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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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(Article begins on next page)

¹ Feasibility of usage of hemp as a feedstock for anaerobic digestion:

² Findings from a literature review of the relevant technological and

3 energy dimensions

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17

18 Abstract

19 Renewable biomasses are used worldwide as inputs for energy production through processes, like

20 Anaerobic Digestion (AD), which is a well-established technology to transform them into bio-gas and

21 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

26 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.

- 50 Of the in plants, with resh 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
- 34 societies.
- 35

36 Keywords

Anaerobic digestion; industrial hemp; energy efficiency; environmental feasibility; energy crops;

- 38 Fossil-carbon footprint reduction
- 39
- 40

41 Acronyms

- 42
- 43 AD: Anaerobic Digestion
- 44 BEY: Biomass Energy Yield
- 45 BMP: Biochemical Methane Potential (or BioMethane Potential)
- 46 CED: Cumulative Energy Demand
- 47 CF: Carbon Footprint
- 48 CHP: Combined Heat and Power
- 49 CSTR: Continuous Stirred Tank Reactor
- 50 DM: Dry Matter
- 51 FM: Fresh Matter
- 52 GHG: Greenhouse Gas
- 53 HHM: Hay Horse Manure
- 54 HHV: High Heating Value
- 55 IH: Industrial Hemp
- 56 LCA: Life Cycle Assessment
- 57 LCSA: Life Cycle Sustainability Assessment
- 58 MEY: Methane Energy Yield
- 59 NEY: Net Energy Yield
- 60 OLR: Organic Loading Rate
- 61 SHM: Silage Horse Manure
- 62 SSF: Simultaneous Saccharification and Fermentation
- 63 UASS: Upflow Anaerobic Solid-State
- 64 VS: Volatile Solid
- 65
- 66

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81 **1. Introduction**

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Energy is considered as one of the most important commodities of life in the present age and, for 83 that, it is essential that it is produced and supplied in secure and sustainable ways, so that 84 ecologically, economically and socially sound energy systems are ensured throughout all societies 85 for the short and long-term future (Rehman et al., 2013). Fossil fuels continue to be important 86 energy sources, due to their abundant availability, the monetary gains from their exploitation and 87 the need to ensure a continuous supply of energy for a rapidly growing human population (Volpe et 88 al., 2014; Sundaram et al., 2017; Ingrao et al., 2018a). Fossil carbon extraction from the earth and 89 its combustion are responsible for multiple negative impacts, affecting the health of humans and 90 the quality of the natural ecosystem. According to the World Health Organization (WHO), 91 approximately seven million humans die prematurely each year, globally, due primarily to fossil-92 carbon-based pollutants. Additionally, as global temperatures are steadily increasing concentrations 93 94 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 95 al., 2017, Sundaram et al., 2017): these are some of the major environmental concerns that need to 96 be addressed and solved. 97

To this end, solutions and strategies are urgently needed to phase out the use of systems based 98 upon fossil-carbon energy and to accelerate the global transition to those utilising renewable energy 99 sources like solar, wind, hydro, geothermal, and biomass, that are promising alternatives (Böske et 100 al., 2014; Schroyen et al., 2018). These are, indeed, delivering lower-environmental impacts (Prade 101 et al., 2012; Schroyen et al., 2017), which is why they are being implemented globally. Valorisation 102 of biomass usage is one of the alternatives that is useful and effective for socio-economic and 103 environmental improvements. Chief among them are crop diversification, reforestation and more 104 sustainable management of forests, and the creation of jobs, particularly in rural communities 105 where large quantities of agricultural biomass and residues are produced (Valenti et al., 2016, 106 2018a). 107

108 Efficient and sustainable utilisation of biomass as an energy source is essential for reduction: of the 109 current dependence upon consumption of fossil fuels in heat, power, and transportation related 110 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

121 et al., 2016; Evangelisti et al., 2017; Ingrao et al., 2018a).

