agronomy

Review

Two Novel Energy Crops: *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L.—State of Knowledge

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Abstract: Current global temperature increases resulting from human activity threaten many ecosystems and societies, and have led to international and national policy commitments that aim to reduce greenhouse gas emissions. Bioenergy crops provide one means of reducing greenhouse gas emissions from energy production and two novel crops that could be used for this purpose are *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. This research examined the existing scientific literature available on both crops through a systematic review. The data were collated according to the agronomy, uses, and environmental benefits of each crop. Possible challenges were associated with high initial planting costs, low yields in low rainfall areas, and for *Sida hermaphrodita*, vulnerability to *Sclerotinia sclerotiorum*. However, under appropriate environmental conditions, both crops were found to provide large yields over sustained periods of time with relatively low levels of management and could be used to produce large energy surpluses, either through direct combustion or biogas production. Other potential uses included fodder, fibre, and pharmaceutical uses. Environmental benefits included the potential for phytoremediation, and improvements to soil health, biodiversity, and pollination. The review also demonstrated that environmental benefits, such as pollination, soil health, and water quality benefits could be obtained from the use of *Sida hermaphrodita* and *Silphium perfoliatum* relative to existing bioenergy crops such as maize, whilst at the same time reducing the greenhouse gas emissions associated with energy production. Future research should examine the long-term implications of using *Sida hermaphrodita* and *Silphium perfoliatum* as well as improve knowledge on how to integrate them successfully within existing farming systems and supply chains.

Keywords: bioenergy crops; Virginia mallow; Virginia fanpetals; Cup plant

1. Introduction

Governments from across the world committed themselves, in Paris in 2016, to restrict the mean rise in global temperature to no more than 1.5–2 °C above pre-industrial levels. In order to achieve this, governments are seeking to reduce net greenhouse gas emissions with a particular focus on reducing the use of fossil fuels for electricity production, heating, and transport.

Bioenergy currently represents 17.5% of gross energy consumption in the European Union (EU) [1]. In Europe in 2017, about 59% of renewable energy was provided from bioenergy, and globally about 10% of this is derived from agriculture [2]. Important bioenergy crops in Europe include maize (*Zea mays* L.) to produce biogas and bioethanol, and short rotation coppice [3] and *Miscanthus* [4] for the production of solid biofuel.

However, there are a number of challenges associated with the use of these crops. For example, maize is a spring-planted annual crop with high fertilization and pesticide needs, which does not cover the ground in the winter and early spring and this can result in severe soil erosion and soil organic matter depletion. In the case of short rotation coppice, the woody material requires the use of specialised harvesting equipment, which is typically not found on farms. Disadvantages in the use of *Miscanthus* include problems of corrosion and slagging associated with its combustion. For these reasons, there is interest in perennial herbaceous crops that (i) do not require annual planting and can be harvested over many years successively, (ii) can be harvested using existing farm equipment, and (iii) can enhance biodiversity at a field- and farm-level. Recent research indicates that compared to annual energy crops, perennial energy crops are a more sustainable option [5]. Two novel biomass crops, *Sida hermaphrodita* (L.) Rusby (also known as Virginia fanpetals or Virginia mallow) and *Silphium perfoliatum* L. (known as cup plant) could fulfil all three of these criteria.

Although both plants originate from North America and have been studied in research institutions in Eastern Europe since the 1980s as fodder and energy crops, there remains a lack of collated information in English on *Sida hermaphrodita* and *Silphium perfoliatum*. Some of the early research on these plants in Eastern Europe was published in Polish and German. The objective of this paper is therefore to synthesize in one location the existing information on the agronomy and uses of *Sida hermaphrodita* and *Silphium perfoliatum* in a state of the art review.

2. Materials and Methods

We undertook a systematic review of published peer reviewed literature for both *Sida hermaphrodita* and *Silphium perfoliatum*. Relevant articles and papers were identified using Scopus as the main search engine, complemented with Google Scholar. The key words used during the search were “Sida hermaphrodita”, “Virginia mallow”, “Virginia fanpetals”, “Silphium perfoliatum”, and “Cup plant”. The search was limited to articles published between 1985, when the first article was published, and 2020.

A total of 225 papers were initially identified in the screening process, as shown in Table 1. The full list of papers is shown in Appendix A. All relevant peer-reviewed publications describing the agronomic, energetic, and environmental aspects of both plant species were included in the review. Data were extracted, compiled, and organized into these key themes which form the broad thematic sections of this literature review. Only articles written in English, German and Polish were included in the review process.

The results are described first for *Sida hermaphrodita* and then *Silphium perfoliatum* in terms of (1) the origin and botany of each crop, (2) the agronomic requirements of each crop including their agro-climatic requirements, establishment method, pests and diseases, nutrient management, and harvesting. The bioenergy production aspects of both crops are then compared in terms of yields produced and timing of harvest. In addition, the use of the crops in terms of solid fuel production, biogas, and gasification are described. Lastly, the alternative uses of the crops, potential environmental benefits, the economics, energy balance, and life cycle assessments (LCA) are detailed. The paper finishes with recommendations for future research and a brief conclusion on the main points.

All economic data reported here in Pound sterling (GBP) and Euros (€) have remained unchanged. Polish złoty (PLN) have been converted into Euros using an exchange rate of 4.18 PLN/€ [6] for economic data reported for Poland in 2012 and 2014.

Table 1. Screening process for the systematic literature review and number of articles.

	S. hermaphrodita	*S. perfoliatum*
Total number of documents initially found	122	103
Number of documents written in other than English, German, and Polish	1	10
Number of documents considered out of scope	3	2
Number of documents with restricted access/not available	12	11
Number of additional papers identified during the review	20	17
Number of documents finally reviewed	125	97

3. Review of *Sida hermaphrodita* (L.) Rusby

3.1. Origin and Botany

Sida hermaphrodita is a perennial herbaceous species belonging to the Malvaceae family, and its common names include Virginia mallow and Virginia fanpetals. From here onwards, we will refer to it as simply *S. hermaphrodita*. *S. hermaphrodita* is indigenous to North America, where it is found in or near to wetlands, floodplains, and rivers [7,8]. In the USA in 1985, large wild populations of *S. hermaphrodita* were documented in West Virginia and Ohio states, with isolated populations in Kentucky, Michigan, and Indiana [9]. Individual plants can reach heights up to 3 m, with hollow canes filled with pith, and delicate leaves of 20–50 cm^2 [10].

The potential use of *S. hermaphrodita* as a fodder and fibre crop was recognised during the 1930s when it was introduced into the former USSR. It found its way to Poland as a fodder and fibre crop in the 1950s, where it was still used for these purposes in the 1980s [7]. Kurucz et al. [11] described the first accidental introduction of the species into Hungary during the 1970s, after which *S. hermaphrodita* became more widespread through trade with Poland, to the point that in 2010 it was included in a list of species for which bioenergy funding could be obtained. In Poland, studies indicated that around 96 ha of *S. hermaphrodita* were cultivated in 2008 [12] and an additional 750 ha was planted up to 2011 [13]. *S. hermaphrodita* is cultivated about 100–150 ha of land in Germany and small areas of land in other eastern European countries including Austria, Hungary, and Lithuania [14].

S. hermaphrodita was first studied by Russian botanists, then by Ukrainian researchers such as Mendvedev and Dmitrashko et al. [9] who investigated its potential for fodder, fibre, and honey production, and soil stabilization. The University of Life Sciences at Lublin in Poland began research on *S. hermaphrodita* for energy production in the 1980s, because of its high yields, low moisture content when harvested in late winter, and ease of harvest, processing, and storage [15]. Selective breeding has produced varieties up to 4 m in height that yield 12 to 20 t dry matter (DM) ha^{-1} y^{-1} [7].

Once planted, *S. hermaphrodita* can be productive over a rotation of 10 years or more, and some authors have suggested that it can remain highly productive for 15–20 years [16]. Recently, Jablonowski et al. [17] produced a BBCH-code for *S. hermaphrodita* (further details in Appendix B) to help identify its different phenological stages, and allow for more accurate comparisons between field trials. There is limited information regarding the invasiveness of *S. hermaphrodita*. However, in the Netherlands an ecological risk assessment concluded that it presented a low risk [18].

3.2. *Agronomy of Sida hermaphrodita*

3.2.1. Agroclimatic Requirements

S. hermaphrodita can tolerate low temperatures during the winter making it suited to continental climates [11]. Jasinskas et al. [19] recommended that commercial production for a humid continental climate (Lithuania), requires a minimum annual precipitation of about 500–600 mm, as drought results in significant yield reductions [20,21]. The high sensitivity of the yield of young *S. hermaphrodita* plants to drought is also reported by Franzaring et al. [10]. The sensitivity of *S. hermaphrodita* to drought is also suggested by wild populations being generally found in wet habitats [9].

In the wild, *S. hermaphrodita* is typically found on silt loam, sandy clay loam, and clay loam soils [9]. The pH of these soils varies between 5.4 and 7.5, with a medium to high organic matter content. Yields can be depressed at low acidities, and Šiaudinis et al. [22] demonstrated that liming of acid soils to increase the pH from 4.3 to 5.6 before establishment increased yields by almost 50%.

3.2.2. Establishment Method

S. hermaphrodita can be established using seeds, seedlings or rhizomes. Nahm and Morhart [14] included a clear table in their review which compiles the different densities used for the three methods in experiments between 2003 and 2011.

Krzaczek et al. [23] reported that sowing was the most common method of establishment of *S. hermaphrodita* in Poland at the time. They also reported the importance of initial weed control, and they recommended keeping a wide distance between rows to allow mechanical/chemical weed control [24]. Pszczółkowska et al. [16] advised against sowing on soils that tend to crust on the surface. By contrast, Borkowska and Wardzińska [25], looking at survival on sewage-sludge treated soil, found that whereas only 10% of plants originating from seeds survived, seedlings had a 53% survival. Hence, yields from *S. hermaphrodita* established using seedlings were 7.7 t DM ha^{-1} y^{-1} greater than from *S. hermaphrodita* established using seeds.

Seedlings can be grown from seeds to then transplant them to the field. In Germany, Franzaring et al. [10] sowed seeds in trays in March, observed germination after 11–25 days, depending on the temperatures, and then transferred the seedlings to the field in April. Having used the Kurucz-Fari method [26] to germinate seeds, Kurucz et al. [24] produced their own over-wintered seedlings using the so called nurse-in-tray technology, increasing reliability and obtaining high yields.

The use of 8–12 cm rhizomes can also lead to rapid and successful plantation establishment [24,27], although rhizomes can carry virus infections [24]. Borkowska and Molas [7] reported annual yields of 20 t DM ha^{-1} using rhizomes and recommended their use for the establishment of energy plantations. Jasinskas et al. [19] reported that the rhizomes can be planted using potato planters.

Establishment by Sowing

S. hermaphrodita seeds have an average weight of 3.4 g per 1000 seeds [23]; they are very small. *S. hermaphrodita* has been established in the field from seed either by sowing in early spring or in the preceding November [22]. However establishment from seed can be “unpredictable, slow, and difficult” [11], with typical germination rates of 5–15% [16]. Because of this, researchers have attempted to find ways of improving the germination rate. During a four year experiment, Kurucz et al. [11] found no relationship between germination and storage period of the seeds. Franzaring et al. [28] kept seeds that had been sown in seeding trays under controlled conditions for four weeks, with alternating temperatures of 3 °C and 11 °C to overcome dormancy. Spooner et al. [9] reported that scarification of the seeds should lead to germination rates of up to 92%. Their method involved perforating the seed coats and then incubating the perforated seeds for 15 days under controlled light (14 h of light at 20 μE m^{-2} s^{-1}) and temperature (35 °C during the day and 20 °C during the night) conditions.

Kurucz and Fári [26] also reported germination rates of up to 80% by combining a floated-seed priming technique with a hot water pre-treatment. First, seeds were immersed in distilled water at 23–25 °C for 30 min. Then, the seeds that had sunk were taken and submerged in water at 80 °C for 2 min, placed on wet filter papers in Petri dishes in total darkness at 26 °C, and counted after three and six days. Borkowska and Molas [7] have reported 20% yield benefits of using seed dressings containing the fungicides carbendazim (no longer approved for use in the EU) or tebukonazol.

Borkowska and Wardzińska [25] compared 3, 6, and 9 kg ha^{-1} of seeds, finding no difference in yield. Stolarski et al. [29] compared sowing 1.5 and 4.5 kg ha^{-1}, obtaining higher yields with the higher sowing density. Feledyn-Szewczyk et al. [30] used a seed rate of 1.5 kg ha^{-1}.

For their field trial at the University of Life Sciences in Lublin, Borkowska et al. [20] applied 25 seeds m^{-2} (250,000 seeds ha^{-1}). The same density of 25 seeds m^{-2} was used again by Borkowska and Molas [7] in their experiment on the effect of seed dressings. Molas et al. [31] established their plantation again using the same density but this time with germinated seeds. A sowing density of 64,000 seeds ha^{-1} was reported by Pszczółkowska et al. [16].

For sowing, Krzaczek et al. [23] used the S071 KRUK seeder. This had a chain and sprocket transmission connected to a cam mechanism that in turn controlled a dosing disk. Working at 0.8 m s^{-1}, their experiment demonstrated the significant impact of the peripheral speed of the disc on seed distribution, with an optimal speed of 0.23 m s^{-1} and decreasing efficiency at higher speeds. Kurucz et al. [24] used the S071/B KRUK pneumatic seeder in their experiment. Hand powered seeders have also been used for establishing small-scale plantations of *S. hermaphrodita* [7].

Establishment by Transplanting Seedlings or Rhizomes

High densities for seedlings have sometimes, but not always, been associated with higher yields. In Hungary, Kurucz et al. [24] reported that densities of 10,000, 13,300, and 20,000 seedlings ha^{-1} gave similar yields, but the plantation was more uniform at the lowest density. In Austria, in a comparison of 13,300, 17,700, and 26,600 seedlings ha^{-1}, von Gehren et al. [32] recommended applying the middle density due to similar yields and reduced costs. Šiaudinis et al. [22,33], Stolarski et al. [34] and Feledyn-Szewczyk et al. [30] used a seedling density of 20,000 seedlings ha^{-1}, equivalent to a spacing of 1.0 m × 0.5 m, and Jablonowski et al. [17] used a spacing of 0.75 m × 0.5 m (27,000 seedlings ha^{-1}). Borkowska and Molas [7] and Franzaring et al. [28] planted seedlings at a density of 40,000–40,800 seedlings ha^{-1}, and a density of 44,000 seedlings ha^{-1} was used in the five field trials across Europe as part of the SidaTim project [35,36]. Borkowska and Wardzińska [25] found no differences in dry biomass yields of seedlings planted at 33,000, 50,000 and 100,000 seedlings ha^{-1}.

In the case of rhizomes, Pszczółkowska et al. [16] proposed 10,000–20,000 cuttings ha^{-1}, and Stolarski et al. [37] and Krzyżaniak et al. [38] used a density of 20,000 cuttings ha^{-1}. Pogrzeba et al. [39] used 3 cuttings m^{-2}, equivalent to 30,000 cuttings ha^{-1}, and Antonkiewicz et al. [40] used a spacing of 0.75 m × 0.4 m, equivalent to 33,300 cuttings ha^{-1}. Borkowska and Molas [7,41] used a spacing of 0.70–0.75 m between rows and 0.33–0.35 m between plants to achieve 40,000–41,000 cuttings ha^{-1}, similar to the value of 44,000 cuttings ha^{-1} reported by Jankowski et al. [42]. Stolarski et al. [29] compared 20,000 and 60,000 cuttings ha^{-1}, obtaining higher yields at the highest density. Despite the risk of viral infections, the establishment of plantations using rhizomes has the potential to produce higher yields from the second year [20].

Irrespective of the method of propagation, as long as the original planting density is not too low, Borkowska and Wardzińska [25] reported that it is common for a density of about 21 shoots per m^2 to establish by the third year. Similar stem densities have generally been reported in other studies. Shoots reached a constant density of around 24 shoots per m^2 [20] and 16–24 shoots per m^2 [43], although Borkowska and Molas [41] reported a relatively high density of 37 shoots per m^2.

3.2.3. Weeds, Pests, and Diseases

Weeding is essential during the establishment phase and it is generally needs to be done manually or mechanically due to the sensitivity of *S. hermaphrodita* to herbicides. In subsequent years, only minimal weeding is needed due to the early onset of the growth in March and its ability to create a closed canopy [11].

S. hermaphrodita is vulnerable to fungal infection by *Sclerotinia sclerotiorum*, which causes bleached and mouldy white stems. The origin of the inoculum of *Sclerotinia sclerotiorum* could be ascospores and mycelium growing on dead plant material [8]. Symptoms, which appear in mid-May when plants are 0.5 m high, can destroy anything from just a few shoots to entire plantations. The same authors explored the potential of yeast-like fungi in controlling *Sclerotinia sclerotiorum* in order to develop a commercial biocontrol product. As such, Dr. G. Bedlan [44] recommended the use of the antagonist *Coniothyrium minitans* (Contans WG, ©2020 Bayer Crop Science). Matyka and Kuś [43] applied a fungicide (Horizon 250 EW 0.018%) with the active ingredient tebuconazole, in June of the first year after planting to control the disease. As *Sclerotinia sclerotiorum* is commonly found in oilseed rape (*Brassica napus* L.), Nahm and Morhart [14] recommend that *S. hermaphrodita* should not be grown in fields previously used for oilseed rape should be avoided.

