harvesting time, varieties and parts (i.e. stalks, or leaves) of hemp plants that are treated, and both technological and operational issues related to the AD systems were important variables, which influenced methane yields from the AD processing of IH.

The harvesting time influences the DM and VS content which Kreuger et al. (2011a) documented as varying from 20.33%$_{FM}$ to 33.07%$_{FM}$ and from 89.36%$_{DM}$ to 94%$_{DM}$ with a growing tendency from July to October. Based upon selected articles, the following yield ranges were obtained: biomass yield (6.6-21.27 t_{DM}/ha); biomass energy yield (200-300 GJ/ha); and methane energy yield (79.32-214.36 GJ/ha).

In agreement with findings reported by Ingrao et al. (2018a), other factors influenced IH's methane yields, such as the design of the AD plant, according to which not only the feedstock was prepared but, also, the treatment technology was chosen and combined with up- and down-stream treatments. In this regard, CHP production is clearly affected by the type of cogeneration systems used and their energy efficiencies. In this regard, Prade et al. (2012) indicated that approximately 90 TJ of biogas is combusted in a CHP plant/yr., with a total annual production of 30 TJ_e and 40 TJ_t, with the remaining 20TJ being waste as the consequence of the cogeneration plant inefficiency.

Other studies including biogas utilisation in the hemp supply chain investigated were those from:

- Kreuger et al. (2011b), who documented that co-production of ethanol and methane from steam pre-treated hemp stems is capable of providing more than twice the energy yield of transportation fuel than ethanol production from hexoses alone, mainly because of the enzymes and yeast added during ethanol production, to convert the ethanol to methane; and
- Barta et al. (2013), who highlighted production prices of methane and ethanol from hemp influencing the process economics more than those of electricity and district heat, and so suggested that the use of cheaper and higher yielding feedstocks or the combined production of higher value products together with ethanol and biogas to better amortise the costs.

All the remaining studies were focussed upon the AD processes and provided characterisation and testing (both at the lab- and industrial-scale) of hemp biomass, under different farming and harvesting conditions, to contribute to enhancement of the knowledge on its suitability as an AD feedstock. Schroyen et al. (2015, 2017, 2018) went further by investigating the inhibitory effects of various phenolic compounds on AD of hemp straw, and on the detoxification effects that can be obtained by providing a pre-treatment based upon application of veratryl alcohol and laccase enzyme. As the final step of their research, they created an AD model to account for and to build upon those and related issues.

Table 1

The selected papers are listed based upon a set of aspects related to research conducted, AD-based system investigated, yields, and main findings. Furthermore, further clarifications on those papers were given to integrate what was discussed in section 3 of this paper.

Team of authors	Brief description of the research conducted	Study area	Feedstock	Information on the AD-based system considered			Information on yields calculated by the authors and related to hemp AD systems. Values were extrapolated from the paper and were related just to IH treatment.			Overall description of findings from the given study, and/or additional clarification comments as needed to integrate what already discussed in section 3.
				AD alone	AD, as part of a more complex system	Comparison among treatment scenarios and/or biomasses	DM yield (t/ha)	Energy content in the biomass (BEY, NEY) – GJ/ha	MEY (GJ/ha)	
2009										
Plöchl et al.	The study is focussed upon assessment of the environmental impact associated with an AD-based supply chain	Germany	Hemp	X	n. a.	X Comparison with other energy crops like winter rye and winter barley, triticale, and maize	8.8-10.7		79.62 (*)	(*) That value was elaborated from a methane yield of 0.207 m^3/kg$_{DM}$, calculated by the authors. The authors documented a 20% decrease when upscaling results (0.259 m^3/kg$_{DM}$) from the lab-scale experiment.
2011										
Prade et al.	Estimation of hemp energy yield, as cultivated for energy purpose under cold climate conditions in Northern Europe and with different amounts of fertiliser applied.	Sweden	Hemp	X	n. a	n. a	14.4	296	n. a.	Two harvesting times were considered based whether hemp is utilised for production of biogas or solid biofuel. A three-year cultivation campaign was considered by the authors. Values alongside are averages of those obtained by the authors from conducted analyses.