- 122 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
- 125 enhance sustainability of agricultural systems, by reducing costs and associated GHGs (Yasar et al.,
- 126 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).
- 130 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
- 142 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 143 144 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 145 146 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 147 148 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 149 150 (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 151 and feeds, generation of bioenergy and biofuels, and construction of green buildings. Such 152 applications can be pursued simultaneously, and so contribute to maximising yields while 153 significantly reducing land use change and other relevant environmental impacts as overall 154 associated with production of those materials. 155
- 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 andnutrients. In particular, the authors sought to:
- 165 1. Develop insights into the current status of research performed on the environmental, 166 technical, energetic and economic dimensions of IH as a feedstock in AD-based systems for 167 producing bio-gas;
- 168 2. Contribute to enhancing the knowledge and literature on IH in AD applications;
- 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.
- 175 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,
- 177 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.
- 180 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 usesof IH in AD.
- 183 The article by Rehman et al. (2013), reviewed potential energy paths for hemp biomass usage, as a 184 gaseous and as a solid biofuel for use in Pakistan. Their publication deepened the knowledge on IH 185 production, by documenting the feasibility of its usage as a bioenergy source.
- 186 Their findings can be useful in stimulating interest for usage of IH in Italy and in other Mediterranean 187 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.
- 194 195

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

211 biogas production in AD plants.

- The literature review helped the authors of this paper, to document that IH has been increasingly 212 investigated during the period 2009-2019. As a matter of fact, by searching 'industrial hemp' in 213 Scopus, in the indexed article-titles, abstracts, and key-words, 352 articles were found. By reviewing 214 the results and limiting them to 'buildings', 95 papers were found. When the search was limited to 215 216 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 217 that the authors made several literatures searches with different search word combinations before 218 a significant number of papers was found to represent this research area. 219
- 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 relatedauthors 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.
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Fig. 1. Overview of the reviewed papers: a) Number of yearly publications¹; 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.*

250 251

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

252 253

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 addedvalue 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:
- Compared the energy yield from IH with the yields from alternative energy crops commonly
 grown in the study region;

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.

- 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.)

- 280 Solid biofuel production was found to be the major application for IH in Sweden, according to 281 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 282 period (2006-2008) of IH cultivation was used for the assessment. In agreement with Prade's et al. 283 284 (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 285 286 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 287 288 higher than the production of transportation fuels from domestically grown crops like cereals and
- 289 rapeseeds.
- 290 Methane production in AD plants was confirmed to be a reliable way of producing renewable 291 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).
- 297 Methane was produced using different biomass types for the different scenarios considered, 298 namely: crushed leaves; chopped stems; ground stems; steam pre-treated stems; pre-hydrolysed 299 steam pre-treated stems; and residues from the ethanol production line.
- 300 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
- 302 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.

- 304 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 305 CHP (for two of the scenarios); and ethanol, biogas, and CHP (for the third scenario). 306
- The scenarios were implemented based upon a cascade, system's efficiency optimisation approach, 307 308 that included:

309 1. AD of chopped hemp alone;

- 310 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 311 312 output effluent into CHP;
- 313

3. Chopped-hemp, steam pre-treated to develop a slurry, with the solid fraction used for SSF 314 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 315 316 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 317 318 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 319 320 scenarios were economically viable, since the biogas selling price was not high enough to generate 321 a net economic benefit.

- 322 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 323 324 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 325 326 other than for energy uses.
- As a future dimension for research, Barta et al. (2013) emphasised the need for utilisation of 327 328 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 329 330 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 331 332 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 333 methane production. Hemp produced an average DM yield of 12.63 tons per ha, which was 334 competitive with traditional energy crops like maize, sunflower and rape. 335
- The range of MEY was 122 to 111 GJ/ha, with an average of 116.5 GJ/ha. Those values referred to 336 September-October harvests which, in agreement with studies previously reviewed in this paper, 337 show that hemp biomass can be profitably used as an AD feedstock. 338
- Those values were lower than the 136±24 GJ/ha, obtained by Kreuger et al. (2011a): this could be 339 attributed to different soil and climate conditions (Sweden vs. Latvia) as well as to different 340 cultivation practices and harvesting time. 341
- This study and others documented that IH is a high biomass yielding crop for production of biogas 342
- and biofuels. The authors highlighted that biomass yields differed according to the variety. The 343
- varietal yield differences ranged from 10.70 t/ha from the variety 'Benico', to 14.20 t/ha form the 344