Fusarium and *Botrytis cinerea* are two other potential diseases for *S. hermaphrodita* mentioned in the literature (Grzesik et al., 2011, cited in [16]). Pszczółkowska et al. [16] also stated that *S. hermaphrodita* could be affected by dock bug (*Coreus marginatus* L.) and the lygus bug (*Lygus* spp.).

In 2015, the symptoms of *Didymella sidae-hermaphroditae* sp. nov. were found on the upper side of leaves in the form of brown rounded spots with a dark outline in Austria [45]. In June 2015 the occurrence of the fungus *Periconia sidae* on *S. hermaphrodita* was first also reported for Europe [46]. Out of the 190 species of the genus *Periconia*, only *Periconia byssoides* and *Periconia sidae* have so far been reported on *S. hermaphrodita*. *Periconia sidae* was visible on the upper leaf side as irregular, light brown, leaf spots, with dark brown border. Microscopic stems with conidia of *Periconia sidae* associated with *Epicoccum nigrum* were found on these spots on both sides of the leaves.

3.2.4. Nutrient Management

Numerous fertiliser trials on *S. hermaphrodita* have been reported in the literature (Table 2), with nitrogen applications ranging from 0 to 200 kg N ha^{-1}, phosphorus applications of 0 to 100 kg P ha^{-1}, and potassium applications of 0 to 150 kg K ha^{-1}. These ranges agree with the data gathered by Nahm and Morhart [14], (0–200 kg N ha^{-1}; 0–90 kg P ha^{-1}; 0–120 kg K ha^{-1}). Once established, *S. hermaphrodita* is considered to have low requirements for N, P, and K because nutrients are allocated to and stored in the unharvested root system when harvest occurs during late winter [16,28].

Generally, higher rates of nitrogen fertiliser application increase the biomass production of *S. hermaphrodita*. Šiaudinis et al. [22] obtained their highest yield of 8.12 t DM ha^{-1} y^{-1} at the highest nitrogen application rate they investigated (120 kg N ha^{-1}). Stolarski et al. [37] obtained a positive response of *S. hermaphrodita* to nitrogen, with the highest yields resulting from the highest nitrogen doses applied in dry digestate and mineral fertiliser. Molas et al. [31] recorded their highest yield with the highest nitrogen application of 200 kg ha^{-1}. By contrast, Borkowska et al. [20] found that increasing nitrogen from 100 kg ha^{-1} to 200 kg ha^{-1} had no significant effect on yield. In situations where the soil nitrogen status is high, it can be possible to obtain high yields without the addition of fertiliser in the initial years after planting. For example Slepetys et al. [21] and Kurucz et al. [24] obtained annual yields of 9.6 and 10.2–11.9 t DM ha^{-1}. However, nutrient depletion led to yield reduction in subsequent years [24].

Some authors recommend splitting the application of nitrogen into two equal doses to maximize nitrogen use efficiency. The suggested timing is generally just before growth starts and then just before canopy closure in July [7,22,31,33] or more specifically at BBCH 11 [35].

Table 2. Reported fertiliser application rates for *S. hermaphrodita* (kg ha^{-1}). Values are for N, P, and K unless indicated otherwise.

N	P	K	Author, Year	Reference
100/200	39/52	83	Borkowska et al., 2009	[20]
100	35	83	Borkowska and Molas, 2012	[7]
0/60 [e]/120	60 [e]	60 [e]	Slepetys et al., 2012	[21]
90	13–39	42–82	Pszczółkowska et al., 2012	[16]
100	39	75	Borkowska and Molas, 2013	[41]
158 [e]/79	88 [e]/44	116 [e]/58	Szyszlak-Bargłowicz et al., 2013	[47]
0/60/120	26	33	Šiaudinis et al., 2015	[22]
90 [e]/120	35 [e]/43	66 [e]/82	Jankowski et al., 2016	[42]
160	5%	8%	Nabel et al., 2016	[48]
0/60/120	60 SSP	31	Šiaudinis et al., 2017	[33]
68/136	23–58	55–204	Stolarski et al., 2017	[49]
0/68/136	0/26/52	0/73/146	Stolarski et al., 2017	[37]
120	30	80	Matyka and Kuś, 2018	[43]
85/170	13	33	Krzyżaniak et al., 2018	[38]
140	-	25	Facciotto et al., 2018	[35]
90/170	-	-	Tilvikiene et al., 2019	[50]
100/200	83	39	Molas et al., 2019	[31]
60 [e]/40–80	35 [e]	80 [e]	Bury et al., 2019	[36]
70	-	-	von Gehren et al., 2019	[32]
90	13	33	Stolarski et al., 2019	[51]
100 [e]/100	35 [e]/35	110 [e]/110	Siwek et al., 2019	[52]
120 [e]/150	44 [e]/44	82 [e]/82	Jankowski et al., 2019	[53]
80 [e]/80	26 [e]/26	44 [e]/44	Feledyn-Szewczyk et al., 2019	[30]
90/170	-	-	Tilvikiene et al., 2020	[50]

[e] establishment year.

Analysis of the macro-element composition of *S. hermaphrodita* showed a nitrogen content in the harvested stems of 7.9–12.8 g N DM kg^{-1}, which is the same order of magnitude as nitrogen found in the stems and branches of poplar SRC (Table 3). Hence, a dry matter yield of 10 t DM ha^{-1} would result in the removal of 79–128 kg N ha^{-1}. Molas et al. [31] studied the effect of different doses and fertiliser compound on the final composition of *S. hermaphrodita*. They observed that the highest dose of nitrogen doubled the sodium content and that the use of K_2SO_4 (instead of KCl) reduced Cl (by 45%), as well as N and crude ash in the plants.

Table 3. Reported values of the nutrient content of harvested stems and branches (g kg^{-1} DM) of *S. hermaphrodita* compared to poplar short rotation coppice.

Nutrient	*S. hermaphrodita*			Poplar
	Antonkiewicz et al. [a] [40]	Sienkiewicz et al. [b] [54]	Bilandžija et al. [c] [55]	
N	8.8	7.9–12.8	-	7.8 [56]
P	0.4	1.8–2.8	-	0.6 [57]
K	2.5	17.5–24.7	11.3	3.9 [57]
Mg	0.4	1.3–1.9	0.5	0.9 [57]
Ca	3.4	18.4–22.6	7.6	13.6 [57]
Na	0.2	1.2–2.2	0.02	0.18 [57]

[a] Receiving sewage sludge (Poland); [b] Receiving digestate or mineral fertiliser (Poland); [c] (Croatia).

If *S. hermaphrodita* is used solely for bioenergy production, and not used in the food chain, sewage sludge and digestates from anaerobic digestion can provide effective alternative sources of nutrients from mineral fertilisers [54,58,59]. In Poland, Antonkiewicz et al. [40] reported that applying 60 t DM of sludge per hectare to *S. hermaphrodita* increased the annual yield from about 8 t ha^{-1} to 14.8 t ha^{-1}. They concluded that *S. hermaphrodita* is capable of efficiently using the nutrients from sewage sludge. Czyzyk and Rajmund [60] compared the application of sewage sludge and sludge compost to *S. hermaphrodita* and *Miscanthus* and reported that it increased soil organic matter. They reported that about 8–12% of the applied nitrogen was leached, with the amount of leaching being less under *S. hermaphrodita* than *Miscanthus*, suggesting that *S. hermaphrodita* was relatively effective in using the applied nitrogen.

In a similar way, Nabel et al. [61] in Germany used biogas digestate from maize silage as a fertiliser for *S. hermaphrodita* and obtained large increases in yield, estimating the optimum digestate application to be 40 t ha^{-1}, containing about 0.5% nitrogen, i.e., 200 kg N ha^{-1}. Nabel et al. [48] also reported that *S. hermaphrodita* yields from applying 160 kg N ha^{-1} using maize fermentation digestate gave similar yields to the equivalent mineral fertilisers. Moreover, the increased organic matter in the soil improved soil health and biodiversity, and reduced the amount of nitrogen leaching. Subsequent work in a pot experiment has demonstrated the yield benefits of soil injection rather than broadcasting of digestates [62], and that the nitrogen content in *S. hermaphrodita* biomass can be further enhanced (+30%) by legume intercropping [63]. Saletnik et al. [64] has also successfully demonstrated that biochar, which can help with water retention, can also increase the growth of seedlings. The use of organic fertilisers was also recommended by Kurucz et al. [24].

In relation to the soil nitrogen cycle, in a comparison of five crop species, Wielgosz [65] found that soil below *S. hermaphrodita* had the highest amount of proteases. Proteases decompose proteins ultimately into amino acids, and the capacity of *S. hermaphrodita* to remove nitrogen from the soil was proposed as an interesting area for research.

3.2.5. Harvesting Methods

To maximise yield, the stems of *S. hermaphrodita* are typically harvested at about 0.10–0.20 m from the ground [7,31]. Although combine/forage harvesters are the most common harvesting equipment, alternatives are often used. Examples of machinery used to harvest *S. hermaphrodita* are: forage harvesters in combination with drum choppers or balers [19,66], self-propelled harvesters [67], mowers [22,30], or cutters [33].

4. Review of *Silphium perfoliatum* L.

4.1. Origin and Botany

Silphium perfoliatum belongs to the daisy family (Compositae/Asteraceae), originates in the Centre and East of the USA and Canada [68], and is extensively grown for forage in China [69]. For the rest of this paper, it is referred to as *S. perfoliatum*. Its lush foliage is composed of up to 3 m tall stems [70] and large leaves of 85–120 cm^2 [10]. Its yellow flowers of 4–8 cm [71] make it an attractive decorative plant and is a reason it was brought to Europe in the 18th century [68,72].

S. perfoliatum is typically not harvested in the first year of cultivation because the growth is concentrated on the development of a rosette. From the second year onwards, *S. perfoliatum* stems reach average heights between 1.5 m and 2.5 m [73]. It can produce high annual yields for 15 years [72], with generous seeding and generally straightforward cultivation [69]. An alien plant survey carried out in Italy in 2009 classified this species as casual [74] and nine years later it was seen as a naturalised neophyte [75].

In the Netherlands, an ecological risk assessment concluded that the species presented low invasive risk [18]. Some organizations in North America regard *S. perfoliatum* as an invasive species due to its fast development [76]. However, after research and cultivation of *S. perfoliatum* in Europe, this species has not shown signs of invasive character [77].

Its potential as an energy crop to produce biogas began to be studied in Germany in 2009 [78], and by 2014, the area of cultivated *S. perfoliatum* had increased to 400 ha (Biertümpfel et al., 2013, cited in [78]). Gansberger et al. [78] concluded their literature review by classifying *S. perfoliatum* as a “valuable, alternative energy crop for biogas production plant with low care requirements and production costs after the first year, promising biomass and bio-methane yields, and associated environmental benefits". The environmental benefits of *S. perfoliatum* have recently been recognised by the EU, which includes *S. perfoliatum* in the list of eligible species for Ecological Focus Areas [79].

Differences between *S. perfoliatum* cultivars is a relatively un-researched area. Comparing *S. perfoliatum* plants of five different origins, Wever et al. [80] reported few genetic differences between plants from the USA, Russia, Scandinavia and Germany, but they varied from plants from Ukraine derived from a Ukrainian breeding programme. Wever et al. [80] advised increasing genetic diversity and the application of genetic breeding and genomics to guarantee *S. perfoliatum* domestication and breeding.

Franzaring et al. [28] studied the performance of six different accessions, finding high variation between them, with the most popular accession in Europe having the highest productivity. Hartmann and Lunenberg [81] explored the theory of yield being dependent on site conditions in six locations across Bavaria, Germany. They did not discover any difference in yield between the three *S. perfoliatum* varieties that they included in their experiment.

As part of the work done during the international joint research SidaTim project (please refer to Acknowledgements for more details) a new BBCH scale was created for *S. perfoliatum*, as included in Appendix B.

4.2. *Agronomy of Silphium perfoliatum*

4.2.1. Agroclimatic Requirements

S. perfoliatum is a flexible crop, able to adapt to different conditions [73,78,82]. Stanford [72] described its optimal growing conditions to be sunny places with temperatures of around 20 °C and sandy soils close to water sources. It is a resilient species, able to withstand flooding (10–15 days) and winter temperatures down to −30 °C (Koshkin, 1875; Niqueux, 1981, cited in [72]). Depending on the initial pH, *S. perfoliatum* can show a positive response to liming. For example, Jasinskas et al. [83] observed a 34% yield increase and Šiaudinis et al. [22] recorded a 23% yield increase, both raising the soil pH from 4.2–4.4 to 5.6–5.7.

Waterlogged fields are areas where traditional arable crops struggle and fail to be highly productive. Some authors have indicated that *S. perfoliatum* could be grown and is able to produce high yields in water saturated areas and poor draining land ([72], Albretch and Bures, 199, cited in [84,85]). Other authors are more cautious with their statements. Zilverberg et al. [86] mentioned that it tolerates moderate flooding while Bauböck et al. [87] acknowledged the resistance of *S. perfoliatum* to water. This observation is supported by Ruf et al. [88], who demonstrated that *S. perfoliatum* not only can withstand waterlogging but benefits from it, doubling the amount of biomass production after waterlogging during the winter period. Interestingly, they observed a strong effect of moisture availability on root biomass (free draining soils resulted in four times root biomass than excess moisture soils).

Maximum yields of *S. perfoliatum* are obtained where it has access to sufficient water, with yield reductions of at least 30% under drought conditions [89,90]. The high leaf area index and long growing season can result in high evapotranspiration rates. From a five year field experiment in China, Pan et al. [91] estimated *S. perfoliatum* to have an average annual evapotranspiration (ET) rate of about 600 mm. Water needs of *S. perfoliatum* are equivalent to maize, between 200–250 mm during the growing season, and 400–500 mm for the rest of the year (Grebe et al., 2012, cited in [78]). Schittenhelm et al. [92] calculated the ET of *S. perfoliatum* to be between 300 and 550 mm. Using an agronomic model, Schoo et al. [90] estimated an annual evapotranspiration rate of 309 and 542 mm for rain-fed and irrigated *S. perfoliatum* respectively, over two years in Lower Saxony, Germany.

As *S. perfoliatum* is a C3 plant, its water use efficiency of 30–36 kg (ha^{-1} mm^{-1}) is lower than a C4 crop like silage maize, showing 45–55 kg (ha^{-1} mm^{-1}). Hence, under conditions of limited water availability, the yields of *S. perfoliatum* are likely to be lower than those for maize. Schoo et al. [89] maintained that *S. perfoliatum* will only produce similar yields to maize in cool areas with high precipitation.

Schoo et al. [93] carried out a detailed study of the rooting system and water uptake of *S. perfoliatum*. They characterised the rooting system as woody rhizomes, which prolong into coarse distributed roots. Although roots were found at maximum depths of 1.5–1.7 m, the greatest density of roots was found in the upper 0.3 m. They observed that for a mature stand, the root depth remained stable, but a large proportion of the rooting system was renewed every year. They concluded that the limited expansion of roots constrained the capacity of *S. perfoliatum* to uptake water, which combined with high water consumption makes *S. perfoliatum* a crop with high water needs. Conversely, because *S. perfoliatum* is a C3 plant, it can produce higher yields than maize under cool conditions, and hence Schittenhelm et al. [94] recommend its use for erosion control in cool and high altitude environments.

Franzaring et al. [10] completed a detailed comparison of the responses of *S. perfoliatum* to increased temperatures, CO_2 concentrations, and drought. Compared to current climatic conditions in Germany, CO_2 fertilization (550 cm^3 m^{-3}) had a positive response, increasing yield by 26%. In the same study, higher temperature (by 4 °C) and reduced water supply (by 50%), negatively affected growth dynamics and energy output. Specific methane yield (SMY) was found to have a negative correlation with protein content and the proportion of senescent leaves.

4.2.2. Establishment Method

Establishment by Sowing

Although *S. perfoliatum* can be established from seeds sown directly in the field, an important focus of research is to develop systems that can produce high-quality seeds with a high germination rate that can achieve rapid field emergence [95]. The ripening of the infructescence of *S. perfoliatum* seeds occurs irregularly and over an extended period due to the constant new formation of flowers, resulting in the harvesting of ripe, unripe, and sterile seeds [95]. In addition, *S. perfoliatum* seeds are not homogeneous, complicating the singling process [96]. The dimension of seeds varies between 9–10 mm long, 4.5–6 mm wide, and 1–1.5 mm thick, with an average weight of 16–20 g per 1000 seeds [70,97,98].

Standard commercial precision drillers can be used to sow *S. perfoliatum* [99]. Gansberger et al. [78] recommended using a precision seeder at 15–20 mm depth. The use of a precision seeder (ED302) to sow *S. perfoliatum* seeds at 15 mm depth can enable uniform emergence [100]. Von Gehren et al. [70] proposed sowing at a more shallow depth of 10 mm. According to Köhler and Biertümpfel [99], sowing depth is a compromise between sufficient deep storage (good water supply to avoid drying out) and sufficiently flat placement for high and fast field emergence rates as well as a good density. In light soils with poorer water supply and a low tendency to crust, sowing should be a maximum of 15–20 mm depth; whilst on heavy clay soils, soils prone to erosion, and silty soils with sufficient water, it is recommended that sowing depth should be 10–15 mm in depth [99]. Schafer et al. [96] observed no significant differences between emergence and different sowing depths.

Schafer et al. [96] adjusted a precision seeder, a pneumatic single-grain seeder type ED 302 Amazone equipped with six contour sowing units and a row spacing of 0.5 m. For their sowing trials, spacing within the row of 0.16 m was chosen, corresponding to 6.4 holes in the row in combination with a row spacing of 0.5 m, leading to 12.8 holes per square meter (2.0–2.2 kg seeds ha^{-1}). Due to the high proportion of holes per square meter and the goal of maximum cover, single discs with a hole diameter of 1.2 mm were most suitable.

