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Energy efficiency of perennial herbaceous crops production depending on the type of digestate and mineral fertilizers

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A B S T R A C T

The aim of this study was to analyse the input and energy efficiency of the biomass production of four species of Perennial Herbaceous Crops (PHC): *Helianthus tuberosus*, *Sida hermaphrodita*, *Helianthus salicifolius*, *Miscanthus* × *giganteus*. The crops were fertilised with three types of biogas plant digestate (wet digestate, dry digestate, torrefied digestate) and mineral fertilizers at two rates (85 and 170 kg ha^{-1} N). Analyses for the study were based on average values of the three years of the experiment (2013–2015) conducted in north-eastern Poland. The total energy input ranged widely (2832–59,080 MJ ha^{-1}), depending on the species, forms and level of fertilisation. The lowest input was observed at control sites. The highest input was recorded where torrefied and dry digestate were used as fertilisers, which was a consequence of the high energy intensity of their production. *Helianthus salicifolius* gave the highest energy gain of all the fertilisation options and in the control plot compared to the other three PHC species. The highest energy efficiency ratio in the experiment (19.1) was obtained for *Helianthus salicifolius* in the no-fertilisation option. Its values for the other species in the control plots were between 5 and 52% lower.

1. Introduction

Biomass (in the broad sense of the word) is the main renewable energy source (RES) in EU-28 and Poland [1]. Therefore, increasing attention has been attracted by production opportunities for agricultural biomass, including Short Rotation Woody Crops (SRWC), such as willow, poplar and black locust [2,3] and Perennial Herbaceous Crops (PHC), e.g. Virginia fanpetals, giant miscanthus and Jerusalem artichoke [4,5]. These plants could be grown on soils of poorer quality which are unusable for growing crops for food or fodder. Depending on the species and the harvest date, perennial plant biomass can be used directly as a solid fuel or transformed into briquette or pellets. It can also be used in biorefineries as feedstock for various bioproducts as well as liquid and gaseous biofuels [6–11].

Agricultural biogas is produced from several different types of agricultural substrates and those from the food industry. The demand for such substrates is growing rapidly. In 2011, for example, ca. 696 thousand Mg of agricultural substrates were used in the production of biogas in Poland. However, in 2014 over 2.1 million Mg were used, including ca. 417 thousand Mg of maize silage [12]. Maize is the main substrate used in biogas production, not only in Poland, but also in other EU countries [13]. Although the development of biogas plants boosts RES production growth, it stimulates the competition for maize as feedstock for fodder and food production. Moreover, biogas plants produce digestate, which is a by-product which can also be used as a yield-enhancing organic fertiliser. On the other hand, utilisation of digestate as a fertiliser is sometimes an issue because of its excessive amounts, varying crop sequence as well as time and quantity limitations in regard to the amounts of nitrogen introduced to the soil with it. Therefore, the cultivation of PHC creates opportunities to use biogas plant

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digestate as a biofertiliser to fertilise a plantation and it can also be a source of biomass as a substrate or co-substrate for a biogas plant. The use of digestate for fertilisation of PHC plantations may be beneficial for biomass yield, however, the energy input of the application of such type of fertilisation should be taken into account. This is very important because producing and supplying biomass from a PHC plantation requires identifying species and technologies to achieve much higher energy output than input. Only then will making bioproducts, biofuels and generation of bioenergy be justified from environmental and energy production points of view [14]. To achieve this, it is necessary to carry out multi-factorial studies to assess different variables influencing the productivity of perennial plants and the energy value of the biomass yield. A novelty in our studies was the application of varied forms of digestates for PHC fertilisation. To date, not much is known about the effect of fertilisation of PHC with biogas plant digestate on the energy efficiency ratios of biomass production. Therefore, the aim of this study was to determine the input and energy efficiency of biomass production of four species of PHC fertilised with three types of digestate from a biogas plant and mineral fertilizers at two rates.

2. Materials and methods

2.1. Field experiment

The study was based on a field experiment carried out between 2013 and 2015 in north-eastern Poland (53°59′ N, 21°09′ E) at the Didactic and Research Station in Łężany, owned by the University of Warmia and Mazury in Olsztyn. The experimental plot was situated on soil formed from sandy loam, on slightly configured land, with a slope not exceeding 2%. Detailed data on the weather conditions and soil properties are presented in Table 1. The experiment was carried out in three consecutive harvest cycles, in the first (2013), second (2014) and third (2015) year of cultivation. Analyses for the study were based on average values of the three years of the experiment (2013–2015) for the biomass yield, energy values of the yield, energy input and energy efficiency ratios for biomass production, depending on the PHC species as well as the form and level of fertilisation applied.