345 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
- $t_{\text{DM}}/\text{ha}),$ followed by hemp (14 $t_{\text{DM}}/\text{ha})$ and fava (10 $t_{\text{DM}}/\text{ha}).$
- 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.
- 352 Authors of the reviewed articles found that energy crops are often compared in terms of resource-
- 353 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;
- 366 b. Heat from spring harvested hemp as briquettes and bales; and
- 367 c. Both CHP and vehicle fuel from autumn-harvested, chopped ensiled IH biomass as feedstock
 368 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.
- 408 Co-digestion of energy crops with waste biomass streams were documented to help to eliminate 409 the need to add micronutrients normally required when energy crops were digested alone. 410 Furthermore, addition of those energy crops to the basic feedstock (only consisting of industrial 411 waste made of pig manure, slaughterhouse waste, food processing and poultry waste) resulted in 412 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

432 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
- 455 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).
- 473 Methane yield was documented to be approximately 50% by Adamovičs et al. (2014) that was in 474 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.
- 487 This could help to reduce the net environmental impacts from production of IH.
- 488 'Futura 75' was the hemp variety used by Gissén et al. (2014) in their study designed to compare 489 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, 490 491 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', 492 493 '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 494 495 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 496 497 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.
- 509 Gissén et al. (2014) concluded that IH, although generally regarded as a reliable producer of 510 biomass, was not found, in their research, to be as good a biomass producer as expected.
- 511 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).

- 521 Similarly, **Plöchl et al. (2009)** assessed the environmental impacts associated with the supply chains 522 of crops usable in AD for biogas production, by focussing upon energy balance and GHG emissions. 523 The energy balance was expressed through the Cumulative Energy Demand (CED) indicator, while 524 the Carbon Footprint (CF) was calculated for computation of GHG-emissions in a 100-year temporal 525 horizon (expressed as kg CO₂ eq). The authors considered a set of biogas crop silages, including 526 maize and hemp, the cultivation of which was conducted through application of different N-fertiliser
- 527 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 $m_{methane}^3/kg_{DM}$. By elaborating those values using methane HHV (39.13 MJ/ $m_{methane}^3$) 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.
- 540 (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 CO₂ eq.
- 548 Energy production results were similar to those obtained by Gissén et al. (2014), who documented 549 that energy input for producing hemp were reduced by 40%, from 14.6 to 8.76 GJ/ha, when fertiliser 550 was partly replaced with digestate.
- 551 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

 $(241 \text{ and } 288 \text{ L/kg}_{VS})$, 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 562 563 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, 564 565 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 566 567 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 568 569 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 570 571 (Schroyen et al., 2017). During the AD, the composition of biogas was measured three times (after 572 11, 21 and 30 days): no differences in methane yield were observed. According to Schroyen et. al. 573 (2017), this indicates that the phenolic compounds have an impact on the amount of biogas

574 produced.

575 Furthermore, to measure the detoxifying potential of laccase enzymes, biogas production 576 associated with biomass samples (IH vs. miscanthus) supplemented with different phenolic-577 compound concentrations was measured with and without addition of those enzymes.

578 The research confirmed the detoxification effects of the enzymes, as they removed almost 80% of 579 the added phenolic compounds, thereby, documenting the benefits of their usage in incubation 580 treatments to remove the toxic effects of the phenolic compounds.

581 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 582 583 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 584 on the lignin degradation and on increasing the methane generation by better fulfilling the needed 585 substrate features of the substrate such as the lignin concentration, which has a large negative 586 impact on methane yield, that is dependent upon the types and quantities of phenolic compounds 587 released (Schroyen et al., 2015). In this regard, Schroyen et al. (2015) suggested to break down the 588 lignin barrier and diminish the lignin concentration, to improve BMP and related production rate. 589 Schroyen et al. (2015) state that enzymatic pre-treatment can help to degrade the matrix, but they 590 suggest to optimise it as much as possible to have greater, positive impacts on lignin degradation 591

592 and BMP.