										Through their study, the authors documented that BEY of hemp was similar to that of maize and sugar beet and 24 and 14% greater than that of lucerne and clover-grass ley.
Kreuger et al. (a)	The MEY from IH AD was determined in this study at four harvest times (in the period July – October) through the biochemical BMP test, starting from computation of the biomass yield.	Sweden	Hemp	X	n. a	n. a	15.6 (±1.5)	286 (±27)	136 (±24)	Those alongside are average values related to harvesting as carried out in the period September-October, and can be considered as the highest obtainable ones. Based upon results from their study, the authors found no significant differences in specific methane yield, based upon the harvest time: the average value found was equal to 234±35 m^3/t$_{VS.}$
Kreuger et al. (b)	Several scenarios for ethanol production, methane production and co-production of this, using autumn-harvested dry hemp biomass were investigated and compared in this study in terms of gross energy input, also to highlight benefits from potential steam pre-treatment.	Sweden	Hemp	n. a	X	X	16	n. a	n. a	Co-production of ethanol and methane from steam pre-treated stems gave a high yield of transportation fuel, 11.1–11.7 MJ/kg processed stem dry matter (DM); more than twice that of ethanol production alone from hexoses, 4.4–5.1 MJ/kg processed stem DM. Co-production from the whole hemp plant would give 2600–3000L ethanol and 2800–2900 m^3 methane. In total, 171–180 GJ would be obtained per 10,000 m^2 of agricultural land, based on a biomass yield of 16 t$_{DM}$
Balodis et al.	The research was conducted to test the comparative biogas	Latvia	Hemp	X	n. a	X	10.70-14.20 (average: 12.63)	n. a.	111-122 (average)	The comparative biomass-yield of the eight IH varieties considered. The two different values for MEY are related to different harvest

	yields of eight IH varieties.					Comparison with amaranth, sunflower, millets, hemp, rape and maize				times: October, and September, respectively.
Pakarinen et al.	Assessment of the suitability of diverse annual plant species as dedicated biomass crops for biogas and ethanol production.	Finland	Hemp	X	n. a	X Comparison with maize and fava bean	15	n. a.	108 -137	The types of biomasses were tested in the digester separately and the results were compared. Differences in MEY values were attributed to whether hemp was chopped finely or coursely.
2012										
Prade et al.	The researchers compared NEYs and energy output-to-input ratios for production of heat, electricity, CHP and transportation fuel from IH biomass, under different scenarios.	Sweden	Hemp	X	n. a.	X	10.2	200-250	83.42 (**)	(**) This value was not directly included in the paper of Prade et al. (2012). However, it was calculated based upon the specific methane yield (0.22 m^3/kg_{VS}) and VS content that, were reported in the paper. The methane HHV was used for computation. Finally, with regard to the energy input-to-output ratio, the authors documented that the scenario for production of biogas from AD for subsequent conversion into CHP or into vehicle fuel produced some of the lowest ratios. This was attributed to high energy inputs and rather low conversion efficiencies.
Nges et al.	The authors studied the feasibility of supplementing a protein/lipid-rich industrial waste mesophilic anaerobic digester with	Sweden	Pig and poultry manure along with waste from slaughterhouses and food processing activities co-	X	n. a.	X Comparison with other energy crops such as maize and triticale	n. a.	n. a.	n. a.	The study was conducted in laboratory scale batch and continuous stirred tank reactors (CSTR) with the plan to scale-up to commercial biogas process. The authors documented that, by adding energy crops to existing

	carbohydrate-rich energy crops		digested with alternative energy crops (i.e. maize, hemp, and triticale).							industrial waste supplements in AD, both methane yield and methane energy production increased significantly, from 46 to 59 Nm^3/t_{WW} and from 26 to 47 GWh/y. The authors reported that, considering that the economy of crop-based biogas production is limited under Swedish conditions, their approach could be a viable alternative for ensuring constant/reliable supplies of feedstock to AD plants.
2013										
Barta et al.	The researchers integrated the results of Kreuger's et al. (2011b) and Prade et al. (2012) with an additional economic analysis of heat demand, energy efficiency, and process economics in terms of annual cash flows and minimum selling prices for biogas and methane	Sweden	Hemp	n. a	X	X	10.2 (***)	n. a.	n. a.	The researchers documented that none of the technological processes considered is economically viable, because the energy output 60-84% of the energy input. (***) as of Prade et al. (2012)
2014										
Böske et al.	The study was performed at lab scale, to investigate the use of up-flow anaerobic solid-state digestion	Germany	Horse manure co-digested with alternative bedding materials.	X	n. a.	X	n. a.	n. a.	n. a.	The researchers found that the highest methane yields were obtained when wheat straw was added to the basic feedstock, with values equal to an average of nearly 230 $L_{methane}/kg_{VS}$.