Continuing their previous research, Schäfer et al. [97] studied the size, geometry, singling and their impact on germination ability and power of *S. perfoliatum* seeds. They observed significant differences in size between years, better germination of two fractions of seeds (second and third), and a correlation between the thousand seeds weight and germination power (best results at 18 g per 1000 seeds). Following their directions, a sowing rate of 12 seeds m^{-2} would be sufficient, reducing costs consequently.

For seeds, Köhler and Biertümpfel [99] report that the optimal sowing time is not a specific date, but depends on the optimal soil and weather conditions to ensure rapid seed germination. On erodible soils, heavy rains after sowing may seriously delay germination or even lead to a total die back of the seedlings due to silting and crusting. Thus, reduced tilling can be beneficial at such sites where the seedbed meets the high requirements of *S. perfoliatum* [99]. Other authors have reported that sowing can be done two weeks before the first frost at the end of autumn [78] or from April [22,83,91] to May in spring, but not later [78]. Recommended sowing densities vary substantially from 2.04–2.28 kg ha^{-1} [98] and 2.0–2.5 kg ha^{-1} [78] up to 8–10 kg ha^{-1} [73,85].

There are various ways of improving the germination rate of *S. perfoliatum* seeds. Von Gehren et al. [70] compared five sowing dates between late April and mid-June and tested nine pre-treatments on the seeds, including seed pellets. The highest field emergences were recorded for the earliest sowing date, in late April, and cooling of seeds at 7 °C for 7 days. They recommend seed pelletization to improve mechanical sowing and advise early sowing. Gansberger [95] described the seed ripening and the germination process of *S. perfoliatum*, developed a reproducible method for seed processing, and adapted the *Helianthus annuus* method to define the viability of seeds. His method was based on mechanical seed screening. He examined the effectiveness of sieving plus gravity precipitation to separate the most viable seeds. Using a screening machine with a set of rounded hole sieves (8.5 mm), followed by elongated hole sieves (3 mm and 1.5 mm) and a weight reader, and resulted in a minimum seed viability of 97.5%, filtering about 50% of the starting material at the end of the process. Gansberger et al. [101], emphasized the need to treat *S. perfoliatum* seeds to increase germination and observed the positive effects of gibberellic acid, alternating light, and temperature regimes (12 h at 20/30 °C), and chilling to enhance germination capacity.

Schäfer et al. [98] also recommend the screening out of small seeds to improve field germination. Incorporating such screening techniques should help improve the field germination of seeds. They also recommend the use of hygroscopic substances to coat the seeds to absorb moisture and avoid death of young seedlings by desiccation.

An existing biogas plant in south-west Germany recently developed and patented their own *S. perfoliatum* seeds with increased establishment success [102], under the name of Metzler and Brodmann Saaten GmbH [103].

Establishment by Transplanting Seedlings

A *S. perfoliatum* field can also be established by transplanting seedling grown in a nursery. Although this is expensive and time consuming [100], it is often more effective than using seeds of variable germination rates, because of the earlier and more regular development of ground cover and higher yields [35,78,87,98,100]. In Europe, seedlings should be established no later than May or early June [78]. Franzaring et al. [10] sowed in trays in March, observing the germination after 22 days, or 9 days in case of increased temperatures (+4 °C), and then transferred the seedlings to the field in April at a density of 4 plants m^{-2}. Zilverberg et al. [86] produced their seedlings in a greenhouse before transferring them to a field experimental site in mid-June.

Vegetable or strawberry planters are commonly used for the mechanical planting of *S. perfoliatum* seedlings [100]. Spacing used between rows have varied from 0.5 m [81,90,91] to 0.6 m [73], 0.75 m [78] and 1 m [22,33,83]. The distance between plants inside rows has ranged from 0.12 m [73] to 0.50 m [22,33,78,83,90].

Slepetys et al. [21] established their *S. perfoliatum* experimental area at 10,000 plants ha^{-1}. Šiaudinis et al. [22,33,104], planted in early June at 20,000 plants ha^{-1}. Pichard [73] selected a higher plant density of about 140,000 plants ha^{-1}. Zilverberg et al. [86] left 30 cm between plants, which would correspond to over 110,000 plants ha^{-1}. Franzaring et al. [10] and Gansberger et al. [78] both recommended a planting density of four plants per square meter, equivalent to 40,000 plants ha^{-1}. This planting density was also used by other researchers [81,90,92,93].

In the second year after planting, *S. perfoliatum* can produce 5–7 flowering stems per plant equating to about 38–40 stems per m^2 (Niqueux, 1981, and Puia and Szabo, 1985, cited in [72]). Mueller and Dauber [105] also reported about 6–7 stems by plant, whereas Gansberger et al. [78] reported 10–25 flowering stems per plant. The number of stems increases with age, with Šiaudinis et al. [33] reporting 5–6 stems per plant on the second year of cultivation, increasing to about 12 stems per plant in the fourth year.

4.2.3. Weeds, Pests, and Diseases

Weed control is critical during establishment as *S. perfoliatum* seedlings are uncompetitive [78]. Köhler and Biertümpfel [99] highlight that successful weed control in the first year is essential for high yields and the cost reduction of maintenance and weed control in the second year. Schorpp and Schrader [106] describe the use of a cultivator for the mechanical control of weeds.

The place occupied by *S. perfoliatum* in the rotation can be important too. According to Köhler and Biertümpfel [99], *S. perfoliatum* should follow weed-suppressing crops, e.g., root crops, cereals, as well as maize but should not follow unfavourable previous crops like rape, sunflowers, peas, vegetables, and potatoes because these are generally regarded as possible host plants for the fungal disease *Sclerotinia*.

Sclerotinia and *Botrytis* can affect the stems and flower buds of *S. perfoliatum* respectively (Niqueux, 1981, cited in [72]). The susceptibility of *S. perfoliatum* to *Sclerotinia* spp. was also mentioned by Köhler and Biertümpfel [99] and Gansberger et al. [78]. Recently, a new species of fungi (*Ascochyta silphii* sp. nov.) causing dark spots on the leaves of *S. perfoliatum* was discovered in Austria [107], but the impact was not significant. Franzaring et al. [28] noticed heavy wilting and necrotic spots on one out of four different accessions, suspected to be caused by the bacteria *Pseudomonas syringae*. Schoo et al. [90] applied boscalid and pyraclostrobin against *Botrytis cinerea*.

There are reports of three species of moth affecting *S. perfoliatum* leaves primarily: the silver Y moth *(Autographa gamma)*; the mouse moth *(Amphipyra tragopogonis)*; and the broad-barred white moth *(Hecatera bicolorata*) (Neumerkerl et al. 1978, cited in [78]). The larvae of the giant Eucosma moth (*Eucosma giganteana*) (Johnson and Boe, 2011; Johnson et al., 2012, cited in [78]) and the tumbling flower beetle (*Mordellistena* cf. *aethiops* Smith) have been reported (Johnson et al., 2012, cited in [78]). Additionally, one species of aphid (*Uroleucon* cf. *ambrosiae*), a parasitoid wasp (*Acanthocaudus n.sp.*), and a fruit fly (*Neotephritis finalis*) are included in the reports (Johnson and Boe, 2011, cited in [78,108]). Gansberger et al. [78] identified larvae of the giant Eucosma moth (*Eucosma giganteana* Riley) as the most concerning pest of *S. perfoliatum*.

4.2.4. Nutrient Management

Varying application rates have been used in experimental studies, ranging for nitrogen from 0 to 400 kg N ha^{-1}, rates of phosphate up to 175 kg P ha^{-1}, and potassium up to 237 kg K ha^{-1} (Table 4).

Jasinskas et al. [83] reported a yield benefit of 27% at a nitrogen application of 120 kg ha^{-1}, compared to the yield at 60 kg N ha^{-1}. Šiaudinis et al. [104] tested different doses of ammonium nitrate, i.e., 0, 60, and 120 kg N ha^{-1}, the latter split in two doses between mid-April and end of July. The application of 120 kg N ha^{-1} produced the greatest yield, 21.94 t DM ha^{-1} y^{-1}. They repeated their experiment using the same fertiliser doses in a subsequent field experiment, this time harvesting 13.67 t DM ha^{-1} y^{-1} at the highest N dose. Han et al. [84] recommended applying 150 kg N ha^{-1} to *S. perfoliatum*. Pichard [73] also found a significant yield response up to 100 kg N ha^{-1} with only moderate yield increases above this value. Pan et al. [91] in China applied 92 kg N ha^{-1} in their experiment, an amount that was chosen based on the averages used by local farmers.

Table 4. Reported fertiliser application rates of *S. perfoliatum* (in kg ha^{-1}).

N	P	K	Author, Year	Reference
150	-	-	Han et al., 2000	[84]
100	80	100	Kowalski, 2007	[109]
92 ^{e}	79 ^{e}	66 ^{e}	Pan et al., 2011	[91]
0/60/120	26	33	Slepetys et al., 2012	[21]
0/60/120	26	33	Šiaudinis et al., 2012	[104]
200 ^{e}/0–400	0–175	55 ^{e}/110	Pichard, 2012	[73]
0/60/120	26 ^{e}	33 ^{e}	Jasinskas et al., 2014	[83]
160	-	-	Emmerling, 2016	[110]
150 ^{e}	40 ^{e}	150–200 ^{e}	Frölich et al., 2016	[111]
170	30–41	199–237	Schoo et al., 2017	[93]
0/60/120	26	33	Šiaudinis et al., 2017	[33]
140	-	25	Facciotto et al., 2018	[35]
50/100/150	21	27	Ustak and Munoz, 2018	[112]
90	13	33	Stolarski et al., 2019	[51]
60 ^{e}/40–80	35 ^{e}	80 ^{e}	Bury et al., 2019	[36]
60	60	60	Šiaudinis et al., 2019	[113]
100 ^{e}/150	-	-	Wever et al., 2019	[80]

^{e} establishment year exclusively.

Applications of 26 kg P and 33 kg K ha^{-1} at establishment have been common in various trials [21]. For phosphorus, the highest application of 175 kg P ha^{-1} (400 kg P_2O_5 ha^{-1} as a triple superphosphate) are reported in an experiment by Pichard [73], and the results suggested that *S. perfoliatum* has very low requirements for P, having no impact on yield after a baseline is reached. By contrast, Šimkūnas et al. [114] in Lithuania observed a negative effect on *S. perfoliatum* yields of an increased soil phosphorus concentration from 220 to 290 mg P_2O_5 kg^{-1}. In Germany, Frölich et al. [111] recommended the application of magnesium in the year of establishment (50–70 kg ha^{-1} Mg), with organic fertilization afterwards. The German specialist agency in renewable resources, *Fachagentur Nachwachsende Rohstoffe e.V.* (FNR) recommended the application of 50 kg N ha^{-1} in the establishment year, and 130–160 kg N ha^{-1}, 55–70 kg ha^{-1} P_2O_5, 180–240 K_2O, and 80–120 kg ha^{-1} MgO annually [115].

Per unit dry mass, harvesting *S. perfoliatum* removes broadly similar amounts of nitrogen, phosphorus, and potassium as a maize crop [116] (Table 5). According to the Thuringian State Institute of Agriculture (TLL), *S. perfoliatum* extracts 140–160 kg N ha^{-1}, 25–30 kg P ha^{-1}, 200–250 kg K ha^{-1}, 50–70 kg Mg ha^{-1}, and 250–300 kg Ca ha^{-1} [117]. Assuming a dry matter yield of 10 t ha^{-1} y^{-1}, the annual harvest of a *S. perfoliatum* crop would remove about 81 kg N, 21 kg P and 141 kg K. The levels of magnesium in harvested *S. perfoliatum* are significantly greater than in harvested maize, an observation also reported by Ustak and Munoz [112]. This could help explain why Frölich et al. [111] applied magnesium fertiliser during crop establishment.

Table 5. Mean concentration of five nutrients (g kg^{-1} DM) of harvested *S. perfoliatum* in comparison to silage maize [116].

Species	N	P	K	Mg	Ca
S. perfoliatum	8.1	2.1	14.1	3.9	22.1
Silage maize	11.0	2.6	12.5	1.2	2.1

In a similar way to the work on *S. hermaphrodita*, studies on *S. perfoliatum* have indicated that some nutrients can be provided by application of digestates. For example Ustak and Munoz (2018) applied 48.6 fresh tonnes of digestate per hectare (3.33 t DM ha^{-1}; 7.8% DM), but this was supplemented with mineral fertilisers to supply potassium, sulphur, calcium, magnesium, copper, cobalt, and boron. Šiaudinis et al. [113] compared mineral fertilization to granulated sewage sludge, recording better performance as well as increased soil quality and microbial activity at a granulated sewage sludge dose of 45 t ha^{-1}.

4.2.5. Harvesting Methods

S. perfoliatum plants are typically harvested at a height of between 0.05–0.10 m [22,91], 0.18 m [73], and 0.2 m [102] above ground. *S. perfoliatum*, like *S. hermaphrodita*, can be cut with a great range of machinery including a rotary mower [104] or rotary reaper [83]. Forage harvesters and balers are recommended by Jasinskas et al. [19]. Von Cossel et al. [102] also noted the use of a forage harvester on an existing commercial *S. perfoliatum* plantation. Standard maize harvesters are suitable for *S. perfoliatum* harvest [10,78]. Schoo et al. [89] used a single-row chopper attached to a tractor.

5. Use of *Sida hermaphrodita* and *Silphium perfoliatum* to Produce Bioenergy

Both *S. hermaphrodita* and *S. perfoliatum* can be used for bioenergy production. As perennial crops, the yields from *S. hermaphrodita* and *S. perfoliatum* increase during the first five years after establishment. However, the optimum timing of harvest and the associated dry matter and energy yields depends on the form of bioenergy production (Figure 1). In broad terms, both crops can potentially be used to produce (i) biomass for direct combustion or (ii) biomass to produce biogas. However, it is generally recommended that *S. perfoliatum* is used for biogas production only. There has also been research on the use of *S. hermaphrodita* for gasification.

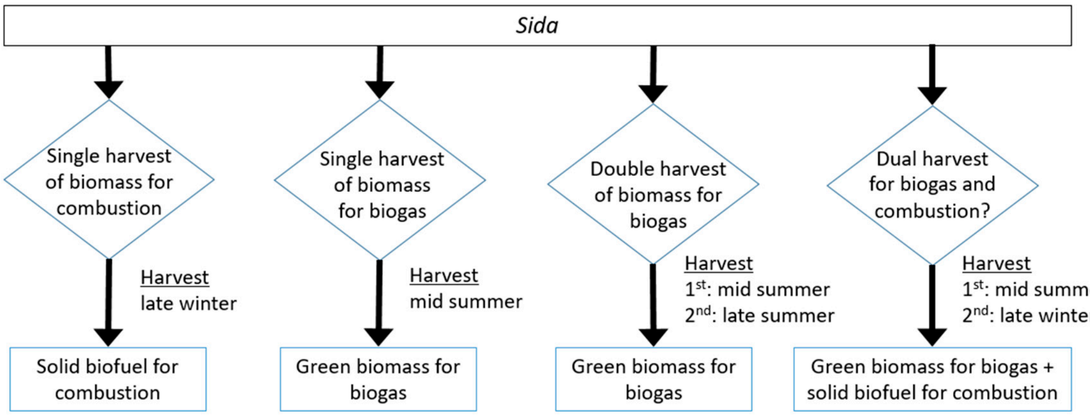

Figure 1. *S. hermaphrodita* can provide biomass for combustion or biomass for biogas; *S. perfoliatum* is generally only harvested as green biomass for biogas.

5.1. *Sida hermaphrodita and Silphium perfoliatum Yields*

5.1.1. *Sida hermaphrodita* Yield

The yield of *S. hermaphrodita*, for a given plant spacing, has been related to the number of shoots per plant and the mean diameter of the shoots [43]. For *S. hermaphrodita*, yields vary greatly depending on soil type, climatic conditions, fertilization, and weed control [14]. Depending on the establishment method and intended use, yields in the first year of cultivation can vary from 0.4 to 6.6 t DM ha^{-1} y^{-1} [35]. In the initial year, the dry matter yields obtained by harvesting biomass for combustion tend to be less than those obtained for biogas. In the first year, von Gehren et al. [32] harvested 1.0–2.1 t DM ha^{-1} y^{-1} for combustion and 1.2–2.4 t DM ha^{-1} y^{-1} for a single cut for biogas production, and Facciotto et al. [35] obtained 0.4–4.3 t DM ha^{-1} y^{-1} for combustion and 2.8–6.6 t DM ha^{-1} y^{-1} for biogas.

Mean annual yields tend to increase in the second and third year with values ranging from 2.9 to 20 t DM ha^{-1}. Facciotto et al. [35] reported second year annual yields of 2.9–10.2 t DM ha^{-1} for combustion and. 2.9–15.1 t DM ha^{-1} for biogas. Other second year annual yields have been: 5 t DM ha^{-1} [10,33]; 8.4 t DM ha^{-1} [20]; 10.2–11.9 t DM ha^{-1} [24], and 20 t DM ha^{-1} [17].