593 **Schroyen et al. (2018)** developed an AD model where those and related issues were addressed by 594 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

597 (233.1 L/kg_{VS}), with corn stove exhibiting a good performance which was estimated by the authors 598 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.

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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 613 crop producing biogas-yielding biomass competitively with energy crops but, on average, with a 614 lower environmental impact. This is mainly because, as Barta et al. (2013) stated, it presents several 615 advantages over those crops like the possibility of being cultivated with relatively low quantities of 616 nitrogen and no pesticides. However, with regard to this point, it is worth underscoring that Plöchl 617 et al. (2009) highlighted IH biomass yield as decreasing with the decrease in N-fertiliser application, 618 thereby emphasising upon the need to find viable, sustainable trade-offs between production rates 619 and application demands. Another advantage was highlighted by Kreuger et al. (2011b) and Prade 620 et al. (2012) and is about IH being characterised by a low susceptibility to pests and diseases, which 621 makes it a suitable candidate in rotation with food and feed crops, especially under organic farming 622 conditions. In addition to this, increased IH cultivation was documented as enhancing bio-diversity 623 of crops and thus, can help to develop integrated bio-economies, in which ecosystem services other 624 than feedstock supply are important (Barta et al., 2013). This agrees with findings from Troiano et 625 al. (2019) who underscored the need to focus upon the multifunctional roles of agriculture and 626 627 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; 628 preservation of biodiversity; and contributions to rural, socio-economic development. In this regard, 629 another important advantage was emphasised by Burczyk et al. (2008) and Kumar et al. (2017) and 630 regards IH helping to remediate soils contaminated by heavy metals, while delivering the biomass 631 products reported above. This is because it acts as a phyto-remedial agent that extracts and 632 accumulates large amounts of heavy metals, like cadmium, lead, copper, and mercury, thereby, 633 helping to restore agricultural productivity of those soils and reducing the negative impacts of the 634 heavy metals in the animal and human food chain. 635

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; coproduction 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 671 testing (both at the lab- and industrial-scale) of hemp biomass, under different farming and 672 harvesting conditions, to contribute to enhancement of the knowledge on its suitability as an AD 673 feedstock. Schroyen et al. (2015, 2017, 2018) went further by investigating the inhibitory effects of 674 various phenolic compounds on AD of hemp straw, and on the detoxification effects that can be 675 obtained by providing a pre-treatment based upon application of veratryl alcohol and laccase 676 enzyme. As the final step of their research, they created an AD model to account for and to build 677 678 upon those and related issues.

679

680 Table 1

681 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 682 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	AD alone	AD, as part of a more complex system	AD-based system Comparison among treatment scenarios and/or biomasses	authors and related to hemp AD systems. Values were extrapolated from the paper and were related just to IH treatment. DM yield Energy MEY (t/ha) content (GJ/ha) in the biomass (BEY, NEY) – GJ/ha			Overall description of findings from the given study, and/or additional clarification comments as needed to integrate what already discussed in section 3.
		I		I	l	2009		03/110		
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	The MEY from IH AD	Sweden	Hemp	Х	n. a	n. a	15.6	286	136 (±24)	Those alongside are average
al. (a)	was determined in this						(±1.5)	(±27)		values related to harvesting as
	study at four harvest									carried out in the period
	times (in the period									September-October, and can be
	July – October) through									considered as the highest
	the biochemical BMP									obtainable ones.
	test, starting from									Based upon results from their
	computation of the									study, the authors found no
	biomass yield.									significant differences in specific
										methane yield, based upon the
										harvest time: the average value
										found was equal to $234\pm35 \text{ m}^3/t_{VS.}$
Kreuger et	Several scenarios for	Sweden	Hemp	n. a	х	Х	16	n. a	n.a	Co-production of ethanol and
al. (b)	ethanol production,									methane from steam pre-treated
	methane production									stems gave a high yield of
	and co-production of									transportation fuel, 11.1–11.7
	this, using autumn-									MJ/kg processed stem dry matter
	harvested dry hemp									(DM); more than twice that of
	biomass were									ethanol production alone from
	investigated and									hexoses, 4.4–5.1 MJ/kg processed
	compared in this study									stem DM. Co-production from the
	in terms of gross									whole hemp plant would give
	energy input, also to									2600–3000L ethanol and 2800–
	highlight benefits from									2900 m ³ methane. In total,
	potential steam pre-									171–180 GJ would be obtained
	treatment.									per 10,000 m ² of agricultural land,
										based on a biomass yield of 16 t_{DM}
Balodis et	The research was	Latvia	Нетр	Х	n. a	Х	10.70-	n. a.	111-122	The comparative biomass-yield of
al.	conducted to test the						14.20		(average)	the eight IH varieties considered.
	comparative biogas						(average:			The two different values for MEY
							12.63)			are related to different harvest