Four species of herbaceous crops were the first factor of the experiment: (i) Jerusalem artichoke (*Helianthus tuberosus* L.) (HT); (ii) Virginia fanpetals (*Sida hermaphrodita* Rusby L.) (SH); (iii) willow–leaf sunflower (*Helianthus salicifolius* A. Dietr) (HS); (iv) giant miscanthus (*Miscanthus* × *giganteus* J.M.Greef & M.Deuter) (MG). Jerusalem artichoke tubers and Virginia fanpetals rhizomes were planted at a density of 20 thousand ha^{-1}. The giant miscanthus rhizomes and herbaceous seedlings of willow-leaf sunflower were planted at a density of 10 thousand ha^{-1}. The second factor was the form of fertilisation: (i) wet digestate (WD); (ii) dry digestate (DD); (iii) torrefied digestate (TD); (iv) mineral fertilisation (MF); (v) control treatment – no fertilisation (C). The contents of the main nutrients in each organic fertiliser were used to calculate their application rates (Table 2) to achieve nitrogen fertilisation at two rates: 85 and 170 kg ha^{-1}. Mineral fertilisation with NPK was balanced against organic fertilisation and the rates of mineral fertilisation were subsequently decreased by 20% relative to organic fertilisation. This was a consequence of the fact that not all nutrients present in the organic fertilizers are available to plants in the year of application. According to the Good Agricultural Practice Code for Poland [15], the effectiveness of organic fertilisation is close to 80% during the first year, so the rates of mineral fertilisation were decreased by 20% compared to the macronutrients supplied with the organic fertilizers. Mineral NPK fertilizers were applied as ammonium nitrate, triple superphosphate and potassium salt. The third factor was the level of nitrogen (N) fertilisation: (i) N 85 kg ha^{-1}; (ii) N 170 kg ha^{-1}.

2.2. Energy output analysis

The yield energy value of perennial herbaceous crops (PHC) was calculated as the product of fresh biomass yield (Fresh Matter – FM) per ha and its lower heating value (1):

$$Y_{ev} = Y_b \cdot Q^r{}_i \tag{1}$$

where:

Y_{ev} – biomass yield energy value (GJ ha^{-1}),
Y_b – fresh biomass yield (Mg ha^{-1} FM),
$Q^r{}_i$ – biomass lower heating value (GJ Mg^{-1}).

2.3. Energy input analysis

The energy inputs used to produce the Jerusalem artichoke, Virginia fanpetals, willow-leaf sunflower and giant miscanthus chips were analysed, including several energy sources: direct energy carriers (diesel fuel), exploitation of fixed assets (tractors, machines, equipment), consumption of materials (digestate fertilizers, mineral fertilisers, agrochemicals, rhizomes, seedlings) and

Table 2
Average amounts of organic and mineral fertilisers applied in fertilisation, equivalent to the doses of N of 85 and 170 kg ha^{-1} in organic fertilisers.

Form of fertilisation	Level of N fertilisation (kg ha^{-1})	
	85	170
Wet digestate (1000 dm^3)	26.0	52.0
Dry digestate (Mg)	5.4	10.8
Torrefied digestate (Mg)	5.6	11.2
Mineral fertilisers – N; P; K (kg)	68.0; 26.0; 73.2	136.0; 52.0; 146.4

Table 1
Weather conditions and some soil properties during the experiment period.

Year	Weather conditions				Soil properties for horizon A (0–26 cm)
	Temperature (°C)		Precipitation (mm)		
	Average (month IV–X)	Average (month I–XII)	Sum (month IV–X)	Sum (month I–XII)	
2013	13.7	7.8	497.5	691.9	pH (KCl): 4.59 Organic matter (%): 2.65 Soil texture (%): clay: 6 silt: 16 sand: 78
2014	14.2	8.8	371.9	571.9	
2015	13.4	9.0	239.7	549.7	
Multi–period 1998–2014	13.8	8.0	479.8	683.2	

human labour (2).

$$E_{i\ total} = E_{i\ diesel} + E_{i\ fixed\ assets} + E_{i\ materials} + E_{i\ human\ labour} \quad (2)$$

where:

$E_{i\ total}$ – total energy input for PHC chip production (GJ ha^{-1}),
$E_{i\ diesel}$ – energy input for diesel fuel consumption (GJ ha^{-1}),
$E_{i\ fixed\ assets}$ – energy input for fixed assets (GJ ha^{-1}),
$E_{i\ materials}$ – energy input for materials (GJ ha^{-1})
$E_{i\ human\ labour}$ – energy input for human labour (GJ ha^{-1})

The total energy input for PHC chip production was calculated based on the unit consumption of materials and the energy intensity of their production. The energy conversion coefficients for diesel fuel (43.1 MJ kg^{-1}), nitrogen fertilizers (48.99 MJ kg^{-1} N), phosphorus fertilizers (15.23 MJ kg^{-1} P_2O_5), potassium fertilizers (9.68 MJ kg^{-1} K_2O) and pesticides (268.4 MJ kg^{-1} of active substance) were based on the indexes presented in literature [16]. The energy input for the use of tractors (125 MJ kg^{-1}), machines (110 MJ kg^{-1}) and human labour (60 MJ h^{-1}) in the production process was calculated with the coefficients provided in the literature and data provided in materials published by manufacturers of tractors and machines [17,18]. It was found on the basis of our own 20-year experience in growing PHC and literature reports [13,19–22] that the energy input for the production of Jerusalem artichoke tubers, rhizomes of miscanthus, Virginia fanpetals and green seedlings of willow-leaf sunflower can vary depending on the conditions and production technology as well as the technique and scale of material harvesting. Therefore, before the experiment was set up, the planting material for each PHC species was weighed and its amount (kg) needed to set up a 1 ha plantation was determined. Subsequently, it was assumed on the basis of earlier studies that the energy input needed to obtain 1 kg of seedlings would be similar to that necessary to obtain 1 kg of willow seedlings (3.04 MJ) [23]. Subsequently, the amount of the planting material used (kg ha^{-1}) and the unit energy input (MJ kg^{-1}) were used to determine the energy input of the planting material of each PHC species (MJ ha^{-1}). The energy inputs for the production of wet digestate, dry digestate and torrefied digestate were: 0.100 MJ dm^{-3}; 2.273 MJ kg^{-1} and 4.347 MJ kg^{-1}, respectively. Wet digestate (WD) was used as a fertilised obtained from a biogas plant with no further processing. To obtain dry digestate (DD), wet digestate was dehydrated in a screw separator and was then dried in a pipe reactor. A torrefied digestate (TD) was then obtained from DD next using a torrefaction reactor. The types of equipment used in field operations and the maximum power of the tractors and those used in different operations carried out in the year that the plantation was set up and in later years of its use are shown in Table 3.