						Comparison with alternative solutions of bedding materials, like wheat and hemp straw				Hemp was confirmed to be a competitive alternative when biomasses like wheat straw were not available. Hemp methane yield about 168 $L_{methane}/kg_{VS}$
Adamovičs et al.	The authors reported on research to test the suitability of different IH varieties for biogas production	Latvia	Hemp	X	n. a.	n. a.	14.55-21.27	n. a.	a) 148.15-208.09 b) 214.36	The range of biomass yields was varied among the hemp varieties investigated. Each value was provided as the average of the cultivation period (2011-2012). With regard to methane yield, values at point a) refer to values obtained from '*Futura 75*', whether the biomass is milled coarsely or finely. While, the values at point b) refers to chopped leaves from '*Uso 31*'.
Gissén et al.	Presented new and dedicated life cycle inventory data for production and supply of biogas crops.	Sweden	Hemp	X	n. a.	X Compared to other crops like maize and sugar beet	6.6-7.7	n. a.	80	The authors calculated that the feedstock costs were so high that they were not profitability for biogas production based solely upon ensiled crops, due to the light of the Swedish biogas selling price. This is in line with Barta et al. (2013) who, in fact, recommended other solutions like maximisation of output yields in a cascade-based system.
2015										
Schroyen et al.	In this paper, the authors studied the effect of an enzymatic pre-treatment on	Belgium	Hemp	X	n. a.	X	n. a.	n. a.	n. a.	As specified by the authors in their paper, the enzymes utilised were laccase and versatile peroxidase, as derived from *Trametes*

	biomass samples from a set of plant species.					Compared to other crops like maize and sugar beet				*versicolor* and *Bjerkandera adusta.* Methane yield was found by the authors in the range 184.1 – 248 L/kg$_{VS}$.
2017										
Schroyen et al.	The inhibiting effect of various phenolic compounds on AD of hemp straw and miscanthus, and the related mitigation solutions, were studied by the authors.	Belgium	Hemp	X	n. a.	X Comparison to miscanthus	n. a.	n. a.	n. a.	To integrate what has already been discussed in section 3 on this paper, the authors found that, per each phenolic compound concentration chosen (0-2000 mg/L), enzyme-treated hemp performs better than the untreated one, in terms of methane yield. In particular, the highest yield was found in untreated samples with no phenolic-compound addition. Highly comparable yield values (in the around of 12 L/kg$_{VS}$/d) were found for treated samples at both 0 and 500mg/L concentration. The major detoxifying effect through enzyme treatment was exhibited at a 2000 mg/L addition rate. However, a decrease in methane yield was recorded by the authors for both untreated and treated samples going from 0 to 2000 mg/L concentrations of phenolic compounds. Overall, methane yield was in the range 9-12 L/kg$_{VS}$/d.
2018										

Schroyen et al.	In this study, an anaerobic digestion model was developed to duly take into account.	Belgium	Hemp	X	n. a.	x Comparison to other crops including ensilaged maize, flax straw, and miscanthus	n. a.	n. a.	n. a.	The biomethane production and hydrolysis rate of seven different substrates were described and simulated by the authors. The study highlighted the important role that is covered by the hydrolysis rate and the need to explore factors like inhibitors and substrate types that influence that hydrolysis step.

n.a. stands for ‘*no applicable*’. With regard to yield information, it should be intended as ‘*not specified in the paper*’.

5. Conclusions, challenges and future prospects

This literature review achieved the author team’s goals to develop an overview that highlighted the technological, energy, and environmental issues of IH AD-based systems, by summarising the knowledge in the field. Some relevant research has been developed thus far in this content area but, according to the authors, a lot more is expected in the future to address and build upon potentials for improvement and innovation.

The study was focussed upon AD of IH: because AD is accepted as the primary technology to derive energy and nutrients from biomass; and because hemp was documented to be a versatile crop for a wide range of applications. Hence, the authors' interest to explore its application as fresh biomass for biogas production in AD plants.