	yields of eight IH					Comparison with				times: October, and September,
	varieties.					amaranth,				respectively.
						sunflower,				
						millets, hemp.				
						rape and maize				
Pakarinen	Assessment of the	Finland	Нетр	Х	n. a	x	15	n. a.	108 -137	The types of biomasses were
et al.	suitability of diverse									tested in the digester separately
	annual plant species as									and the results were compared.
	dedicated biomass					Comparison with				Differences in MEY values were
	crops for biogas and					maize and fava				attributed to whether hemp was
	ethanol production.					bean				chopped finely or coursely.
				<u> </u>		2012			1	
Prade et	The researchers	Sweden	Hemp	х	n. a.	х	10.2	200-	83.42 (**)	(**) This value was not directly
al.	compared NEYs and							250		included in the paper of Prade et
	energy output-to-input									al. (2012). However, it was
	ratios for production of									calculated based upon the specific
	heat, electricity, CHP									methane yield (0.22 m^3/kg_{VS}) and
	and transportation fuel									VS content that, were reported in
	from IH biomass, under									the paper. The methane HHV was
	different scenarios.									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	Sweden	Pig and poultry	Х	n. a.	Х	n. a.	n. a.	n. a.	The study was conducted in
	the feasibility of		manure along			Comparison with				laboratory scale batch and
	supplementing a		with waste from			other energy				continuous stirred tank reactors
	protein/lipid-rich		slaughterhouses			crops such as				(CSTR) with the plan to scale-up to
	industrial waste		and food			maize and				commercial biogas process.
	mesophilic anaerobic		processing			triticale				The authors documented that, by
	digester with		activities co-							adding energy crops to existing

				1						1
	carbohydrate-rich		digested with							industrial waste supplements in
	energy crops		alternative							AD, both methane yield and
			energy crops							methane energy production
			(i.e. maize,							increased significantly, from 46 to
			hemp, and							59 Nm ³ /t _{ww} and from 26 to 47
			triticale).							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
				1		2013		<u> </u>		
Barta et al	The researchers	Sweden	Hemp	na	x	x	10.2 (***)	na	na	The researchers documented that
Burta et un	integrated the results	Sweden	nemp	in a	~	~	10.2 ()			none of the technological
	of Kreuger's et al									processes considered is
	(2011b) and Prade et									economically viable because the
	(20110) and trade et									energy output 60-84% of the
	additional oconomic									onorgy input
	additional economic									energy input.
	dialysis Of field									
	officiency and process									
	enciency, and process									
	economics in terms of									
	annual cash flows and									(***) f D (2042)
	minimum selling prices									(***) as of Prade et al. (2012)
	for biogas and									
	methane					2014				
Däska at	The study was	6			1	2014	L		1	The measure found that the
BOSKE EL	The study was	Germany	Horse manure	^	11. d.	^	11. d.	n. d.	n. d.	the researchers found that the
aı.	performed at lab scale,		co-algested							nignest methane yields were
	to investigate the use		with alternative							obtained when wheat straw was
	ot up-tlow anaerobic		bedding							added to the basic feedstock, with
	solid-state digestion		materials.							values equal to an average of
										nearly 230 L _{methane} /kg _{vs.}