2.4. *Energy efficiency analysis*

Accumulated energy gain was the difference between the PHC yield energy value and the total input for its production (3):

$$E_g = Y_{ev} - E_{i\ total} \quad (3)$$

where:

E_g – accumulated energy gain (GJ ha^{-1}),
Y_{ev} – biomass yield energy value (GJ ha^{-1}),
$E_{i\ total}$ – total energy input (GJ ha^{-1}).

Energy intensity was the energy consumption per 1 Mg of fresh or dry (FM or DM) PHC chips, it was the ratio of total energy input to the yield (4):

$$EI = E_{i\ total} / Y_b \quad (4)$$

where:

EI – energy intensity (GJ Mg^{-1} FM or DM),
$E_{i\ total}$ – total energy input (GJ ha^{-1}),
Y_b – biomass yield (Mg ha^{-1} FM or DM).

Diesel fuel consumption per 1 Mg of fresh or dry PHC chips, was the ratio of the diesel fuel consumption to the yield (5):

$$C_D' = C_D / Y_b \quad (5)$$

where:

C_D' – diesel fuel consumption (kg Mg^{-1} FM or DM),
C_D – diesel fuel consumption (kg ha^{-1}),
Y_b – biomass yield (Mg ha^{-1} FM or DM).

The energy efficiency ratio of PHC chips production was the ratio of the yield energy value (energy output) to energy input for its production (6):

$$ER = Y_{ev} / E_{i\ total} \quad (6)$$

where:

ER – energy efficiency ratio of PHC chips production,
Y_{ev} – biomass yield energy value (GJ ha^{-1}),
$E_{i\ total}$ – total energy input (GJ ha^{-1}).

2.5. *Statistical analysis*

A three–way analysis of variance was carried out to determine the effects of species (factor A), the form of fertilisation (factor B), the level of N fertilisation (factor C) and all interactions between the main factors for fresh and dry biomass yield and yield energy value. The level of significance of the analysis was established at $P < 0.05$. Homogeneous groups for the examined traits were determined by Tukey's (HSD) multiple-comparison test. All statistical analyses were done with the STATISTICA software (StatSoft, Inc., 2014).

3. Results and discussion

3.1. *Biomass yield of PHC and energy output*

Fresh biomass yield of PHC was significantly differentiated by the species ($P < 0.0001$), form of fertilisation ($P = 0.0226$), level of N fertilisation ($P = 0.0018$) and within an interaction between the species and the form and fertilisation ($P = 0.0233$) (Table 4).

A significantly higher yield of fresh biomass was obtained for *Helianthus salicifolius* (HS) and *Helianthus tuberosus* (HT), and a lower yield for *Sida hermaphrodita* (SH) and *Miscanthus* × *giganteus* (MG). Moreover, fertilisation and an increase in its rate in general resulted in a growth of the yield of most species compared to the control. More varied, and sometimes different, effects were observed for MG (Table 5). Furthermore, the yield of dry biomass was significantly differentiated only by the main factors (species, form of fertilisation and level of N fertilisation), whereas no significant effect was observed within an interaction between the main factors (Table 4).

A significantly higher yield of dry biomass was achieved for HS;

Table 3
Data for field operations.