Mean yields in the second and third years continue to vary with establishment method and the sort of biomass harvested. Stolarski et al. [29] reported average annual yields from the second and third years of 10.4 t DM ha^{-1} from seeds, 11.2 t DM ha^{-1} from rhizomes, and 11.8 t DM ha^{-1} from seedlings. After the second year, the yield benefit of harvesting for biogas, rather than for combustion, seems to reverse. For the second and third year of *S. hermaphrodita* cultivation, Bury et al. [36] recorded 5.8–10.7 t DM ha^{-1} y^{-1} for combustion and 6.0–19.5 t DM ha^{-1} y^{-1} for biogas. Siwek et al. [52] obtained biogas yields of 9.2–15.1 t DM ha^{-1} y^{-1} and 4.8–8.5 t DM ha^{-1} y^{-1} on the second and third year respectively. Von Gehren et al. [32] harvested respectively 7.1–9.7 t DM ha^{-1} y^{-1} and 13.2–14.3 t DM ha^{-1} y^{-1} on the second and third year of cultivation for combustion, and 6.6–9.5 t DM ha^{-1} y^{-1} (second year) and 7.3–8.6 t DM ha^{-1} y^{-1} (third year) for biogas production.

From the second to fourth year of cultivation, Tilvikiene et al. [50] reported a mean yield of 12.30 t DM ha^{-1} y^{-1}. Jankowski et al. [42] obtained a yield of 11.5 t DM ha^{-1} y^{-1} on the fourth year of cultivation. After the fourth year, yields typically plateau [7,16,41]. Borkowska et al. [20] harvested 8.4 t DM ha^{-1} from the first to the fourth year. Molas et al. [31] obtained on average 12.4, 8.8, 13.7 t DM ha^{-1} y^{-1} from the third, fourth, and fifth year of cultivation. Šiaudinis et al. [22] obtained increasing yields of 4.7, 6.2, 6.0, 7.4 t DM ha^{-1} y^{-1} on the third, fourth, fifth, and sixth years of experiment respectively. Harvesting for biogas in a six years experiment, Jankowski et al. [53] recorded average yields of 4.1–5.4 t DM ha^{-1} y^{-1} (increasing yield up to 9.4 t DM ha^{-1} y^{-1} on the third year and progressively reducing to 2.9 t DM ha^{-1} y^{-1} on the sixth year).

From a nine years experiment, Matyka and Kuś [43] reported average yields of 1–2 kg DM m^{-2} y^{-1}, corresponding to 10–20 t DM ha^{-1} y^{-1}. From their fifteen years experiment, Krzyżaniak et al. [38] report total yields from 42.9 t ha^{-1} (lowest) to 86.7 t DM ha^{-1} (highest), equivalent to 2.9–5.8 t ha^{-1} y^{-1} for the control and dried digestate fertilised options respectively.

Yields from a single annual harvest varied between 8 and 14 t DM ha^{-1} [15]. Reported yields from double harvesting are 7–10 t DM ha^{-1} y^{-1} [32], 10–12 t DM ha^{-1} y^{-1} [36], 15–20 t DM ha^{-1} y^{-1} [15]. However, Oleszek et al. [15] indicated that double harvests could reduce the life span of the crop in the long term. In line with this theory, von Gehren et al. [32] observed a reduction in the yield after the second year from double harvesting of *S. hermaphrodita* for biogas production. Another possibility with *S. hermaphrodita*, is dual harvesting, harvesting first at BBCH 55 in summer for biogas production and then harvest a second time at BBCH 98 in winter for combustion [17].

The highest *S. hermaphrodita* yields are obtained when it is grown on rich soils but not too heavy, with good water supply and aeration, under favourable weather conditions [43]. Yields of 15–20 t DM ha^{-1} y^{-1} are reported for water-retentive clay loamy soils (Borkowska, 2007, cited in [20]), compared to 13 t DM ha^{-1} y^{-1} on clay sandy soils [41] and 8.4 t DM ha^{-1} y^{-1} on light sandy loams [20]. Szwaja et al. [118] mentioned yields of 10 t DM ha^{-1} y^{-1} without including further details. Tilvikiene et al. [50] reported an average of 12 t DM ha^{-1}. Feledyn-Szewczyk et al. [30] harvested 17.7 t DM ha^{-1} y^{-1} as opposed to 14.5 t DM ha^{-1} y^{-1} from two plantations established by seedlings and seeds respectively.

5.1.2. *Silphium perfoliatum* Yield

For *S. perfoliatum*, a rosette is produced in the establishment year and the crop is not harvested. Flowering occurs from the second year, and maturity is achieved in the fourth-fifth year after planting [72]. Annual yields in the second year after planting range from 4.5–8.5 t DM ha^{-1} [104], 5.5 t DM ha^{-1} [70], 7 t DM ha^{-1} [22], 11.5 t DM ha^{-1} [10], to 9.5–26.6 t DM ha^{-1} [35]. Siwek et al. [52] obtained yields of 14.5/25.7 t DM ha^{-1} y^{-1} and 19.9/12.2 t DM ha^{-1} y^{-1} from single/double harvesting on the second and third year respectively. From three year *S. perfoliatum* plantations, reported annual yields vary from 7.5 t DM ha^{-1} [21], 10.2–18.0 t DM ha^{-1} [36], 13.5 t DM ha^{-1} [33], and 11.5–22 t DM ha^{-1} [104].

After the third year, yields can start to stabilise. Šiaudinis et al. [113] harvested 5.5, 12.9, and 12.0 t DM ha^{-1} on the 2nd, 3rd, and 4th years. From the 2nd, 3rd, 4th, and 5th years, von Cossel et al. [119] collected 17.3, 18.1, 21.7, and 27.8 t DM ha^{-1}. Šiaudinis et al. [22] harvested 13.1, 13.5, 11.1, 12.4 and 8.2 t DM ha^{-1} on the 3rd, 4th, 5th, 6th and 7th year of experiment, respectively. These values are similar to predicted yields from the PIXGRO model developed by Ruidisch et al. [120] ranging from 12.7 to 23.3 t DM ha^{-1} y^{-1} over a 10 year period. From two six-year old plantations Schorpp and Schrader [121] harvested between 13–18 t DM ha^{-1} y^{-1}.

Mature reported *S. perfoliatum* yields range between 12 t DM ha^{-1} y^{-1} and 21 t DM ha^{-1} y^{-1}. Reported annual DM yields per hectare include 12–18 t [112]; 13 t [83]; 15 t [102]; 15.6 t by double harvest [104]; 15 t [111]; 15.5 t [80], 17.6 t (Conrad M., 2015, cited in [78]), and 15–21 t [73]. A yield of 18.3 t DM ha^{-1} y^{-1}, based on an actual average yield from East Central Germany, was used to calibrate a model (PIXGRO) [120]. Combining mineral and organic fertilization, Vetter et al. (2010, cited in [78]) obtained 20 t DM ha^{-1} y^{-1}. Zilverberg et al. [86] recorded 25 t DM ha^{-1} y^{-1}.

In their literature review, Gansberger et al. [78] noted a reduction in the yield of *S. perfoliatum* grown at high latitudes, explained by short growing season. They estimated an average yield of 15 t DM ha^{-1} y^{-1} and concluded that this species "can compete with current energy crops in terms of dry matter yield". However Franzaring et al. [10] has highlighted that *S. perfoliatum* yields can increase when the crop is grown at high altitudes, perhaps because of the increased water availability. Hartmann and Lunenberg [81] in a study of *S. perfoliatum* yields across six locations across Bavaria, Germany, also identified water availability and nutrient-rich soils as a key determinant for high yields, and Ruidisch et al. [120] found a similar correlation with the yields of *S. perfoliatum* in a modelling study increasing from lowland to highland sites in Germany. Schittenhelm et al. [92] also highlight the importance of water availability obtaining 16.1 t DM ha^{-1} y^{-1} from irrigated plants and 10.8 t DM ha^{-1} y^{-1} from non-irrigated plants.

The above yield results suggest that *S. hermaphrodita* and *S. perfoliatum*, in the correct environment and with the correct management, can achieve similar yields to other biomass crops such as maize and short rotation coppice. In their modelling study, Ruidisch et al. [120] reported that *S. perfoliatum* (13–23.5 t DM ha^{-1} y^{-1}) could produce higher yields than silage maize (9.8–15.4 t DM ha^{-1} y^{-1}). However Schoo et al. [89] reported that *S. perfoliatum* could only achieve similar yield to maize in cool areas with high precipitation.

5.2. Growing Sida hermaphrodita and Silphium perfoliatum as Solid Biofuel for Combustion

An important positive aspect of bioenergy crops for combustion is the low moisture content of the biomass at harvest, simplifying very much the logistic of biomass. Because of this, biomass for direct combustion is best left to be harvested in winter when (i) the moisture content is reduced due to the absence of green leaves, and (ii) nutrients are reallocated back to the unharvested roots [111].

Comparing the combustion of three tree species and three energy crops including *S. hermaphrodita*, Majlingová et al. [122] concluded energy crops to be more advisable for the production of bioenergy, based on energy properties and yields.

Biomass quality for combustion is defined by its moisture content, which changes with harvest time. If *S. hermaphrodita* is to be used for biomass combustion, delaying harvest until the end of winter allows the material to dry on the field, lowering moisture and ash content [55], achieving moisture contents of around 20% and, therefore, minimizing drying costs. In contrast, willow and poplar contain 45–60% moisture when harvested [123] and does not vary much with harvest date [124]. Pszczółkowska et al. [16] and Šiaudinis et al. [22] recommend that *S. hermaphrodita* stems for combustion should be harvested after late September and before the start of new growth in March. Harvesting late in winter enables the stems to naturally dry in the field as the moisture content can decline from 28–40% in November to 14–20% in February–March [16,41]. Stolarski et al. [124] compared five harvest times (November-April) and eleven energy crops. They recorded that spring harvested *S. hermaphrodita* had lower moisture content, lower ash and sulphur content, higher low heating value (LHV), higher carbon content, higher hydrogen content, and generally was the highest quality solid fuel among all. In the same line, Bilandžija et al. [55] compared three harvest times, obtaining lower moisture, ash, nitrogen, sulphur, and carbon, and higher fixed carbon contents in spring.

In their literature review, Nahm and Morhart [14] reported average high heating values (HHV) and low heating values (LHV) for *S. hermaphrodita* of 18.4 MJ kg^{-1} and 16.1 MJ kg^{-1} respectively. The reported calorific value of *S. hermaphrodita* stems ranges from 15.0 (LHV) to 19.4 (HHV) MJ kg^{-1} (Table 6). At the upper range, this value is similar to industrial wood [125].

If harvest is delayed too long, then the calorific value of the biomass can decline. Franzaring et al. [28] observed a reduction in the calorific value from 17.4 to 15.8 MJ kg^{-1} when *S. hermaphrodita* stems were harvested in early December compared to mid-April. After monitoring the heating value of *S. hermaphrodita* for six years, Jankowski et al. [53] noted an increase of the HHV with the age of the plantation (from 18.5 to 19.4 MJ kg^{-1}).

After harvest, the stems of *S. hermaphrodita* can be used to produce high quality pellets that meet the standards of solid biofuels [32] using common wood pellet production technology: chopping, milling followed by horizontal array granulator, and pressing [19,66]. The reported calorific values for *S. hermaphrodita* pellets range from 16.5 to 19.5 MJ kg^{-1} (Table 6). After combustion, they found minor slag formation and recorded ash to be around 3%. Von Gehren et al. [32] obtained better quality pellets, lower energy consumption, and greater process stability after using a pan grinder mill and a flat die press. They suggested replacing artificial drying with storage, allowing *S. hermaphrodita* stems to dry naturally for six months. Urbanovičová et al. [126] produced *S. hermaphrodita* briquettes using a hydraulic press, reporting a calorific value of 15 MJ kg^{-1}. They reported that the briquettes had a similar density, durability, moisture content, and calorific values as briquettes produced from other crops.

The ash and sulphur content of bioenergy crops can be a major constraint to their use in biomass burners, but the ash and sulphur content of *S. hermaphrodita* is remarkably low. Among more than 10 herbaceous plants as well as three woody species, Slepetys et al. [21] found this species to contain among the lowest amounts of sulphur and the smallest of ash, i.e., 2.80%. Additionally, the ash composition after the combustion of *S. hermaphrodita* was studied [17,118]. They attempted to characterize the ash melting point and were able to say that it is higher than 1500 °C. This suggests that issues of ash melting and deposition are less likely during the combustion of this material. Von Gehren et al. [32] detected high levels of Ca and Mg in the ashes from *S. hermaphrodita*, indicating positive ash melting behaviour. Szwaja et al. [118] detected high levels of Ca, K, and P_2O_5. The fertilising potential of the ashes from the combustion of *S. hermaphrodita* need further investigation. In addition, Stolarski et al. [34] demonstrated how moisture and ash content decrease in concentration, and how the heating value increases for both *S. hermaphrodita* and *S. perfoliatum* as the harvest date is postponed, improving in March.

The concentration of emissions originated during the combustion process of *S. hermaphrodita* pellets has also been investigated. In comparison to standard wood pellets, Zajac et al. [127] observed that the combustion of *S. hermaphrodita* pellets produced very low sulphur dioxide emissions, lower CO_2 emissions, and higher concentrations of other pollutants (CO, NO, NO_x). Streikus et al. [66] and von Gehren et al. [32] both analysed the combustion of *S. hermaphrodita* pellets recording the composition of the gas emitted in the process, registering adequate levels of CO and NO_x, but high levels of particulate matter (PM).

Some studies have more recently focussed on the combustion process itself. Using a three pseudo-component model, Trinh et al. [128] studied the kinetics of the thermal decomposition process of *S. hermaphrodita,* obtaining the derivative thermogravimetric (DTG) curves and kinetic data. Continuing the experiment, Werle et al. [129] published the corresponding thermogravimetric (TG) and DTG curves, observing that variations in thermal composition between sites were caused by the different pH and heavy metal composition of the soils.

Calorific values for *S. perfoliatum* stems of about 16.5–18.9 MJ kg^{-1}, and for pellets values of 17.2–17.5 MJ kg^{-1} have been reported (Table 6). Wrobel et al. [130] studied the mechanical durability and specific density of *S. perfoliatum* briquettes manufactured under different conditions. According to their experiments, crushing the plant material is adequate for briquette fabrication, observing a correlation between compaction pressure and durability. They concluded encouraging the use of this plant for briquette production, classifying it as a "suitable raw material". After considering chaff and mill fractional composition, *S. perfoliatum* was found more suitable for pelletizing than common mugwort (*Artemisia vulgaris* L.) [83].

Jasinskas et al. [19] used a drum chopper to harvest *S. perfoliatum*, followed by the use of a hammer mill and subsequent pressing for pelletizing, including a granulator with horizontal array, followed by evaluation of the fraction composition. They obtained moisture contents of 15.2% and 8.2% for chopped and milled material, respectively. Styks et al. [131] studied the density and durability of *S. hermaphrodita* and *S. perfoliatum* pellets. They observed best results at a compaction pressure of 262 MPa and a moisture content of 8% for *S. perfoliatum* and 11% for *S. hermaphrodita*. Šiaudinis et al. [22] analysed the fractional composition and pellet characteristics of both *S. perfoliatum* and *S. hermaphrodita*, obtaining moisture contents of 9.6% and 11.6%, respectively. They concluded recommending the use of the first species for biogas production and the second as solid biofuel.

Table 6. Reported calorific value, and moisture, ash, and sulphur content of *S. hermaphrodita* and *S. perfoliatum* for biomass combustion.

		Calorific value ($MJ\ kg^{-1}$)	Moisture Content (%)	Ash Content (%)	Sulphur Content (%)	Details	Author, Year	Reference
S. hermaphrodita	**Stems**	16.0 (CV)	-	-	-	December/April	Franzaring et al., 2014	[28]
		18.7 (CV)	14.1/5.9	-	-	chaff/mill	Jasinskas et al., 2014	[19]
		18.7 (HHV); 14.9 (LHV)	18.0	2.4	0.029	April	Stolarski et al., 2014	[124]
		19.2 (HHV); 15.0 (LHV)	20	1.8	0.03	March	Stolarski et al., 2018	[34]
		16.1 (LHV)	14.0	-	-	-	Kurucz et al., 2018	[24]
		18.7 (HHV); 15.6 (LHV)	32.2	2.9	-	-	Zachar et al., 2018	[132]
		17.6 (LHV)	18.6	1.9	0.23	spring	Bilandžija et al., 2018	[55]
		16.1 (CV)	9.9	-	-	-	Schonhoff et al., 2019	[133]
		17.0–17.7 (LHV)	19.0–23.6	2.1–5.1	0.024–0.042	BBCH 98	von Gehren et al., 2019	[32]
		18.0 (HHV); 16.6 (LWV)	10	1.57	-	-	Szwaja et al., 2019	[134]
		17.3–19.4 (HHV)	-	-	-	-	Jankowski et al., 2019	[53]
		17.5 (HHV)-16.2 (LHV)	7.5	0.55	0	mill	Magdziarz et al., 2020	[135]
		17.8 (HHV)-16.5 (LHV)	6.9	1.97	-	-	Śliz and Wilk, 2020	[136]
	Pellets	17.5–18.4 (LHV)	9.6	6.1	0.17	-	Šiaudinis et al., 2015	[22]
		16.8 (CV)	7.7	2.9	0.07	-	Zajac et al., 2017	[127]
		19.5 (HHV); 16.5–17.2 (LHV)	12	2.7–3.0	0.024–0.028	-	Jablonowski et al., 2017	[17]
		17.4 (CV)	9.6	-	-	-	Streikus et al., 2019	[66]
		17.2 (CV)	7.1	-	-	-	Schonhoff et al., 2019	[133]
		17.5 (LHV)	7.8	2.6	-	-	von Gehren et al., 2019	[32]
S. perfoliatum	**Stems**	16.5 (CV)	-	-	-	September	Šiaudinis et al., 2012	[104]
		18.9 (HHV); 14.9 (LHV)	18.5	3.0	0.034	April	Stolarski et al., 2014	[124]
		17.2–17.5 (CV)	15.2/8.2	-	-	chaff/mill	Jasinskas et al., 2014	[19]
		18.8 (HHV); 14 (LHV)	22	3.4	0.04	March	Stolarski et al., 2018	[34]
	Pellets	17.2–17.5 (LHV)	11.6	10.0	0.07	-	Šiaudinis et al., 2015	[22]

HC: Heat of combustion; CV: Calorific value; HHV: Higher heating value; LHV: Lower heating value5.3. Growing Sida hermaphrodita and *Silphium perfoliatum* as green biomass to produce biogas.