										Hemp was confirmed to be a
						Comparison with				competitive alternative when
						alternative				biomasses like wheat straw were
						solutions of				not available.
						bedding				Hemp methane yield about 168
						materials, like				Lmethane/kgvs
						wheat and hemp				
						straw				
Adamovičs	The authors reported	Latvia	Hemp	х	n. a.	n.a.	14.55-	n. a.	a) 148.15-	The range of biomass yields was
et al.	on research to test the						21.27		208.09	varied among the hemp varieties
	suitability of different									investigated. Each value was
	IH varieties for biogas									provided as the average of the
	production								b) 214.36	cultivation period (2011-2012).
									-,	With regard to methane yield.
										values at point a) refer to values
										obtained from ' <i>Futura</i> 75'.
										whether the biomass is milled
										coarsely or finely While the
										values at point b) refers to
										chonned leaves from 'Uso 31'
Gissón et	Presented new and	Sweden	Hemn	v	n a	Y	66-77	n 2	80	The authors calculated that the
al	dedicated life cycle	Sweden	nemp	^	n. a.	~	0.0-7.7	n. a.	80	feedstock costs were so high that
aı.	inventory data for									they were not profitability for
	nivenitory uata for									history were not promability for
	of biogos grops									upon ansiled grans due to the
	of blogas crops.									light of the Swedick bigger colling
										light of the Swedish blogas selling
										price. This is in line with Barta et
										al. (2013) Who, in fact,
						Compared to				recommended other solutions like
						other crops like				maximisation of output yields in a
						maize and sugar				cascade-based system.
						beet				
			T		1	2015	-	1	1	
Schroyen	in this paper, the	Belgium	Нетр	X	n. a.	X	n. a.	n. a.	n.a.	As specified by the authors in their
et al.	authors studied the									paper, the enzymes utilised were
	ettect of an enzymatic									laccase and versatile peroxidase,
	pre-treatment on									as derived from Trametes

	biomass samples from									versicolor and Bierkandera
	a set of plant species									adusta
	a set of plant species.									Mathana yield was found by the
						Compared to				authors in the range 184.1 248
						compared to				authors in the range 184.1 – 248
						other crops like				L/ Kg _{VS} .
						maize and sugar				
						beet				
		1		1	1	2017		1	1	1
Schroyen	The inhibiting effect of	Belgium	Hemp	х	n. a.	х	n. a.	n. a.	n. a.	To integrate what has already
et al.	various phenolic									been discussed in section 3 on this
	compounds on AD of									paper, the authors found that, per
	hemp straw and									each phenolic compound
	miscanthus, and the									concentration chosen (0-2000
	related mitigation									mg/L), enzyme-treated hemp
	solutions, were studied									performs better than the
	by the authors.									untreated one. in terms of
	,									methane vield. In particular, the
										highest vield was found in
										untreated samples with no
										nhenolic-compound addition
										Highly comparable yield values (in
										the around of 12 L/kg (d) were
										found for troated complex at both
										ound for treated samples at both
										U and Soung/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
						Comparison to				yield was in the range 9-12
						miscanthus				L/kg _{vs} /d.
	1	ı				2018				1

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

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 704 705 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. 706 707 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 708 709 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 710 711 of producing foods, feeds, materials and energy commodities, while protecting ecosystems to sustainably provide dynamic services for the long-term future. 712
- 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. 726 It is hoped that this review will be useful to readers for deepening their knowledge on IH-based AD 727 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 andcomparisons difficult to make without additional elaborations.
- Furthermore, the number of papers used for this study may be judged as relatively low, but that canbe understood due to:
- 734 735

736

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 indepth 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.
- 752

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761 **References**

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