Operation	Tractors				Machinery		Operating period	Comments
	Name	Mass (kg)	Power (kW) (max/ used)	Utilisation of the power capacity (%)	Name	Mass (kg)	(h ha^{-1})	
Work of setting up a plantation and its liquidation is done once in the entire period of the plantation use (once per 15 years)								
Spraying	New Holland TM 130 HP	5465	95.6/47.8	50	Krukowiak sprayer. working width 18 m	2110	0.2	Glyphosate. Roundup 360 SL. 5 l ha^{-1}
Disking	New Holland TM 130 HP	5465	95.6/60.2	63	Kverneland disk harrow. working width 4 m	1160	0.7	1 x coverage
Winter ploughing	New Holland TM 175 HP	7150	128.6/ 90.0	70	Kverneland PG 100 plough. working width 2 m	1120	1.5	5–ridge plough. ploughing depth 30 cm
Harrowing	New Holland TM 130 HP	5465	95.6/52.6	55	Harrow. working width 6 m	530	1.0	2 x coverage
Planting with a planting machine	New Holland TM 90 HP	4410	66.0/33.0	50	4-row planting machine	300	2.0	[b]4-row planting machine, suitable for seedlings, rhizomes or tubers of local production,
Weeding	New Holland TM 90 HP	4410	66.0/33.0	50	Mechanical weeder P 430/2. working width 3 m	340	1.0	3 x coverage
Liquidation of plantation	New Holland TM 175 HP	7150	128.6/ 102.9	80	Kverneland PG 100 plough. working width 2 m	1120	2.0	5–ridge plough. ploughing depth 30 cm
Work done every year								
Wet digestate fertilisation[a]	New Holland TM 90 HP	4410	66.0/33.0	50	Sipma WA 600 DELFIN cart, capacity – 6.6 thousand litres	2400	2.8; 5.6	[c] operation time varies depending on the fertiliser rate
Dry and torrefied digestate fertilisation[a]	New Holland TM 90 HP	4410	66.0/33.0	50	UPR spreader, capacity – 2.83 m^3	1500	1.0; 2.0	[d] operation time varies depending on the fertiliser rate
Mineral fertilisation[a]	New Holland TM 90 HP	4410	66.0/33.0	50	Rauch 3.0 t spreader. working width 18 m	350	0.5	The same time for a smaller and higher fertilisation rate
Soil loosening and mixing fertilisers	New Holland TM 90 HP	4410	66.0/39.6	60	MG4 inter row rotary cultivator, working width 3 m	380	1.5	1 x coverage. applied in all cultivation combinations
Harvesting	New Holland TM 175 HP	7150	128.6/ 115.7	80	Forage harvester Z–374	1400	0.5–2.9	[e] depending on the yield of a PHC species. average productivity of harvester 10 tons of chips per hour
Field transport	New Holland TM 90 HP	4410	66.0/33.0	50	T 169/2 tractor trailer. loading capacity ca. 15m^3	1940	1.3–8.8	[f]to ensure continuity of receipt of chips 3 transportation units

[a] Performed depending on the fertilisation option.
[b] Up to 4 people for the planting machine operation, depending on the plant species.
[c] Operation time varies depending on the fertiliser rate 2.8 and 5.6 h ha^{-1}, for the lower and the higher fertiliser rate, respectively.
[d] Operation time varies depending on the fertiliser rate 1.0 and 2.0 h ha^{-1}, for the lower and the higher fertiliser rate, respectively.
[e] Operation time varies depending on the yield of a PHC species, average productivity 10 Mg h^{-1} of chips.
[f] Operation time varies depending on operation time of the forage harvester.

it ranged from 7.2 Mg ha^{-1} of DM to 10.6 Mg ha^{-1} of DM, for fertilisation at a lower rate of TD and a higher rate of DD, respectively (Table 5). Another homogeneous group in terms of the dry biomass yield included HT, range 4.0–9.0 Mg ha^{-1} DM. SH and MG were in the third homogeneous group in terms of the yield of dry biomass, ranges: 2.9–5.8 Mg ha^{-1} DM and 2.2–4.3 Mg ha^{-1} DM, respectively. Fertilisation and an increase in its rate in general resulted in a growth of the biomass yield of most species. However, MG reacted

Table 4
Analysis of variance (ANOVA) for fresh and dry biomass yield and yield energy value.

Source of variation	Yield of fresh biomass		Yield of dry biomass		Yield energy value	
	F–value	*P*–value	*F*–value	*P*–value	*F*–value	*P*–value
Species (A)	104.406	<0.0001	61.953	<0.0001	54.589	<0.0001
Form of fertilisation (B)	2.887	0.0226	2.526	0.0408	2.177	0.0713
Level of N fertilisation (C)	9.949	0.0018	9.437	0.0023	8.345	0.0041
A x B	2.006	0.0233	1.450	0.1421	1.176	0.2990
A x C	0.828	0.4794	0.342	0.7952	0.254	0.8583
B x C	0.942	0.4396	0.909	0.4588	0.839	0.5010
A x B x C	0.383	0.9690	0.293	0.9902	0.258	0.9946

Table 5
Yield of fresh and dry aboveground biomass and yield energy value of four species PHC depending on the form and level of fertilisation. Mean of the first three years of cultivation.

Form of fertilisation	Level of N fertilisation (N kg ha^{-1})	Species and feature											
		HT^{a}	SH^{b}	HS^{a}	MG^{b}	HT^{b}	SH^{c}	HS^{a}	MG^{c}	HT^{b}	SH^{b}	HS^{a}	MG^{c}
		Yield of fresh biomass (Mg ha^{-1})				Yield of dry biomass (Mg ha^{-1} DM)				Yield energy value (GJ ha^{-1})			
Wet digestate (WD)	85	18.8	4.7	23.1	5.1	5.2	3.0	9.4	2.2	55.9	51.7	143.7	35.2
	170	28.9	7.9	26.0	5.6	8.0	4.9	10.3	2.4	87.2	85.3	156.8	38.4
Dry digestate (DD)	85	20.8	7.4	19.6	6.2	5.9	4.7	7.9	2.7	66.4	82.7	118.7	43.8
	170	21.9	9.2	26.3	8.1	6.3	5.8	10.6	3.5	69.9	102.0	161.9	57.0
Torrefied digestate (TD)	85	22.3	5.7	18.1	7.1	6.6	3.6	7.2	3.1	77.1	64.7	108.6	50.2
	170	29.4	7.1	24.5	9.6	9.0	4.5	10.0	4.1	109.0	80.1	153.5	67.0
Mineral fertilisers (MF)	85	18.6	7.6	24.3	9.0	5.8	4.9	9.8	3.7	70.2	85.7	150.6	57.8
	170	21.7	8.6	25.8	10.3	6.5	5.5	10.4	4.3	76.3	98.6	156.4	67.6
Control – no fertilisation (C)		13.4	4.5	20.9	8.5	4.0	2.9	8.7	3.7	45.8	51.2	133.8	58.5

a.b.c … homogenous groups average for PHC species, separately for each feature.