S. hermaphrodita has been recommended as biomass stocks for the production of methane through the process of anaerobic digestion [137]. *S. perfoliatum* has been used in the same process in Germany, where extensive research has been conducted and where *S. perfoliatum* is seen as an interesting biogas feedstock alternative, as well as a complementary option to forage maize, from both an economic and ecological point of view [111]. Methane yields of *S. perfoliatum* differ only 5–10% from methane yields of maize [112]. Frölich et al. [111] introduced the patented idea of growing *S. perfoliatum* together with maize as cover crop.

The capacity of a biomass source to produce methane depends on the dry matter content, which determines the concentration of lignin, hemicellulose and cellulose, and ultimately the amount of carbohydrates, proteins, and fats. The higher the lignin, hemicellulose and cellulose contents, the lower the methane yield. The carbon nitrogen ratio in *S. hermaphrodita* varies substantially from 22.4:1 reported by Oleszek et al. [15] to 198.8:1 reported by Slepetys et al. [21]; the carbon nitrogen ratio in *S. perfoliatum* ranges from 75:1 to 124:1 [21], as can be seen in Table 7.

By contrast, biogas production is maximised if the biomass has appropriate quantities of sugars, proteins, and fats and, hence, highest yields are typically achieved by harvesting the crop during the summer. Maximising biogas production requires that both crops are harvested at the right time. As the crop develops, the levels of acid detergent fibre (ADF) and neutral detergent fibre (NDF) vary, crude protein declines, and the proportion of dry matter tends to increase (Majtkowski et al., 2009, cited in [78]. Early harvests also imply lower content of ash, ADF, NDF, and higher content of favourable compounds for anaerobic digestion [10], (Majtkowski et al., 2009, cited in [78]). Franzaring et al. [10] reported that the specific methane yield from *S. perfoliatum* decreased with reduced water supply as the level of protein and crude ash increased. Increased concentrations of both ADF and acid detergent lignin (ADL) in *S. perfoliatum* have a negative influence on specific methane yield [80].

The production of methane requires high concentrations of sugars, fats, and proteins. Reported biogas and methane yields for *S. hermaphrodita* and *S. perfoliatum* are summarised in Table 8. Biogas yields of *S. hermaphrodita* vary between 256 $dm^3\ kg^{-1}$ organic dry matter (oDM) [17] and 730 $dm^3\ kg^{-1}$ oDM [138] and methane yields vary between 131 $dm^3\ kg^{-1}$ oDM [17] and 394 $dm^3\ kg^{-1}$ oDM [138]. Methane yields of *S. perfoliatum* vary between 227 $dm^3\ kg^{-1}$ oDM [77] and 315 $dm^3\ kg^{-1}$ oDM [92].

S. hermaphrodita can be harvested once or twice to produce biogas. Single harvesting *S. hermaphrodita* should be performed at the flowering phase in summer [67], at BBCH 55 [17], or BBCH 71 [53]. Double harvesting is recommended to be done at BBCH 55 and 71 [17].

Initially, the recommended harvest date of *S. perfoliatum* for the production of biogas was unclear. Some authors mentioned quite a wide window ranging from late August or early September [121], to mid-end September [104], and some advised harvesting at the end of flowering, corresponding to BBCH 69, or at the start of seed ripening [78,112] (BBCH 81). Depending on the harvest date, the dry matter content of harvested *S. perfoliatum* material ranges from 20–25% in spring [104] to 51% at the end of summer [21], and the dry matter content can be used to identify the best harvest date. More recently, some authors have recommend harvesting *S. perfoliatum* to maximise biogas production when the dry matter content is specifically 26–28% [81] or 30% [88].

Table 7. Physicochemical properties of *S. hermaphrodita* and *S. perfoliatum* for anaerobic digestion.

	S. hermaphrodita							***S. perfoliatum***		**Maize**
Parameter	**Michalska et al., 2012**	**Slepetys et al., 2012**	**Oleszek et al., 2013**	**Pokój et al., 2015**	**Dębowski et al., 2017**	**Rusanowska et al., 2018**	**Dudek et al., 2018**	**Slepetys et al., 2012**	**Haag et al., 2015**	**Pokój et al., 2015**
Material			Silage	Silage	Silage	Silage	Silage		Silage	Silage
Time of harvest		October	July	Flowering	BBCH 55			October	August	BBCH 12
Dry matter, DM (%) [a]		51.0	25.55		37.43	28	27.60	38.5	24.65	
Organic dry matter, oDM (% DM) [b]			90.91		77.12	92.20	91.90		22.02	
pH			5.53		7.24	7.6–7.9				
C (%)	45.9	47.3	39.21	44.7	43.95 $C_{T\ org} =$ 39.77	41.3	41.7	44.67		43.9
N (%)	0.3	0.34	$N_{org} = 1.68$ $N_{am} = 0.13$	1.5	0.28	0.5	0. 5	0.50		1.6
C:N		129.7–198.8	22.43		142.55			75.0–124.4		
S (%)	0.0	0.05						0.04		
Ash (%)	3.6	3.75	9.46			6.8 (%DM)		9.76	10.6	
Neutral detergent fibre, NDF (%)		81.17		60.2				69.83	54.9	40.0
Acid detergent fibre, ADF (%)		71.40		50.3				62.73	47.7	25.0
Lignin content (%)	19.1	12.60		8.5				12.97		3.6

[a] Dry Matter (DM) = Total Solids (TS); [b] Organic Dry Matter (oDM) = Volatile Solids (VS).

Table 8. Values of the biogas and methane yields from *S. hermaphrodita* and *S. perfoliatum* reported in the literature.

	Details	**Biogas yield (dm^3 kg^{-1} oDM)**	**Methane yield (dm^3 kg^{-1} oDM)**	**Reference**
S. hermaphrodita	Double harvest	435	220	[15]
	BBCH 55	420	204	[17]
	BBCH 77	269	131	[17]
	BBCH 91	256	125	[17]
	Novel reactor	630–730	340–394	[138]
	Batch/Continuous	-	316/252	[32]
S. perfoliatum	BMP *	-	260	[78]
	BMP	-	290	[10]
	CBT */HBT *	-	227/251	[77]
	-	-	296/315	[92]
	Batch	-	254–298	[112]
	HBT	-	266	[80]
	Batch	-	260	[119]
	Real biogas plant	-	300	[102]

* BMP = Biochemical methane potential; CBT = Continuous biogas test; HBT = Hohenheim biogas yield test.

Using *S. perfoliatum* for biogas production can also be done as a single or double harvest. Bury et al. [36] harvested once in October. Double harvest has been recommended to increase yields [104]. The harvest date for double harvesting vary in literature: mid-June (during early development of flower buds) and September (prior to the first frost) (Sokolov and Gritsak, 1972; Neumerkel, 1978, cited in [78]), mid-July and mid-October [84], July and October [35].

Compared to single harvesting, Siwek et al. [52] obtained higher yields per ha after double harvesting on the second year but lower yields on the third year. This could indicate the same effect as observed in *S. hermaphrodita*: double harvesting might increase yields in the short term but be counterproductive in the long term, reducing yields in years to come. Pichard [73] experimented with different harvest dates, obtaining their highest yields from single harvesting.

Regarding biogas and methane production based on kg^{-1} DM, Michalska et al. [137] reported the production of 26.1 dm^{-3} kg DM^{-1} from the anaerobic digestion of *S. hermaphrodita*, producing biogas that contained 65% methane. Using a double harvesting strategy on a six year stand, Oleszek et al. [15] produced biogas and methane yields of 99/50 dm^3 kg^{-1} FM (fresh mass), 395/201 dm^3 kg^{-1} DM.

Haag et al. [77] compared the Hohenheim biogas yield test (HBT) and the continuous biogas test (CBT) for the anaerobic digestion of *S. perfoliatum*, obtaining average specific methane yields of 251 dm^3 kg^{-1} oDM and 227 dm^3 kg^{-1} oDM, respectively. Although the batch method produced higher amounts of methane, the results from the continuous method are considered more realistic and therefore recommended to use for further calculations.

Siwek et al. [52] estimated the biogas yields per ha of both crops, *S. hermaphrodita* (double harvesting) and *S. perfoliatum* (single/double harvesting), based on their composition. From the concentration of crude fibre, crude protein, crude fat, and crude ash, they calculated the specific biogas and specific methane yields, 505–514 dm^3 kg^{-1} DM for *S. hermaphrodita* and 483–504 dm^3 kg^{-1} DM for *S. perfoliatum*. From those they obtained the methane content in the biogas (51.0–52.5%) and the methane yield per ha, accounting on average for 4759 m^3 ha^{-1} and 8598 m^3 ha^{-1} for *S. hermaphrodita* and *S. perfoliatum* respectively. They observed significant differences in plant composition depending on the weather conditions, the establishment method, and the harvest regime.

Von Cossel et al. [102] recently published a case study of an existing biogas plant in Baden-Württemberg (Germany) that used a mix of *S. perfoliatum*, maize, manure, grass, whole-crop cereals silage and apple pomace. They analysed the effect of increasing *S. perfoliatum* cultivation from 44 to 70% of the cultivated area (replacing maize) using a SMY of 254 dm^{-3} kg^{-1} oDM in their calculations despite the reported 300 dm^{-3} kg^{-1} oDM obtained from the plant.

A variety of pre-treatments to increase biogas production have been applied prior to the anaerobic digestion of *S. hermaphrodita*: chemical hydrolysis [137], chemical and enzymatic hydrolysis [139–141], mechanical, chemical plus enzymatic hydrolysis [142], as well as various mechanical [138,143,144], thermal [32,145–147], and thermochemical treatments [148]. Ensiling of *S. hermaphrodita* is common practice prior to anaerobic digestion [42,67]. From their two-step hydrolysis of *S. hermaphrodita*, using 5% NaOH and the addition of both cellulase and cellobiase, Michalska et al. [140] generated a biogas yield of 316.3 dm^3 kg DM^{-1}, containing 63% methane. After the application of ultrasounds, Dudek et al. [143] recorded highest yields from the fermentation of *S. hermaphrodita* together with cattle manure, obtaining 1011 dm^3 kg^{-1} oDM with a methane content 66–69%. Kisielewska et al. [149] also demonstrated the effectiveness of ultrasound in increasing solubilisation and biogas production from a mix of *S. hermaphrodita* and cattle manure, obtaining methane yields of up to 337.9 dm^3 kg^{-1} oDM. After applying hydrodynamic cavitation to a mix of *S. hermaphrodita* and cattle manure for 20 min, Zieliński et al. [144] produced a maximum methane yield of 439.1 dm^3 kg^{-1} DM. They recorded the highest process efficiency for the 5 min treatment, which increased biogas production by 30%. Von Gehren et al. [32] used heat to pretreat *S. hermaphrodita* before anaerobic digestion, increasing biogas yields by 23.6–36.7% in the batch test and 13% in the continuous test. Nowicka et al. [148] combined the application of microwaves and sodium hydroxide on the mix of *S. hermaphrodita* silage and bovine slurry, obtaining 1311 dm^{-3} kg^{-1} oDM. Zieliński et al. [147] compared the use of microwaves and hot water on *S. hermaphrodita* silage and cattle manure, producing maximum methane yields (at 150 °C, 15 min) of 590 dm^3 kg^{-1} oDM and 575 dm^3 kg^{-1} oDM, respectively. They developed two regression functions to calculate the methane and energy output for both treatments.

In terms of *S. perfoliatum*, Bauböck et al. [87] used a model (BioSTAR) to determine that triticale and *S. perfoliatum* could produce comparable biomass yields as maize. Gansberger et al. [78] introduced the idea of ensiling *S. perfoliatum* prior to the production of biogas. This approach was tested by Haag et al. [77] in their laboratory biogas experiments in which they incorporated seven varieties of *S. perfoliatum* using the HBT against a CBT. A continuous anaerobic digestion experiment was carried out by Vetter et al. (2007, cited in [78]) who co-digested 20% of *S. perfoliatum* with 80% of cow manure and obtained 185 dm^3 kg^{-1}. Comparing five origins, Wever et al. [80] produced on average 266 dm^3 kg^{-1} oDM.

Some studies have focussed on improving the biogas and methane yield by mixing *S. hermaphrodita* with other biomass. Dębowski et al. [150] mixed *S. hermaphrodita* silage and microalgae (*Chlorella* sp. and *Scenedesmus* sp.) at different ratios, observing increased biogas and methane yields, better C:N ratios, and a more stable anaerobic digestion process in general. The highest yields were obtained at 40% microalgae to 60% *S. hermaphrodita* and 60% microalgae to 40% *S. hermaphrodita*, achieving biogas and methane productions of 540–595 and 344–352 dm^3 kg^{-1} oDM respectively. Zieliński et al. [145] obtained the highest biogas and methane yields of 385 and 210 dm^3 kg^{-1} oDM respectively, from a hybrid bioreactor combining suspended sludge and immobilized biomass technologies.

In practice, *S. perfoliatum* is commonly used as a co-substrate to aid the fermentation of maize [10], producing methane yield of 292 dm^3 kg^{-1} oDM [112]. Ustak and Munoz [112] attributed the enhanced biogas yield to the improvement of overall digestibility of the anaerobic digestion process, due to the high concentration of macro and microelements in *S. perfoliatum*.

There have been studies of the composition of digestates obtained after the anaerobic digestion process. Pokój et al. [67] compared the composition of 10 digestates, including *S. hermaphrodita* and maize (Table 9) as fertilisers in agriculture. Interestingly, *S. hermaphrodita* was the digestate containing the least amounts of heavy metals. The authors generally encourage the use of biomass digestates as fertilisers in agriculture.

Table 9. Physicochemical composition of digestates from *S. hermaphrodita* and maize.

Parameter	***S. hermaphrodita***		**Maize**
	Pokój et al. [67]	**Sienkiewicz et al. [54]**	**Pokój et al. [67]**
DM (%)	3.66	4.04	3.39
oDM (% DM)	76.5		76.2
pH	7.35		9.96
Electric conductivity (mS cm$^{-1)}$	7.9		9.7
N (% DM)	1.8	0.07	4.1
P (% DM)	0.66		3.48
Available P (% DM)	0.50	0.11	0.44
K (% DM)	3.46	0.22	0.59
Mg (% DM)	0.37	0.00	3.62
Ca (% DM)	1.33	0.05	0.37
Heavy metals (mg kg^{-1} DM)	0.0 Cd, 8.4 Cu, 5.1 Ni, 0.0 Pb, 23.4 Zn		0.15 Cd, 81.6 Cu. 10.9 Ni, 0.0 Pb, 80.6 Zn

5.3. Using Sida hermaphrodita for Gasification

Gasification is a high temperature process that is used to convert carbon-based fuels (under conditions of low oxygen) to hydrogen, carbon dioxide, and carbon monoxide. It can be a sustainable way to produce hydrogen gas. Smoliński et al. [151] compared the gasification of four biomass crops, including *S. hermaphrodita*, with lignite and hard coal. Through the gasification of biomass between 59–62% of the produced gas was hydrogen gas, compared to 59–94% from hard coal and 66–67% from lignite. Overall biomass gas yield was about half in comparison with coal gasification. Lower calorific values were recorded for biomass fuels, being 11.95 MJ kg^{-1} for *S. hermaphrodita*.

Steam gasification combined with Carbon Capture and Storage (CCS) can be a sustainable way to generate hydrogen [152]. In their steam gasification experiment, Howaniec and Smoliński [152] provide a calorific value for *S. hermaphrodita* of 15.03 MJ kg^{-1}. This experiment showed *S. hermaphrodita* to have the highest char reactivity for 50% carbon conversion, being also the quickest to achieve this point among the tested feedstocks. The addition of CaO for CCS was also tested, demonstrating to increase the hydrogen yield by 22–23%, as well as to increase the heating value by 22–27% at the lowest temperature (650 °C).

Through gasification it is possible to control the output emissions and destiny of heavy metals, minimizing emissions to the atmosphere and obtaining energy from heavy metal contaminated biomass [39]. Werle et al. [153] studied the biomass of three bioenergy crops grown in contaminated land, including *S. hermaphrodita*, as feedstocks for gasification. Their results indicate the output gas of the three crops to have similar carbon, hydrogen, and oxygen composition, volatile matter and moisture content, with *S. hermaphrodita* containing the lowest amounts of ash. After a series of gasification experiments, they found *S. hermaphrodita* to be acceptable for gasification, with best results at an air ratio of 0.18:1.

Uchman et al. [154] conducted a three-step experiment comprising a gasification test, a thermodynamic cogeneration analysis, and an economic analysis, including a sensitivity analysis of electricity and heat generation from *S. hermaphrodita* grown on contaminated land. They calculated a lower heating value of 19 MJ kg^{-1}.

Werle et al. [155] studied the gasification of *S. hermaphrodita* and seven other energy crops grown on contaminated land. They combined thermogravimetric analysis (TG) with spectroscopy (Fourier Transform Infrared, FTIR), concluding it is an “excellent and easy way to characterize biomass thermal treatment processes”.