Based upon the findings of the review conducted, AD of IH biomass emerged to be a promising, effective technology for production of renewable energy sources, with yields that were highly competitive in comparison with those of the commonly-used energy crops.

In addition, this review contributed to the understanding of the diversity of the methane yielding parts of the IH plants, with fresh leaves yielding the highest quantities per unit DM. Appropriate harvesting methods to obtain the leaves are needed to take advantage of that valuable part of the IH, which is currently seen and treated as a residual biomass from IH cultivation and harvesting. Such a methodological improvement could make it possible to produce biogas energy without competing with the production of foods and feeds, as well as with other important applications for the greening of downstream sectors where the remaining parts of the hemp plant can be utilised.

By doing so, in line with the principles of a circular bio-economy, the leaves would be treated to capture their greater methane production value, compared to the current practices. IH production can be done on marginal land and therefore, it does not compete for land for food-and-feed. According to the authors, this is one great finding of the review study conducted, as it can really contribute to filling the existing gap in the current knowledge on IH plant and on the application paths that each composing part of it can follow, thereby stimulating further research in the field. It would be desirable, however, that land usage practices were organised to best meet the demands of producing foods, feeds, materials and energy commodities, while protecting ecosystems to sustainably provide dynamic services for the long-term future.

According to the authors of this review, such multi-functional systems can be achieved by setting priorities in land usage and, in doing so, tools like Life Cycle Assessment (LCA) and Life Cycle Sustainability Assessment (LCSA) and other tools can be used to help to ensure that those priorities are identified and implemented in responsible, equitable, and sustainable ways for the short and long-term future.

Other challenges are connected with farming practices, like fibres wrapping around moving parts in the combine harvesting, or seeds cracking during drying after harvesting. So, it is important to identify the optimal use of those practices to preserve the functions that IH was planted to accomplish: for instance, for the integrity and quality of seeds, aeration systems should be preferred to auger-equipped dryers.

Additionally, time of harvest was documented to be an important factor to be considered in the agronomic design and growing of IH plantations, as it influences biomass and methane of IH when used as green feedstock in AD systems.

It is hoped that this review will be useful to readers for deepening their knowledge on IH-based AD systems and about related issues. Hopefully, this review will contribute to creating a platform from which to expand research on improving AD systems designed to treat green IH biomass.

Limitations were found in seeking to extrapolate information and production values from the papers reviewed, due to their absence or to the way they were presented, thus making evaluations and comparisons difficult to make without additional elaborations.

Furthermore, the number of papers used for this study may be judged as relatively low, but that can be understood due to:

a. the topic chosen was not previously widely researched, although it is highly relevant and promising;
b. the impossibility to accessing some relevant papers that were identified.

Finally, this review provided insights about the relevant literature, that is rich in studies addressing technological and energy related issues of IH AD-based supply chains; future research is needed to address unsolved challenges and advances for improvement and revitalisation of hemp SCs.

The literature was deficient on studies exploring environmental and socio-economic sustainability of supply chains of IH. As a matter of fact, most studies only addressed part of the chains or just one environmental impact indicator, so making an urgent need for studies covering the entire chains including the economic, ecological, and technological costs and benefits of IH in AD systems, highlighting ways to contribute to reducing emissions of GHGs and of other harmful pollutants.

There is also an urgent need for studies to investigate this field of research and to contribute to in-depth assessments of the sustainability of the use of IH as an AD feedstock in comparison with the currently, utilised energy crops. Doing so will help scientists, engineers, educators, company leaders and governmental policy makers to develop more sustainable energy generation routes to help to accelerate the transition to post-fossil-carbon societies that are sustainable in integrated, holistic ways for the short and long-term future. The authors of this review, hope that the findings will help to stimulate further research in these areas.

Acknowledgements

Dr. Carlo Ingrao wishes to warmly thank my co-authors for collaborating effectively in the design and development of the study, by providing valuable advice and by performing multiple step-by-step revisions of this manuscript. Additional thanks go to Dr. Francesca Valenti for being corresponding author of this paper.

Furthermore, he deeply thanks Prof. Donald Huisingh, for his key contributions for development of the study and for his multiple, in-depth revisions of this manuscript.

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