negatively (by a decrease in the yield) to most forms and levels of fertilisation compared to the control. Other studies also found that fertilisation did not have a significant effect on above-ground biomass production of *Miscanthus* × *giganteus* [24], however, the obtained yields were several times higher than in our studies [11,13,19,24–28]. A much higher yield of the above-ground biomass than in our study was also obtained for *Helianthus tuberosus*. Moreover, when mineral fertilisation was applied, biomass yield was considerably higher (22.7 Mg ha^{-1} DM) in comparison with a control plot (14.7 Mg ha^{-1} DM) [29]. Meanwhile, HT grown on sandy soil gave a similar yield to our studies in the C plot and responded only slightly to fertilisation [30]. *Sida hermaphrodita* also yielded higher than in our studies and responded positively to fertilisation [13,22,31].

It should be concluded that the biomass yield of the PHC species achieved in our experiment was generally low. However, it must be stressed that our yield is the mean value of the first three growing periods. It is known that the yield of PHC is low in the first year of cultivation and that it increases later as the plantation is used. Commercial use of a plantation is estimated to last for 15–20 years and it depends on habitat-related, agrotechnical and economic factors. A considerable amount of literature analyses concerning the yield and energy value of PHC biomass involves data from older plantations at a full development phase. On the other hand, the first year (plantation establishment) and the second and third years of cultivation (and approaching a full yield as the initial years) are "of little interest" and are often omitted in published analyses since data from this period are not as spectacular (due to a low yield) as data collected from plantations with a full yielding period. However, we conducted such studies since studies carried out in the initial years of operating a PHC plantation are also important since they affect the effectiveness of operation of the plantation over the period of their use.

The energy value of the PHC yield obtained in our study was significantly differentiated only by species ($P < 0.0001$) and the level of N fertilisation ($P = 0.0041$) (Table 4). Significantly higher yield energy values were obtained for HS and they ranged from 108.6 GJ ha^{-1} to 161.9 GJ ha^{-1} (Table 5). Another homogeneous group in terms of the yield energy value included HT (range 45.8–109.0 GJ ha^{-1}) and SH (range 51.2–102.0 GJ ha^{-1}). MG was in the third homogeneous group in terms of the yield energy value. An increase in the N fertilisation rate from 85 to 170 kg ha^{-1} in general resulted in an increase in the yield energy value in the species under study. However, a higher yield energy value in the cultivation of MG was achieved at the control plot (58.5 GJ ha^{-1}) than in the majority of plots with fertilisation applied.

The energy value of PHC biomass (like the yield itself) is strongly differentiated by the species, habitat-related and agrotechnical factors, year of cultivation, date of harvest and other factors. The energy value of *Miscanthus* × *giganteus* in a full yielding plantation was from 3.5 to 7-fold higher than the highest value achieved in our study [13,19–21,32]. On the other hand, the highest yield energy value of *Sida hermaphrodita* (SH) obtained in our studies was similar [22], or about 2-fold lower, than was found in other studies [13,33,34].

3.2. Energy inputs

The energy inputs for setting up and running 1 ha of a plantation of PHC during the first year of growth and its liquidation after its exploitation was completed were differentiated by species. They were the smallest for MG (9813 MJ ha^{-1}) (Table 6). They increased by 24%, 39% and 43% for setting up plantations of HT, SH and HS, respectively. Calculated per year of plantation use (when a plantation was exploited for 15 years) energy inputs ranged from 654 to 934 MJ ha^{-1}, for MG and HS, respectively.

Consumption of diesel fuel dominated among the energy inputs for setting up and running a plantation during the first year of growth and its liquidation after its exploitation was completed (Fig. 1). The inputs accounted for 40.4%–57.7% of total inputs, for HS and MG, respectively. They were followed by consumption of materials, which accounted for 21.0%–44.7% in the whole experiment. However, the much lower energy input was related to the use of tractors and machines (8.4%–11.9%) and human labour (6.1%–9.4%).

Energy inputs for the production of PHC chips were significantly differentiated by species, forms and level of N fertilisation and the consequent yield level. The lowest energy inputs among all of the PHC under study were in the control plots, and among the energy sources, the consumption of diesel fuel (62–70%) was dominant. However, increasing the level of N fertilisation increased the energy inputs for all forms of fertilisation (Tables 7–10). Among the forms of fertilisation applied in the study, the lowest input was made at sites where wet digestate (WD) was used and the largest input was recorded at sites where torrefied digestate (TD) and dry digestate (DD) were used to fertilise the plants, which was a consequence of the high energy intensity of their production. Depending on the species, forms and level of N fertilisation, the application of MF, WD, DD and TD constituted 35–68%; 22–44%; 62–84% and 76–91% of the total energy inputs, respectively. The total energy inputs for the production of HT chips ranged between 5000 MJ ha^{-1} and 59,080 MJ ha^{-1}, for the C and TD 170 options, respectively (Table 7). The input was lower for SH – 2832 MJ ha^{-1} and 53,528 MJ ha^{-1},

Table 6
Energy input for setting up and running PHC plantations in the first year and for their liquidation in the last year of cultivation (MJ ha^{-1}).