Smoliński and Howaniec [156] obtained 11.52% more volume of gas during gasification of *S. hermaphrodita* at 900 °C than at 700 °C. They observed that total gas volume increased in co-gasification of biomass as opposed to single feedstock gasification. The greatest volumes after the gasification of

S. hermaphrodita were recorded for 40% *w*/*w* blends at 700 °C and highest amounts of hydrogen gas were obtained after co-gasification of 20% *w*/*w* blends.

6. Alternative Uses

6.1. Forage and Fibre

S. hermaphrodita was originally brought to Eastern Europe as a potential fodder plant among other potential utilisation purposes. The potential replacement of traditional concentrate feedstock in the diet of cattle with a mix of 50% *S. hermaphrodita* and 50% *Vicia faba* L., was assessed by Tarkowski [157]. Chemical and nutritional properties of the resulting milk were equivalent, only finding 4% to 7% milk fat and protein increase. The author suggested this forage mix could complement traditional diets of dairy cows. Several authors described the fodder nutritional content of *S. hermaphrodita* and its similarity to alfalfa (*Medicago sativa* L.) (Borkowska and Styk, 2006, cited in [7], [158]). Fijałkowska et al. [159] also studied the silage produced from *S. hermaphrodita* after harvesting at the bud formation stage, in early-mid June, identifying that the species had a similar chemical constitution to alfalfa, as well as favourable protein and carbohydrate contents for cattle feed.

The concentration of beta-carotene, tocopherols, and vitamin E equivalent in fresh and silage *S. hermaphrodita* was analysed, detecting similar amounts to grasses and legumes [158]. A higher content of beta-carotene and tocopherols in fresh *S. hermaphrodita* and variations accompanied with cutting height and harvest date, recording higher results when the material was cut at 35–45 cm and later harvest dates could be found. Purwin et al. [160] tested the inclusion of dehydrated *S. hermaphrodita* in the diet of rabbits, showing that it could replace up to 20% of dried alfalfa.

The potential of *S. perfoliatum* as a forage plant has been studied in Wisconsin since 1990 [84]. If *S. perfoliatum* is to be used as fodder it can be harvested from mid-June [85] to mid-August, as late as possible before the first frost [78]. Stanford [72] recommended dual harvesting to obtain high yields, doing the first harvest when the first flower buds open and the second when the first flower buds of the regrowth open. In their *in-vitro* experiment, Han et al. [85] found this species to have analogous digestion parameters to alfalfa, as well as high digestibility with maturity. According to Pichard [73] double harvest reduces slightly the yield of the second harvest but increases its nutritional content.

S. perfoliatum is a rich and appealing forage for the first and second vegetative stages when digestibility is very high and crude protein contents are high, before protein levels decrease [73]. *S. perfoliatum* has been compared with alfalfa, red clover (*Trifolium pratense* L.) [73], and maize [72] in terms of production and chemical composition. Although these species have higher nutritional value they are not productive for so long [73].

A very effective way of preserving fodder is ensiling, but the ensilage of crops containing low dry matter content at harvest deteriorate easily. Dry matter content varies with harvest date and can increase if the material is left to dry on the field. Han et al. [84] studied the influence of different moisture contents on the fermentation components of *S. perfoliatum* harvested in June and October. They found moisture management crucial to produce high quality silage from *S. perfoliatum*, benefiting from drying on the field for 48 h, which increased DM by 42%. Piłat et al. [161] observed that ensilaged *S. perfoliatum* forage had the most suitable fermentation coefficient of 36.54, when collected at the beginning of seed setting (125 days after start of regrowth).

The potential use of *S. hermaphrodita* as a source of fibre for the paper and pulp industry is also mentioned in the literature [9]. After studying more than ten herbaceous plants and three woody species, Slepetys et al. [21] found *S. hermaphrodita* to contain the highest amount of fibre.

Klímek et al. [162] have demonstrated the suitability of *S. perfoliatum* stems to be used to manufacture particleboards of standard density, 600 kg m^{-3}. Despite displaying weaker mechanical properties than boards made of spruce (*Picea abies* L.) particles, particleboards using methylene diphenyl diisocyanate (MDI) as adhesive, still met the Class P2 EN312 standards for general-purpose items in dry conditions.

According to Martens [163], *S. hermaphrodita* also has the potential to be used in the manufacturing of natural fibre products, such as alternative turf, and it could even be used as raw material to produce 3D printing resin. Rumpf et al. [164] found that through organosolv pulping, they could achieve a high quality lignin yield of 15.7% from *S. perfoliatum* that could be used to manufacture biodegradable plastics.

6.2. Other Uses

Extracts from *S. hermaphrodita* seeds have shown antifungal properties against *Candida albicans* [165]. Potentially useful biosurfactants were isolated from a bacteria (*Pseudomonas putida* E41) extracted from *S. hermaphrodita* roots [166]. Disposing of heavy metal contaminated biomass can be done through the production of biochars. To reduce leaching risk of toxic metals and improve oxidation resistance and carbon stability of *S. perfoliatum* biochars, Du et al. [167] recommended using higher pyrolysis temperatures (750 °C).

The use of biochars as a soil amendment is becoming increasingly popular. The production of biochars from *S. hermaphrodita* has been studied. Madej et al. [168] recorded high quality and low content of polycyclic aromatic hydrocarbons (PAHs) in the biochar obtained from several crops, including *S. hermaphrodita*. After elemental analysis of the biochars, they concluded that the material met the standards of the European Biochar Certificate (EBC) and the International Biochar Initiative (IBI). They suggested that the continuous removal of syngas via continuous nitrogen flow could be the key to obtaining low PAHs.

Bogusz et al. [169] investigated the adsorption properties of the biochar produced with *Triticum* straw and *S. hermaphrodita* to remove Cd, Cu, and Zn from contaminated water. They found both materials to be suitable for the purpose, but the biochar from *S. hermaphrodita* was more effective capturing heavy metal ions. They propose the use of this biochars to lock up these substances in contaminated soils.

From a strong positive correlation between the carbon content of *S. hermaphrodita* biochars and the acetic acid of the condensate, Szwaja et al. [134] obtained a polynomial function useful to supervise the quality of the biochars during the torrefaction process. They also found a negative correlation between carbon and hydrogen content of biochars and a negative correlation between the ash content and volatile matter of biochars. Szwaja et al. [118] focussed on the composition of biochar and condensate, noticed how it is affected by torrefaction temperature, and established that such temperature should not go above 400 °C. They suggested potential chemical usefulness of the condensates.

Hydrochars are a form of char produced via a different production process. Magdziarz et al. [135] investigated the production of hydrochars through hydrothermal carbonization of *S. hermaphrodita*. They characterised both the hydrochars and resulting liquid, using thermogravimetric and gas chromatography analyses to study the combustion and pyrolysis of the hydrochars. Śliz and Wilk [136] analysed the fuel properties of hydrochars produced from *S. hermaphrodita* at different temperatures and different reaction times, using a number of analyses, observing combustion behaviour and surface changes. Von Cossel et al. [102] described how digestates from anaerobic digestion could be treated using hydrothermal carbonization, followed by acid leaching and struvite precipitation to recover phosphorus.

A wide range of useful chemical substances has been isolated from *S. perfoliatum* leaves, stalks, inflorescences, and rhizomes with potential applications in different industries [170]. Only for the pharmaceutical sector the following substances have been studied: sesquiterpenes from roots [171], trypsin from seeds [172], flavonoids from leaves [173], sesquiterpenoids [174], phenolic acids [161], alcohol extracts from roots [68], and oleanolic acid from leaves [109]. Feng et al. [175] even isolated a kaempferol trioside from the aerial parts of *S. perfoliatum* and proved the efficiency of this substance to inhibit and delay the proliferation of certain carcinogenic cells in laboratory conditions.

S. perfoliatum has potential application in multiple industries, such as construction [80], pharmaceutical, agrochemical industry, or the food industry. The following substances contained in *S. perfoliatum* have been investigated:

- lipophilic substances from leaves, inflorescences, and roots [176];
- essential oils [177];
- phenolic acids, oleanolic acids, ursolic acids, amino acids, flavonoids, terpenes, and essential oils from roots and seeds [178–180];
- stabilizers: Kowalski [179] verified the stabilizer action of extracts from three *S. perfoliatum* species on fatty acids of sunflower oil. Their research shows the extracts to have a similar effect to artificial stabilizers, even outperforming them in some cases, such as *S. perfoliatum* rhizome extracts after 120h heating of the sunflower oil;
- triterpenoid glycosides: Davidyans [181] demonstrated the effect of them on seed germination, noticing that these compounds increased α-amylase and total amylase activity, as well as total protein content;
- saponins: obtained from *S. perfoliatum* leaves reduced cholesterol from 12–19% in rats (Syrov et al., 1992, cited in [182]);
- anti-fungal properties: Zabka et al. [183] found inhibitory effects of extracts made from *S. perfoliatum* leaves on Fusarium oxysporum, Fusarium verticillioides, Penicillium brevicompactum, Aspergillus flavus, and Aspergillus fumigatus. Jamiolkowska and Kowalski [180] tested the antifungal properties of alcohol extracts from *S. perfoliatum* leaves on common fungal pathogens of pepper plants, obtaining very positive results and recommending its use for the creation of an organic antifungal control product. The highest growth inhibition was observed on Alternaria alternata and Colletotrichum coccodes, followed by Botrytis cinerea and Fusarium oxysporum;
- polysaccharides: Shang et al. [184] studied both extraction and drying methods and their antioxidant properties. They estimated the parameters for extraction of the highest number of polysaccharides and indicated freeze-drying as the best drying process to preserve antioxidant properties. Wu et al. [185] compared a variety of extraction methods and the antioxidant properties of the resulting polysaccharides, identifying the enzyme-assisted extraction method as most effective. Based on this result, Guo et al. [186] used the enzyme assisted extraction method and a purification method to isolate a polysaccharide with antioxidant as well as hypoglycaemic abilities;
- proteins: von Cossel et al. [102] described a protein extraction process from *S. perfoliatum*, suggesting that the residues after extraction could then be used in a biogas feedstock mix. They calculated that it is possible to extract 1479 kg of crude protein per ha from *S. perfoliatum*. They suggested this could increase the economic output of farms and create positive environmental impacts by reducing the use of soya for protein [102].

Kowalski and Kędzia [68] also mentioned the use of the execrated resin and whole *S. perfoliatum* plants in traditional American Indian medicine to treat numerous illnesses, as well as studies done in the late 1980s and 1990s that demonstrated regenerative, anti-cholesterol, anti-sclerotic, and antifungal properties. *S. perfoliatum* was selected among 24 other native perennials for its aptitude to attract natural enemies against common pests as the plant develops, outperforming commonly used annual exotics [187].

7. Environmental Benefits

7.1. Phytoremediation and Phytostabilisation

Spooner et al. [9] reported the ability of *S. hermaphrodita* to grow on disturbed environments, like land on the sides of roads and railways, where it could help with soil stabilisation. Zhang et al. [69] mentioned that *S. perfoliatum* could be used for the same purposes. Borkowska et al. [139] compared the heavy metal intake of four bioenergy species including *S. hermaphrodita*. Under the experimental conditions, *S. hermaphrodita* produced the highest yield (6.8 t DM ha^{-1} y^{-1}) and it captured the most heavy metals. *S. hermaphrodita* was also reported to improve the soil structure [25]. *S. hermaphrodita* has also been quoted as a candidate plant species, in an examination of the effect of laser radiation on the uptake of heavy metals by plants [188].

Krzywy-Gawronska [58] monitored the content of heavy metals in *S. hermaphrodita* under various fertilization programs. Intense bioaccumulation was found for Cd, Cu, Ni, Pb, and Zn when fertilized with high calcium brown coal ash; for Ni, Pb, and Zn when fertilized with municipal sewage sludge compost and high calcium brown coal ash; and for Pb when fertilized with sewage sludge compost. She concluded that *S. hermaphrodita* displayed average to intense capacity for the absorption of heavy metals. Among the fertilizing programs, she found that the application of sewage sludge generally favoured the uptake of larger quantities of heavy metals.

Wierzbowska et al. [189] compared the use of wet sewage sludge and pelleted sewage sludge to traditional nitrogen and phosphorus mineral fertilization. Potassium was added in the form of potassium chloride. They sorted the accumulation of heavy metals on the aerial parts of *S. hermaphrodita* from highest to lowest as follows: Cd > Cu > Cr > Ni > Zn > Mn. They found that two forms of sewage sludge promoted the accumulation of higher quantities of certain heavy metals than mineral fertilization on both the plant biomass and the soil. After their literature review on the phytoremediation potential of several energy crops, including *S. hermaphrodita*, Prelac et al. [190] expressed the outstanding potential of this species to remove Cd, Ni, Pb, and Zn plus its storage capacity of Cr and Cu.

Kocoń and Jurga [191] compared the bioaccumulation factors of *S. hermaphrodita* and *Miscanthus x giganteus* on two types of soil. *S. hermaphrodita* accumulated more Cd, Cu, Ni, Pb, and Zn in aerial parts during the first year of cultivation on loamy soils. The crops performed better on sandy soils, giving 4.4 and 2.6 times more yields respectively, and accumulated higher quantities of Zn but lower quantities of Cd. Since the bioaccumulation factor is the ratio of heavy metal concentration in the aerial parts to the heavy metal concentration in the soil, it does not account for the accumulation of heavy metals in the roots of plants. This could potentially have a significant impact on the results and should be taken into account in future research.

Antonkiewicz et al. [27] compared the phytoextraction potential of *S. hermaphrodita* and *Rosa multiflora* var. 'Jatar'. They noticed that the amounts of heavy metals extracted from the soil that had been fertilized with sewage sludge, increased with the dose of sludge and the yield of plants. However, the highest percentage of heavy metals recovered was associated to the lowest sludge dose. These results could indicate that high levels of heavy metal accumulation can become toxic and reduce the effectiveness of removal. The authors ranked the efficiency of *S. hermaphrodita* to uptake heavy metals in the following decreasing order: Cd > Zn > Ni > Cr > Cu > Pb.

Antonkiewicz et al. [27] additionally studied the activity of microorganisms in the soil under *S. hermaphrodita*, which was confirmed to be positively influenced by the use of sewage sludge. They recorded increased levels of enzymatic activity with increasing sludge doses, and found a correlation between enzymatic activity and heavy metal uptake.

Pogrzeba et al. [39] compared the heavy metal bioaccumulation factor between two types of arable land, heavy metal contaminated and sewage dewatering. They observed that *S. hermaphrodita* was able to extract 12 and 18 times more Cd and Zn (bioaccumulation factors of 0.21–0.55 and 0.23–0.86) from heavy metal contaminated land, with a 7% higher LHV. Werle et al. [129] compared and characterised the plant composition of *S. hermaphrodita* grown on heavy metal contaminated arable land in Poland and a former sewage sludge dewatering site in Germany. They observed variation in plant composition and the thermogravimetric analysis due to differences in soil. Khanh-Quang et al. [192] however, found higher phytoextraction potentials for *Miscanthus* compared to *S. hermaphrodita* and provided kinetic parameters to use as model and system design inputs.

In one contaminated soil experiment [69] *S. perfoliatum* showed evidence of Zn to be detrimental for its growth. Zhang et al. [69] found *S. perfoliatum* capable of storing Cd in the rhizomes without it spreading to the rest of the plant, exhibiting high tolerance to this heavy metal. Wrobel et al. [130] also mentioned the potential of *S. perfoliatum* to restore degraded areas.

7.2. Biodiversity and Pollination

Because *S. hermaphrodita* and *S. perfoliatum* are perennial crops present throughout the year, they provide relative stable habitats for a range of earthworms and small animals. *S. perfoliatum* can contribute about 8 t DM ha^{-1} y^{-1} of litter [92], and this can be positive for the diversity and activity of soil organisms. Chmelíková and Wolfrum [193] recorded the beneficial effect of *S. perfoliatum* cultivation on arthropod diversity. Emmerling [194] and Schorpp and Schrader [121] report that *S. perfoliatum* increased the number and species of earthworms compared to arable crops. Although the highest numbers were found in grasslands, Burmeister and Walter [195] also reported a six-fold increase in the density of earthworms in *S. perfoliatum* rather than arable plots. A study in the Czech Republic [196] suggests that novel species such as *S. perfoliatum* may result in lower abundance of soil meso- and macrofauna than indigenous perennial crop species such as willow and reed canary grass.

Schorpp et al. [71] in Germany found a greater abundance and double the number of springtail (Collembola) families under *S. perfoliatum* plants, compared to maize. Although *S. perfoliatum* did not increase the diversity of nematodes, compared to maize, they observed more herbivorous and fungivorous species and less bacterivorous species. Although high numbers of the plant parasitic nematode Helicotylenchus spp. were reported, these did not have an impact on yield. A follow-up paper by Schorpp and Schrader [106] ratified the above mentioned results and provided evidence that the most stable food webs occurred in the oldest plots. They suggested that changes in the fungal decomposing pathway and slower nutrient cycling was related to an increase in soil fertility.

Whilst weeds are detrimental to biomass yields, the presence of some weeds can help support farmland biodiversity. Feledyn-Szewczyk et al. [30] monitored weed density and species associated with energy crops, including *S. hermaphrodita,* compared to arable crops. They registered an increase of 11% in perennial species, 10% in ruderal species, 7% in grassland species, and 4% in forest species.

Both *S. hermaphrodita* and *S. perfoliatum* produce a great number of flowers. *S. hermaphrodita* provides an extended source of food for pollinators due to its long flowering season. Blooming from early summer till the first frost in autumn [9,24], *S. hermaphrodita* can be used to produce from 110 kg to 315 kg of honey per ha (Borkowska and Styk, cited in [16]. From a three year experiment, Jabłonski and Kołtowski [197] reported that *S. hermaphrodita* can produce an average of 230 kg of honey ha^{-1}. Kurucz et al. [11] indicated the direct correlation between precipitation and flowering of *S. hermaphrodita*, consequently affecting seed formation. Franzaring et al. [10] also observed that flowering was greatest with higher temperatures and rainfall.