Operation	HT[a]					SH[a]	HS[a]	MG[a]
	Labour	Tractors + Machinery	Diesel fuel	Materials	Total	Total	Total	Total
Spraying (glyphosate)	18.0	57.8	87.8	483.1	646.7	646.7	646.7	646.7
Disking	48.0	95.7	387.0	0.0	530.7	530.7	530.7	530.7
Winter ploughing	96.0	204.1	1262.9	0.0	1563.0	1563.0	1563.0	1563.0
Harrowing (2x)	72.0	95.8	482.7	0.0	650.5	650.5	650.5	650.5
Planting	180.0	174.4	605.9	4116.2	5076.4	6590.8	6916.3	2721.1
Weeding (3x)	198.0	271.4	908.8	0.0	1378.2	1378.2	1378.2	1378.2
Liquidation of plantation	126.0	272.2	1924.4	0.0	2322.6	2322.6	2322.6	2322.6
Total	738.0	1171.3	5659.6	4599.3	12,168.1	13,682.5	14,008.0	9812.8
1/15 Σ	49.2	78.1	377.3	306.6	811.2	912.2	933.9	654.2

[a] Data for HT broken down into energy flows and their sum, whereas only total energy inputs for individual operations are given for SH, HS and MG.

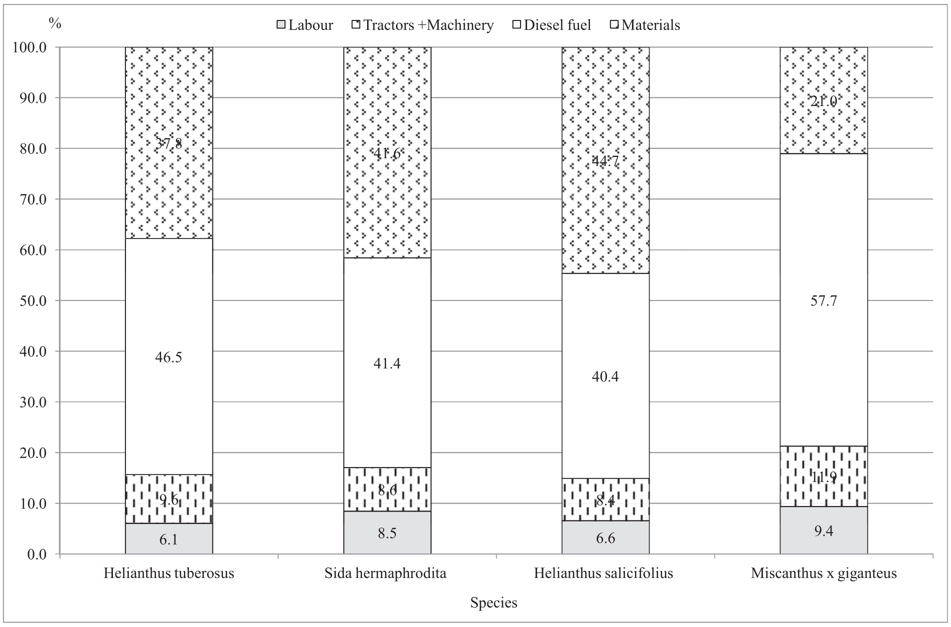

Fig. 1. Structure of energy input (%) for setting up and running PHC plantation in the first year and for their liquidation in the last year of cultivation in the energy flow.

Table 7
Energy input for the production of *Helianthus tuberosus* (HT) chips depending on the form and level of fertilisation by energy flow (MJ ha^{-1}).

Item	Form and level of fertilisation								
	WD 85	WD 170	DD 85	DD 170	TD 85	TD 170	MF 85	MF 170	C
Human labour	781.7	1193.5	721.9	809.8	758.2	988.8	640.1	715.0	479.8
Tractors + Machinery	1869.0	3165.2	1395.8	1754.7	1459.5	2069.2	1149.8	1281.3	776.4
Diesel	5282.8	8032.1	5113.6	5633.6	5396.1	7029.4	4558.0	5141.8	3437.3
Materials from 1st year	306.6	306.6	306.6	306.6	306.6	306.6	306.6	306.6	306.6
Fertilisers	2600.0	5200.0	12,274.2	24,548.4	24,343.2	48,686.4	4435.9	8871.8	0.0
Total	10,840.1	17,897.4	19,812.2	33,053.1	32,263.6	59,080.5	11,090.4	16,316.4	5000.1

Table 8
Energy input for the production of *Sida hermaphrodita* (SH) chips depending on the form and level of fertilisation by energy flow (MJ ha^{-1}).