S. perfoliatum provides a long blossoming season for pollinators from July to September [187], with highest flower abundance in August [105]. *S. perfoliatum* produces 10–25 flowering stems and 8–10 flowers from each stem [78], and the number of flowers produced per plant each season is between 64 and 250 flowers. After monitoring the entire flowering period, Mueller et al. [198] calculated an average of 188 flowers (inflorescences) per plant each season and highest pollen and nectar production during the second fortnight of August. They calculated that a single flower (inflorescence) of *S. perfoliatum* produces 1.75×10^6 pollen grains on average, 12.5×10^{12} pollen grains per ha, and 80 kg of nectar sugar per ha each season, potentially providing for 34 honey bee larvae per season, and 6 worker honey bees per day. They analysed the composition of pollen and nectar, recording low levels of total amino acids but high levels of specific essential amino acids. They recommend postponing the harvest of *S. perfoliatum* to the end of flowering to maximise the flowering window for pollinators, whilst combining *S. perfoliatum* with other flowering crops to provide a rounded diet. According to Schorpp et al. [71], this species produces from 14,106–14,200 pollen grains per inflorescence. Considering the average amount of inflorescences per plant to be 150 per season, they calculated that this species produces 2.12–2.13 million of pollen grains. They also calculated that every flower contained 0.09 mg of sugar in its nectar produced per day (each flower head/inflorescence has 117–128 tubular flowers), as opposed to the lack of pollen/nectar in maize. Mueller et al. [199] studied the effect of different water regimes on floral resources and pollinators, finding more inflorescences, more nectar sugar, double visits from honeybees, and later maturation in irrigated, rather than rainfed, *S. perfoliatum* plants. The use of *S. perfoliatum* as an ornamental and melliferous (i.e., honey producing) plant is often mentioned in literature, having demonstrated to produce about 560 kg on average of honey per hectare [197]. The flowering ability of *S. perfoliatum* could be valuable from a landscape perspective.

Compared to maize, *S. perfoliatum* produces nectar and pollen for pollinators [198,199]. Burmeister and Walter [195] recorded honeybees (*Apis mellifera*), bumblebees (*Bombus* spp.), and members of several other families including hymenoptera, syrphidae, diptera, coleoptera, and lepidoptera. In Germany, Mueller and Dauber [105] demonstrated the benefit from the cultivation *of S. perfoliatum* on farms for hoverflies, counting a total of 30 species. Microphagous hoverflies such as *Eristalis tenax* benefited from the semi-natural habitat, and zoophagous hoverflies benefited from increased crop diversity.

A particular feature of *S. perfoliatum* is the capacity of the leaves to capture rainfall next to the stems; Schoo et al. [90] estimated the amount of water contained in these cups is about 4 mm per month, representing only about 2% of total evapotranspiration (ET), being most likely an adaption to provide water for pollinators. For all the above mentioned positive effects on biodiversity, Schorpp et al. [71] classified *S. perfoliatum* as a more sustainable crop for bioenergy than silage maize.

7.3. Soil Health Regulation

S. hermaphrodita and *S. perfoliatum* can result in less soil erosion and less use of pesticides than bioenergy crops such as maize. The perennial nature of the crop means once the year of establishment has passed, there is very little soil disruption, and field operations are restricted to fertilization and harvest [71,77,78,120]. After the first year, if the crops established a full canopy, weeds are suppressed [111] which minimises the need for herbicides.

Both *S. hermaphrodita* and *S. perfoliatum* are a good crop choice in areas where nitrogen leaching is an issue. This is due to the capacity of the crops to take up nitrogen and the relatively low fertilization and pesticides needs [16,73]. Intercropping with legumes has been reported to reduce nitrogen application and leaching [63], however often aspects of the effects of *S. perfoliatum* on soil nitrogen dynamics are complicated. Under laboratory conditions, Schorpp et al. [200] observed that NO_2 emissions increased under *S. perfoliatum* due to the increased denitrification induced by enhanced anecic earthworm population. They recommended that field experiments were needed to study the actual impact of *S. perfoliatum* on emissions of nitrogen oxides. According to Ruf et al. [88], the use of *S. perfoliatum* on waterlogged conditions lead to improved shoot-root gas exchange and root exudation of sugars and amino acids, which induced higher microbial activity.

Beyond farmland, there may also be a role for *S. hermaphrodita* in terms of directly controlling soil erosion and flooding. Flood plains are among the natural habitats of *S. hermaphrodita* [9], making it an ideal candidate to be included in flood mitigation strategies. Stolarski et al. [124] observed *S. hermaphrodita* to withstand flooding relatively well compared to ten other energy crops. In addition the benefits of perennial crops for earthworms (see previous section) can in turn have positive effects on soil aeration and water infiltration, thus reducing erosion and run-off [71,121].

Integrated on farms, *S. perfoliatum* could help support the biological control of common agricultural pests [187]. Initial research suggests that *S. perfoliatum* is not a host to European corn borer (*Ostrinia nubilalis* Hübner) or the Western corn rootworm (*Diabrotica virgifera* LeConte).

In general, the lack of annual cultivation would be expected to result in an increased level of soil carbon compared to an annual crop where cultivation occurs annually [194]. Schoo et al. [93] recorded that an average of 8.4 t DM ha^{-1} is produced from *S. perfoliatum* roots alone, which was double that of silage maize roots (4.0 t ha^{-1}). Where *S. hermaphrodita* or *S. perfoliatum* receives organic fertilisation, this can further increase soil carbon [61,113,201].

Ruf et al. [5] examined the organic carbon, microbial biomass, and aggregate stability of three different land use systems, with permanent grassland ranked highest, followed by perennial energy crops (including *S. hermaphrodita* and *S. perfoliatum*), and lastly annual energy crops. For a six-year perennial energy plantation, they found positive correlations between soil organic carbon and clay content, rooting depth, microbial biomass, and age of plantation. Negative correlations were observed between soil organic carbon and both higher mean annual temperatures and inorganic carbon. They recorded soil organic carbon content to increase steadily with the age of the plantation until the tenth year. In their two year pot experiment, Ruf et al. [88] recorded an increase of soil organic carbon content from 13.0 g kg^{-1} in the control treatment to 19.8–20.9 g kg^{-1} under *S. perfoliatum.*

8. Economics of *S. hermaphrodita* and *S. perfoliatum* Cultivation

S. hermaphrodita and *S. perfoliatum* are long-term crops and their financial and economic impact should ideally be calculated over the length of a rotation. The costs of establishment are large, but decommissioning costs should also be included; these have been estimated at 234 € ha^{-1} [29]. Costs for establishing of *S. hermaphrodita* have been calculated as 1860–2715 € ha^{-1} [16]. Total costs of establishment for *S. hermaphrodita* of 1159 € ha^{-1} using seeds and 8096 € ha^{-1} using seedlings were reported by Stolarski et al. [29] and Franzaring et al. [10] reported a cost of establishment about 5000 € ha^{-1} for seedlings. Franzaring et al. [10] also reported a total cost of establishing *S. perfoliatum* using seedlings of over 5000 € ha^{-1}, which is similar to values reported by Biertümpfel and Conrad (2013, cited in [78]) (Table 10). They calculated that the establishment cost per tonne of dry matter was greater for transplanted rather than sown stands of *S. perfoliatum* [99]. Von Cossel et al. [102] indicated that establishment costs could be greatly reduced from 5159 € ha^{-1} (establishment using seedlings) to 1950 € ha^{-1} (establishment using seeds).

Table 10. Cost comparison of planting vs. direct sowing of *S. perfoliatum* (Biertümpfel and Conrad 2013, cited in [78]).

Method	Total (€ ha^{-1})	Plant Material (€ DM t^{-1})
Sowing	3159–3190	129–138
Transplanting	5159–5190	148–161

For the detailed analysis of establishment costs for *S. hermaphrodita*, in Poland, the cost of 1 kg of seeds was 287 €, rhizomes costed between 0.06 € [29] and 0.17 € per unit [16], and seedlings 0.12 € per unit [29]. For Hungary, Kurucz et al. [24] calculated the cost of self-production of *S. hermaphrodita* seedlings to be 0.38–0.61 € per unit. Depending on the establishment method, the cost of material accounted for 37–89% of total establishment costs [29]. In turn, the cost of establishment accounted for 15–51% of total production costs [29].

The cost of *S. perfoliatum* seeds is €600 kg^{-1} [97], equivalent to 1700 € ha^{-1} [98]. Schäfer et al. [98] explained that the cost of *S. perfoliatum* seeds is due to the highly demanding and time consuming collection because of irregular maturation. In addition to processing, further mechanical scarification is needed to improve germination. The additional cost of coating with a hygroscopic substance will increase the cost by 200 € kg^{-1}. Following the observations made by Schäfer et al. [97] the cost *S. perfoliatum* seeds could be potentially reduced to 1100–1400 € ha^{-1}.

At harvest, production costs of *S. hermaphrodita* chips were calculated to be between 34–52 € per tonne, for sown and transplanted seedlings respectively, 415–828 € ha^{-1} ex-farm, 61–426 € ha^{-1} y^{-1} [29]. Considering a plantation cycle of 20 years, Kurucz et al. [24] calculated the production costs of *S. hermaphrodita* to be between 36–60 € DM t^{-1}. Producing an extra tonne of biomass through fertilization had associated costs of 13.8 € [24].

The price of 1 tonne of *S. hermaphrodita* in the market varies widely in the literature. *S. hermaphrodita* for combustion has been reported to be about 66–68 € t^{-1} [29], 36–60 € t^{-1} [24]. *S. hermaphrodita* pellets are sold at 215 € t^{-1} and *S. hermaphrodita* for biogas is sold at 55 € DM t^{-1} [24]. On a per hectare basis, Stolarski et al. [29] reported a price of 825–1080 € ha^{-1}.

The investment costs associated with the production of pellets and briquettes are significant, between 12,080–12,400 € [24]. The extra processing costs associated with manufacturing are 101 € t^{-1} y^{-1} and 111 € t^{-1} y^{-1} for pellets and briquettes respectively [24]. Total production costs of *S. hermaphrodita* pellets and briquettes was calculated to be 137–161 € t^{-1} and 147–171 € t^{-1} by Kurucz et al. [24]. Streikus et al. [66] estimated the cost of pellet production from *S. hermaphrodita* at 0.013 € kg^{-1} (dried artificially) and the cost of energy production at 0.006 € MJ^{-1} and 0.017 € KWh.

Stolarski et al. [29] calculated that a profit of 252–433 € ha^{-1} ex-farm could be made establishing a *S. hermaphrodita* plantation using seedlings and seeds respectively. Kurucz et al. [24] calculated the profit per tonne that could be obtained through the various final uses of *S. hermaphrodita*: through direct combustion 70–94 €, via pelleting 54–78 €, briquetting 7–31 €, by the production of biogas from −4–20 €, and the production of honey 144 €. In order to counteract the production cost of *S. hermaphrodita*, Stolarski et al. [29] calculated that a farmer should produce more than 6.2 t ha^{-1} when the plantation was established by seeds or 12.3 t ha^{-1} when the plantation was established by seedlings.

In a different analysis, focused on a cogeneration gasification system using *S. hermaphrodita* as fuel, Uchman et al. [154] concluded that break-even prices of the electricity were between 48–90 € MWh^{-1}. They concluded that these costs were uncompetitive, and the system would only be economically viable if environmental benefits were also included. The need to include payments for environmental benefits to improve the competitiveness of *S. perfoliatum* has also been proposed by von Cossel et al. [102]. Kurucz et al. [24] estimated that placing on the value of the CO_2 sequestered by *S. hermaphrodita* would equate to an addition 2 € DM t^{-1}.Another way to aid the economics of *S. hermaphrodita* and *S. perfoliatum* is the production of honey. Both species have proven to produce good quantities of smooth and aromatic honey, honey that can be sold for more than 5 € per 250 g.

9. Energy Balances and LCAs

If *S. hermaphrodita* and *S. perfoliatum* are to be large-scale bioenergy crops then it is important to understand their energy and environmental impacts. A positive energy balance occurs if the energy produced by the crops is larger than the energy invested (excluding solar radiation). The annual energy inputs (excluding solar radiation) required to produce *S. hermaphrodita* range from a low of 9 GJ ha^{-1} [29] to a mean of 36 GJ ha^{-1} over six years including 128 GJ ha^{-1} in the year of establishment [53]. By contrast, the energy outputs from *S. hermaphrodita* if combusted range from 51 GJ ha^{-1} y^{-1} [38] to 439 GJ ha^{-1} y^{-1} [17] (Table 11). Hence the reported ratios ranged from 4:1 to 20:1, with the ratio increasing from planting to the sixth year [51]. The methane yields from *S. hermaphrodita* (2370–3780 m^3 ha^{-1}) typically result in a lower energy yield (85–135 GJ ha^{-1}) than combustion [17]. Von Gehren et al. [32] also recommended the use of *S. hermaphrodita* as a solid fuel for combustion rather than biogas. The highest methane yields are typically achieved by having two harvests rather than one harvest per year [17]. The application of pre-treatments can increase methane yields, but they incur additional energy costs [138,148,150]. For example, Kisielewska et al. [149] concluded that the increase in biogas and methane yields after ultrasound pre-treatments could not be justified from an energy balance perspective. Szwaja et al. [118] estimated that 56 GJ ha^{-1} y^{-1} of electricity could be produced from *S. hermaphrodita* through a Rankine cycle (35% efficiency).

If *S. perfoliatum* is combusted, then depending on the yields and technology, the annual energy output can be 188 to 362 GJ ha^{-1} [104] (Table 11). The associated annual energy inputs range between 7 and 28 GJ ha^{-1} [104], resulting in an energy out: energy in ratio of between 12:1 and 25:1. *S. perfoliatum* is also widely used for methane production. Annual rates of production include 2189–3161 m^3 ha^{-1} [77], 3100 m^3 ha^{-1} [78], 3600–4250 m^3 ha^{-1} [112], 3697–4634 m^3 ha^{-1} [80], 4855 m^3 ha^{-1} [119], 8598 m^3 ha^{-1} [52], and 3854–6414 m^3 ha^{-1} [119]. Assuming a methane energy density of 36 MJ m^{-3}, these values are equivalent to energy yields of 79 to 309 GJ ha^{-1}. Haag et al. [77] reported that *S. perfoliatum* produced methane yields between grass and maize silage.

Table 11. Reported energy requirements and energy outputs, and corresponding energy balances for *S. hermaphrodita* and *S. perfoliatum*.

	Technology	Input (GJ ha^{-1} y^{-1})	Output(GJ ha^{-1} y^{-1})	Energy gain (GJ ha^{-1} y^{-1})	Energy Efficiency Ratio	Reference
S. hermaphrodita	Combustion	9–19	172–226	185	12–20	[29]
		19	79–101	71	4.7	[22]
		22	152	123	7.0	[42]
		19	78	59	4.1	[37]
		-	51–102	-	-	[38]
		-	218	-	-	[31]
		8.4	177	-	7.3–21.8	[51]
		30–36	60–75	30–40	2.0–2.1	[53]
	Combustion: 2 cuts	-	439	-	-	[17]
	Biogas: 1 cut	-	85	-	-	[17]
	Biogas: 2 cuts	-	136	-	-	[17]
	Dual harvest	-	212	-	-	[17]
	Electricity	-	56	-	-	[118]
S. perfoliatum	Combustion	7–28	188–362	180–334	12–25	[104]
		19	200–236	199	11.5	[22]

Life cycle assessments of *S. hermaphrodita* have examined the energy balance, and also the effect on climate change, human toxicity, particular matter formation, terrestrial acidification, freshwater eutrophication, and terrestrial and freshwater ecotoxicity [38]. In a comparison of the cultivation of *S. hermaphrodita* under different fertilizing regime, the fewest negative environmental effects were obtained when fertiliser was applied as a digestate. The application of digestates helps to minimise the energy costs associated with mineral fertilisers and the environmental effect of nutrient leaching [53]. In a study of energy generation from *S. hermaphrodita* on 16 categories, Schonhoff et al. [133] reported that, although the negative environmental impacts of producing *S. hermaphrodita* chips or pellets were greater than for *Miscanthus* pellets, they were lower than for standard wood chips. The process of pelletizing *S. hermaphrodita* uses about 0.53 GJ t^{-1} [32]. When the multi-criteria decision making model (MULTIMOORA) was applied in Lithuania [202], both *S. hermaphrodita* and *S. perfoliatum* ended up within the top five energy crops to use. This multi-criteria assessment included the following categories: photosynthesis type, soil carbon sequestration, water adaptation, N input requirement, erosion control, DM yield, and energy yield.

10. Recommendations for Future Research

Future research on *S. hermaphrodita* and *S. perfoliatum* could cover genetic improvement, field management, and methods to increase energy efficiency after harvest, improve environmental impact, and increase profitability [77].

Genetic improvement: Kurucz et al. [11] pointed out the lack of research in the genetics and biotechnology areas, which could greatly benefit *S. hermaphrodita* and help this crop to achieve its full potential. Jablonowski et al. [17] reported that plant breeding would help to have a more uniform cultivation, characteristics, and yields.