Item	Form and level of fertilisation								
	WD 85	WD 170	DD 85	DD 170	TD 85	TD 170	MF 85	MF 170	C
Human labour	471.0	715.8	428.3	531.0	387.8	481.1	403.6	427.1	292.7
Tractors + Machinery	1274.0	2276.8	830.8	1215.8	759.6	1128.1	685.1	726.4	398.6
Diesel	2642.8	4089.8	2606.4	3242.4	2290.2	2853.2	2496.1	2679.5	1760.8
Materials from 1st year	379.6	379.6	379.6	379.6	379.6	379.6	379.6	379.6	379.6
Fertilisers	2600.0	5200.0	12,274.2	24,548.4	24,343.2	48,686.4	4435.9	8871.8	0.0
Total	7367.4	12,662.0	16,519.3	29,917.2	28,160.3	53,528.4	8400.3	13,084.4	2831.7

Table 9
Energy input for the production of *Helianthus salicifolius* (HS) chips depending on the form and level of fertilisation by energy flow (MJ ha^{-1}).

Item	Form and level of fertilisation								
	WD 85	WD 170	DD 85	DD 170	TD 85	TD 170	MF 85	MF 170	C
Human labour	897.4	1135.4	704.6	925.7	669.6	882.2	787.2	824.6	669.8
Tractors + Machinery	2051.1	3042.1	1344.4	1937.3	1282.8	1860.9	1387.2	1453.0	1089.3
Diesel	6091.1	7485.7	4885.3	6443.8	4612.2	6105.1	5611.4	5903.3	4825.6
Materials from 1st year	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3	417.3
Fertilisers	2600.0	5200.0	12,274.2	24,548.4	24,343.2	48,686.4	4435.9	8871.8	0.0
Total	12,056.9	17,280.5	19,625.9	34,272.4	31,325.1	57,952.0	12,638.9	17,469.9	7002.0

Table 10
Energy input for the production of *Miscanthus* × *giganteus* (MG) chips depending on the form and level of fertilisation by energy flow (MJ ha^{-1}).

Item	Form and level of fertilisation								
	WD 85	WD 170	DD 85	DD 170	TD 85	TD 170	MF 85	MF 170	C
Human labour	466.1	645.8	384.0	489.1	406.6	525.8	421.7	453.1	373.7
Tractors + Machinery	1293.4	2181.9	781.1	1170.3	820.7	1234.8	745.0	800.2	568.9
Diesel	2728.9	3668.8	2385.6	3040.3	2561.5	3326.6	2761.8	3006.9	2516.8
Materials from 1st year	137.6	137.6	137.6	137.6	137.6	137.6	137.6	137.6	137.6
Fertilisers	2600.0	5200.0	12,274.2	24,548.4	24,343.2	48,686.4	4435.9	8871.8	0.0
Total	7225.9	11,834.1	15,962.5	29,385.7	28,269.5	53,911.2	8501.9	13,269.6	3597.0

respectively (Table 8). Furthermore, the total energy input for HS cultivation at the C plot was 7002 MJ ha^{-1} and it was over 8 times larger at the TD 170 plot (Table 9). Similar energy outlay relationships were observed for MG; they were 3597 MJ ha^{-1} at plot C and they were nearly 15 times larger at the TD 170 plot (Table 10).

The total energy input for production of SH chips in our earlier studies was differentiated by the three types of planting material and two sowing or planting densities. The energy inputs were the lowest when a plantation of SH was set up by sowing seeds (9.1 and 9.4 GJ ha^{-1}). Higher inputs were made in technologies where vegetative planting material was used (rhizomes and herbaceous seedlings), especially when it was planted at a density of 60 thousand plants ha^{-1} (11.7–18.9 GJ ha^{-1}) [34]. Similar energy inputs for the production of SH biomass were made when the medium- and high-input technology was applied – 12.8 and 19.5 GJ ha^{-1}, respectively [33]. Larger inputs for production of this species biomass (21.8 GJ ha^{-1}) were made on a large-scale farm [13]. Highly varied energy input for the production of SH (8.6–29.3 GJ ha^{-1}) has also been recorded in other studies when fertilisation with various levels of N and $CaCO_3$ was applied [22]. However, energy input may vary in the cultivation of MG. In an experiment conducted in Germany, it lay within a low range (4–8 GJ ha^{-1}) [19], although in Poland it was much higher (18.7 GJ ha^{-1}) [13].

3.3. *Energy efficiency*

3.3.1. *Energy gain*

The energy input for production of PHC in various fertilisation options and for obtaining biomass, as well as the energy value, significantly differentiated the energy efficiency factors of the species under study. The highest energy gain (139.6 GJ ha^{-1} $year^{-1}$) was achieved in growing *Helianthus salicifolius* (HS) at a site where wet digestate (WD) at a higher rate of N was applied (Table 11). It must be emphasised that HS gave the largest energy gain with all the fertilisation options and at the control plot compared to the other three PHC species. Moreover, the energy gain for HS on the control plot was higher than when fertilisation with DD at a lower rate and TD at both rates was applied. The maximum increase in the energy gain compared to the control plot in this species was 10% when MF and a higher rate of WD were applied. Energy gain in the cultivation of *Helianthus tuberosus* (HT) was much lower and ranged from 36.8 to 69.3 GJ ha^{-1} $year^{-1}$, for a plot where DD and WD at an increased rate were applied. The maximum increase in the energy gain compared to the control plot in HT was 70% when a higher rate of WD was applied. A still higher energy gain (77%) compared to the control plot was obtained in the cultivation of *Sida hermaphrodita* (SH) when MF at an increased rate was applied. However, when TD and WD at a lower rate were applied in fertilisation of the species, this resulted in reduced energy gain compared to the control plot. A different relationship was observed in the cultivation of *Miscanthus* × *giganteus* (MG), because the highest energy gain was obtained in the control plot (54.9 GJ ha^{-1} $year^{-1}$). All forms and levels of N fertilisation applied in the experiment decreased the energy gain in MG. It must be emphasised that the energy gain obtained on the control plot in MG cultivation was higher than in the same combination in the cultivation of HT and SH. The energy gain in the production of MG in another study was 4–9 times higher than the highest value achieved in this study [13,19–21]. The energy gain in the cultivation of SH was also higher (130–226 GJ ha^{-1}) than that obtained in this study [13,33,34].