For *S. perfoliatum*, van Tassel et al. [82] emphasized the need for genetic studies to characterise existing populations and to help produce desirable characteristics. After their genetic study of five *S. perfoliatum* populations, Wever et al. [80] advised selection (targeting height and diameter) and breeding to reduce variation in biomass and methane yield, and increase genetic diversity (using wild populations). Schittenhelm et al. [92] suggested the production of varieties with smaller leaves in order to increase yields and decrease yield variability. Cultivar selection could help to identify if there are specific high-value natural chemicals associated with the crops, which could enhance the value and hence the profitability of the crops.

Seed technology: Functioning seed technology would contribute to lower the establishment costs of *S. perfoliatum* [78]. The same applies for *S. hermaphrodita*.

Field management: the need for field trials of *S. hermaphrodita* has been emphasized to test the performance of this crop: in separate regions with different climate and soil conditions from an agronomical and energetic point of view, including multiple harvest and determining optimum harvest dates [28]; for diverse agricultural practices and ecological conditions [53]; under digestate depot fertilization [62]; to study root distribution dynamics of legume intercropping with *S. hermaphrodita* on marginal soils [63].

Jankowski et al. [53] emphasized the urgency to investigate weed and disease control methods, seed technology, and the use of organic fertilisers to maximise energy efficiency of *S. hermaphrodita*. Nahm and Morhart [14] observed a lack of research on pre-treated seeds to lower establishment costs, studies on the pathogens, competitiveness and invasive potential of *S. hermaphrodita*, and determination of its optimal growth conditions, plantation life financial analysis, as well as the establishment of value chains and appropriate marketing strategies.

For the field management of *S. perfoliatum*, Franzaring et al. [28] recommended that there was a need to evaluate the crop in different climate and soil conditions with different harvest dates, with a particular focus on places with temperate humid weather [10], and on marginal land [120]. The possibility of growing *S. perfoliatum* on land which is often saturated with water [88], needs further investigation including a variety of soil textures, as well as comprehensive photosynthesis and water monitoring experiments. Von Cossel et al. [119] recorded the superior methane production of wild plant mixtures grown under maize as cover crop. This experiment could be replicated for wild plant mixtures to be sown under *S. perfoliatum* to maximise biogas production and control of weeds, which could increase biodiversity simultaneously. Optimising the establishment [100] and cultivation [98] of *S. perfoliatum* are requirements to increase its cultivation area. Šiaudinis et al. [33] regard the development of weed control technology for the establishment year as one of the principal causes stopping the widespread cultivation of *S. perfoliatum*. It is also necessary to study how signal processing affects photosynthesis and growth of *S. perfoliatum* [114].

Post-harvest energy studies: further research is necessary to determine the precise causes of enhanced biogas production obtained after co-digesting maize and *S. perfoliatum* [112]. Potential ways to raise *S. perfoliatum* dry matter content need further investigation [102].

Nutrient recycling: the recovery process of phosphorus from biogas digestates would benefit from expanded research [102].

Environmental impact: there is a particular interest in how perennial crops affect the wider environment, including at landscape-scale [5]. Von Gehren et al. [32] suggested that research is needed to decrease PM emissions and ash removal during the combustion process of *S. hermaphrodita*. The fertilising potential of the ashes from the combustion of *S. hermaphrodita* needs further investigation. Stolarski et al. [51] also highlighted the importance of researching environmental LCA too. Chmelíková and Wolfrum [193] pointed out the need to explore the effect of *S. perfoliatum* and other perennial energy crops on arthropods within the agricultural landscape. Schoo et al. [90] advised the study of the long-term effects of no-tillage cultivation of this kind of crops on soil properties. Schoo et al. [89] recommended examining the positive environmental impacts associated to its cultivation and determining the requirements for the cultivation of *S. perfoliatum*. Mueller et al. [199] encouraged studying the impact of water availability on inflorescence production. The potential use of *S. perfoliatum* biochars produced from heavy metal contaminated land for water purification and soil remediation was suggested by Du et al. [167].

Ruidisch et al. [120] encouraged the inclusion of factors like environmental benefits in planning strategies, as well as the creation and development of local and regional databases that will feed the models and eventually help making decisions.

Profitability: Borkowska and Molas [41] accentuated the need for economic analyses to help in the decision making process, by providing sufficient and reliable information, maintaining profitability and minimising environmental impacts. Nahm and Morhart [14] also reported the need for plantation life financial analysis, as well as the establishment of value chains and appropriate marketing strategies. Financial and economic models will also help with regional economic evaluation, supporting both farmers and decision makers by providing output data to be used for up-scaling potential, different land-use scenarios, and calculations on crop profitability [120].

11. Conclusions

The research highlighted the potential utility of *S. hermaphrodita* and *S. perfoliatum* within farming systems. Both crops can generate large energy surpluses with environmental benefits such as improved pollination, soil health, and water quality relative to current bioenergy crops, such as maize and *Miscanthus*. The process of completing this synthesis has highlighted the substantial amount of research that has already been completed on these two crops. Collating this information in one place should help advisors and farmers who are interested in growing the crop in other regions, not just in Europe, but elsewhere. Some of the reviewed literature is not freely available to the public and some was not available in English.

Future research needs to focus on the long-term agronomic and environmental behaviour of *S. hermaphrodita* and *S. perfoliatum* as well as the development of knowledge on how to integrate them successfully into farming systems, supply chains, and integrated biorefineries. Further breeding and cultivar selection of *S. hermaphrodita* and *S. perfoliatum* are needed, particularly in terms of field establishment from seed, as well as appropriate seed technology. Successful and cost-effective establishment methods are critical to the successful upscaling of both crops. Some studies found high inter-annual variability in *S. hermaphrodita* yields, which may have been due to inter-annual variations in the standard of field management in term of weed, pest and disease control, or irrigation. Long-term field experiments including high and low management regimes could help test this theory. Most of the field studies provide results for only two to three years research, which is not long enough to characterize all the key agronomic and energy properties of *S. hermaphrodita* and *S. perfoliatum* or determine how these evolve over their full rotations which can be as long as 16 to 20 years. Additional research is also needed on the greenhouse balance of the crops, as well as their invasive potential. From an economic perspective, the economic impact of scaling up *S. hermaphrodita* and *S. perfoliatum* production needs to be investigated. At the same time, *S. hermaphrodita* and *S. perfoliatum* provide other valuable by-products that could be extracted before they are used in energy production. The economics and energy balances associated with this need to be investigated.

The environmental costs associated with maize, such as biodiversity loss and increased soil erosion, do not appear on a standard net margin analysis. This puts less damaging crops such as *S. hermaphrodita* and *S. perfoliatum* at a disadvantage. In the EU, modifications to the Common Agricultural Policy are seeking increasingly to pay farmers when they provide public goods such as carbon sequestration. Schemes that recognise the ecosystem services provided by *S. hermaphrodita* and *S. perfoliatum*, could be used to support farmers for their relatively high costs of establishment, increasing the overall profitability of the crops, and creating an incentive for farmers to adopt them.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

List of documents reviewed for *Sida hermaphrodita*:

Author	Title	Year
Tilvikiene, V., Kadziuliene, Z., Liaudanskiene, I., Zvicevicius, E., Cerniauskiene, Z., Cipliene, A., Raila, A. J., Baltrusaitis, J.	The quality and energy potential of introduced energy crops in northern part of temperate climate zone	2020
Khanh-Quang, T., Werle, S., Trinh, T. T., Magdziarz, A. Sobek, S., Pogrzeba, M.	Fuel characterization and thermal degradation kinetics of biomass from phytoremediation plants	2020
Kisielewska, M., Rusanowska, P., Dudek, M., Nowicka, A., Krzywik, A., Dębowski, M., Kazimierowicz, J., Zieliński, M.	Evaluation of ultrasound pretreatment for enhanced anaerobic digestion of *Sida hermaphrodita*	2020
Magdziarz, A., Wilk, M., Wądrzyk, M.	Pyrolysis of hydrochar derived from biomass—Experimental investigation	2020
Śliz, M., Wilk, M.	A comprehensive investigation of hydrothermal carbonization: Energy potential of hydrochar derived from Virginia mallow	2020
Lewtak, K., Fiołka, M.J., Czaplewska, P., Macur, K., Kaczyński, Z., Buchwald, T., Szczuka, E., Rzymowska, J.	*Sida hermaphrodita* seeds as the source of anti—*Candida albicans* activity	2019
Purwin, C., Gugołek, A., Strychalski, J., Fijałkowska, M.	Productivity, nutrient digestibility, nitrogen retention, and meat quality in rabbits fed diets supplemented with *Sida hermaphrodita*	2019
Bernat, P., Nesme, J., Paraszkiewicz, K., Schloter, M., Płaza, G.	Characterization of extracellular biosurfactants expressed by a *Pseudomonas putida* strain isolated from the interior of healthy roots from *Sida hermaphrodita* grown in a heavy metal contaminated soil	2019
Feledyn-Szewczyk, B., Matyka, M., Staniak, M.	Comparison of the effect of perennial energy crops and agricultural crops on weed flora diversity	2019
Jankowski, K.J., Dubis, B., Sokólski, M.M., Załuski, D., Bórawski, P., Szempliński, W.	Biomass yield and energy balance of Virginia fanpetals in different production technologies in north-eastern Poland	2019
Szwaja, S., Magdziarz, A., Zajemska, M., Poskart, A.	A torrefaction of *Sida hermaphrodita* to improve fuel properties. Advanced analysis of torrefied products	2019

Author	**Title**	**Year**
Siwek, H., Włodarczyk, M., Mozdzer, E., Bury, M., Kitczak, T.	Chemical composition and biogas formation potential of *Sida hermaphrodita* and *Silphium perfoliatum*	2019
Zieliński, M., Kisielewska, M., Dudek, M., Rusanowska, P., Nowicka, A., Krzemieniewski, M., Kazimierowicz, J., Dębowski, M.	Comparison of microwave thermohydrolysis and liquid hot water pretreatment of energy crop *Sida hermaphrodita* for enhanced methane production	2019
Stolarski, M.J., Krzyżaniak, M., Warmiński, K., Olba-Zięty, E., Penni, D., Bordiean, A.	Energy efficiency indices for lignocellulosic biomass production: Short rotation coppices versus grasses and other herbaceous crops	2019
Saletnik, B., Bajcar, M., Zaguła, G., Saletnik, A., Tarapatskyy, M., Puchalski, C.	Biochar as a stimulator for germination capacity in seeds of Virginia mallow (*Sida hermaphrodita* (L.) Rusby)	2019
Nowicka, A., Zieliński, M., Dębowski, M., Dudek, M., Rusanowska, P.	Progress in the production of biogas from Virginia mallow after alkaline-heat pretreatment	2019
Szwaja, S., Poskart, A., Zajemska, M.	A new approach for evaluating biochar quality from Virginia mallow biomass thermal processing	2019
von Gehren, P., Gansberger, M., Pichler, W., Weigl, M., Feldmeier, S., Wopienka, E., Bochmann, G.	A practical field trial to assess the potential of *Sida hermaphrodita* as a versatile, perennial bioenergy crop for Central Europe	2019
Zielinski, M., Rusanowska, P., Krzywik, A., Dudek, M., Nowicka, A., Ebowski, M.D.	Application of hydrodynamic cavitation for improving methane fermentation of *Sida hermaphrodita* silage	2019
Schonhoff, A., Zapp, P., Schreiber, A., Jablonowski, N.D.	Environmental evaluation and comparison of process chains for the production and use of *Sida hermaphrodita* as a solid biofuel	2019
Bury, M., Facciotto, G., Chiocchini, F., Cumplido-Marín, L., Graves, A., Kitczak, T., Martens, R., Morhart, C., Możdżer, E., Nahm, M., Paris, P., Siwek, H., Włodarczyk, M., Burgess, P., Kahle, H.-P.	Preliminary results regarding yields of Virginia mallow (*Sida hermaphrodita* (L.) Rusby) and cup plant (*Silphium perfoliatum* L.) in different condition of Europe	2019
Antoszkiewicz, Z., Fijałkowska, M., Mazur-Kuśnirek, M., Przemieniecki, S., Purwin, C.	Effect of a harvest date and cutting height on the concentrations of carotenoids and tocopherols in Virginia fanpetals (*Sida hermaphrodita*) herbage and silage	2019
Werle, S., Tran, K.-Q., Magdziarz, A., Sobek, S., Pogrzeba, M., Løvås, T.	Energy crops for sustainable phytoremediation—Fuel characterization	2019
Kawecki, B., Podgórski, J., Głowacka, A.	Methods for determining elastic modulus in natural plant stems	2019
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Appendix B

BBCH-code – *Sida hermaphrodita*: presented in the "Supporting Information" of Jablonowski et al. [17] (https://doi.org/10.1111/gcbb.12346).

BBCH—*Silphium perfoliatum*: A standard coding for the phenological growth stages of *Silphium perfoliatum* (L.)

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Silphium perfoliatum **BBCH-code**	
Germination, sprouting, bud development	
00	S: dry seed (achene) R: winter dormancy or resting period
01	S: beginning of seed imbibition R: beginning of bud swelling
02	S:seed imbibition complete R: end of bud swelling
05	S: radicle emerged from seed
06	S: elongation of radicle, formation of root hairs and/or lateral roots
07	S: hypocotyl with cotyledons merged from seed
08	R: hypocotyl with cotyledons growing towards soil surface
09	Emergence: cotyledons emerge through soil surface
1st year after sowing or planting	
1	**Leaf development (single shoot)**
10	S: cotyledons completely unfolded
11	S: one true leaf
12	S:two true leaves unfolded
13	S: three true leaves
14	S: four true leaves (second pair) unfolded (stages continuous till 18)
19	S: nine or more true leaves
2	**Formation of basal rosette**
21	10% of plants of neighbouring rows strike each other/leaves cover 10% of ground
22	20% of plants of neighbouring rows strike each other/leaves cover 20% of ground
23	30% of plants of neighbouring rows strike each other /leaves cover 30% of ground (stages continuous till 28)
29	90% or more of plants of neighbouring rows strike each other/leaves cover 90% of ground
2nd year after sowing or planting	
1	**Leaf development (single shoot)**
11	1 pair of oppositely arranged leaves
12	2 couples of oppositely arranged leaves
13	3 couples of oppositely arranged leaves
19	9 or more couples of oppositely arranged leaves

3	**Stalk development**	
31	10% of final length	
32	20% of final length	
33	30% of final length (stages continuous till 38)	
39	Maximum stem length reached	

5	**Inflorescence emergence**	
51	501	Inflorescence just visible between youngest leaves
53	503	Inflorescence separating from youngest leaves, bracts distinguishable from foliage leaves
55	505	Inflorescence separated from youngest leaves
57	507	Inflorescence clearly separated from youngest leaves
59	509	Golden-yellow ray florets visible between the bracts
	521	Second order stem inflorescence visible
	525	Second order stem inflorescence separated from youngest
	529	First flower formed on secondary inflorescence
	5N1	N*th* order stem inflorescence visible
	5N5	N*th* order stem inflorescence separated from youngest
	5N9	First flower formed on n*th* inflorescence

6	**Flowering**	
61	601	Beginning of flowering: ray florets extended, disc florets visible in outer part of inflorescence
62	602	Disc florets in blooms (stages continuous till 64)
65	605	Full flowering: disc florets in middle part of inflorescence in bloom
67	607	Flowering declining: disc floret in inner part of inflorescence in bloom
69	609	End of flowering: most disc florets finished flowering, ray florets dry or fallen
	621	Ray florets extended and disk florets visible in outer part on secondary inflorescence
	625	Full flowering: disc florets in middle part of inflorescence in bloom on secondary inflorescence
	629	End of flowering: most disc florets have finished flowering, ray florets dry or fallen on secondary inflorescence
	6N1	Ray florets extended and disk florets visible in outer part on *nth* order inflorescence
	6N5	Full flowering: disc florets in middle part of inflorescence in bloom on *nth* order inflorescence
	6N9	End of flowering: most disc florets have finished flowering, ray florets dry or fallen on *nth* order inflorescence

7	**Development of seeds**	
71	701	Seed on the outer edge of the first head have reached the final size
79	709	Seed on the inner edge of the first head have reached the final size
	721	Seed on the outer edge of the secondary head have reached the final size
	729	Seed on the inner edge of the secondary head have reached the final size
	7N1	Seed on the outer edge of the *nth* order head have reached the final size
	7N9	Seed on the inner edge of the *nth* order head have reached the final size
Outer bracts of the head still green seeds of on outer edge ripe and grey		

8	**Ripening or maturity of seed**	
81	801	Outer bracts of first head still green, seeds of on outer edge ripe and grey-brown
82	802	Outer bracts of first head begin to became grey-brown, 20% of seed grey-brown
89	809	Outer bracts of first head completely grey-brown, all seeds ripe and grey-brown
	821	Outer bracts of secondary head still green, seeds of on outer edge ripe and grey-brown
	822	Outer bracts of secondary head begin to became grey-brown, 20% of seed ripe and grey-brown
	829	Outer bracts of secondary heads completely grey-brown, all seeds ripe and grey-brown
	8N1	Outer bracts of *nth* order head still green, seeds of on outer edge ripe and grey-brown
	8N2	Outer bracts of *nth* order head begin to became grey-brown, 20% of seed ripe and grey-brown
	8N9	Outer bracts of *nth* order head completely grey-brown, all seeds ripe and grey-brown

9	**Senescence, beginning of dormancy**
91	Shoot development completed, foliage still green
93	Basal leaf completely dead, caulicle leaves discoloured
95	Majority of leaves are dead
97	All leaves dead
98	Above ground parts dead
99	Plant dead and dry (dry matter more than 80%)

Additional descriptions: S: plant from seed; R: plant from rhizome; C: crop carpet
If the description is valid for all, no additional description is given.

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