3.3.2. *Diesel fuel consumption*

Diesel fuel consumption calculated for 1 ha of a plantation was much higher in the production of HT and HS chips than in the production of SH and MG, which was a consequence of a different level of fresh biomass yield for the species (Table 12). Depending on the form and level of fertilisation, diesel fuel consumption in the production of HT ranged from 79.8 to 186.4 kg ha^{-1} and for HS the range was from 107.0 to 173.7 kg ha^{-1}. Diesel fuel consumption in the production of SH and MG biomass production was much lower. Diesel fuel consumption per 1 Mg of fresh biomass was the lowest (5.3 kg Mg^{-1} FM) in the production of HS biomass on the MF 170 plot (Table 12). Diesel fuel consumption in the production of HT lay within a similar range as for HS. The index was higher for the production of SH and MG biomass. Diesel fuel consumption per 1 Mg of dry biomass was the lowest (11.2 kg Mg^{-1} DM) in the production of SH biomass on the MF 170 plot. This index for the species in the other fertilisation combinations was higher by 6%–85%. Diesel fuel consumption per 1 Mg DM as calculated for the production of HT and MG biomass was higher by 62%–113% and

Table 11
Energy gain for the production of PHC chips depending on the form and level of fertilisation; mean values for the first three years of cultivation.

Species of PHC	Form and level of fertilisation								
	WD 85	WD 170	DD 85	DD 170	TD 85	TD 170	MF 85	MF 170	C
Helianthus tuberosus									
GJ ha^{-1} $year^{-1}$	45.0	69.3	46.6	36.8	44.8	49.9	59.1	60.0	40.8
Changes %, C = 100%	110	170	114	90	110	122	145	147	100
Sida hermaphrodita									
GJ ha^{-1} $year^{-1}$	44.4	72.6	66.2	72.1	36.5	26.6	77.3	85.5	48.4
Changes %, C = 100%	92	150	137	149	76	55	160	177	100
Helianthus salicifolius									
GJ ha^{-1} $year^{-1}$	131.6	139.6	99.1	127.6	77.2	95.6	138.0	139.0	126.8
Changes %, C = 100%	104	110	78	101	61	75	109	110	100
Miscanthus × giganteus									
GJ ha^{-1} $year^{-1}$	28.0	26.6	27.9	27.6	21.9	13.1	49.3	54.4	54.9
Changes %, C = 100%	51	48	51	50	40	24	90	99	100

Table 12
Diesel fuel consumption for the production of PHC chips depending on the form and level of fertilisation; mean values for the initial three years of cultivation.

Species of PHC	Form and level of fertilisation								
	WD 85	WD 170	DD 85	DD 170	TD 85	TD 170	MF 85	MF 170	C
Helianthus tuberosus									
kg ha^{-1}	122.6	186.4	118.6	130.7	125.2	163.1	105.8	119.3	79.8
kg Mg^{-1} FM	6.5	6.4	5.7	6.0	5.6	5.5	5.7	5.5	5.9
kg Mg^{-1} DM	23.8	23.3	20.1	20.9	19.0	18.1	18.3	18.4	20.2
Sida hermaphrodita									
kg ha^{-1}	61.3	94.9	60.5	75.2	53.1	66.2	57.9	62.2	40.9
kg Mg^{-1} FM	13.2	12.1	8.2	8.2	9.3	9.4	7.6	7.2	9.1
kg Mg^{-1} DM	20.7	19.3	12.9	13.0	14.6	14.7	11.9	11.2	14.3
Helianthus salicifolius									
kg ha^{-1}	141.3	173.7	113.3	149.5	107.0	141.7	130.2	137.0	112.0
kg Mg^{-1} FM	6.1	6.7	5.8	5.7	5.9	5.8	5.4	5.3	5.4
kg Mg^{-1} DM	15.0	16.8	14.4	14.2	14.9	14.2	13.2	13.2	12.9
Miscanthus × giganteus									
kg ha^{-1}	63.3	85.1	55.4	70.5	59.4	77.2	64.1	69.8	58.4
kg Mg^{-1} FM	12.4	15.2	8.9	8.7	8.3	8.0	7.1	6.8	6.9
kg Mg^{-1} DM	28.5	35.4	20.4	20.0	19.0	18.6	17.4	16.3	15.9

42%–216%, respectively, compared to the lowest value for SH.

Lower diesel fuel consumption was observed in the production of short rotation woody crops in the four-year harvest rotation. Depending on the option of soil enrichment, the value of this index for willow ranged from 9.6 to 10.2 kg Mg^{-1} DM. It was 10.6–11.3 kg Mg^{-1} DM for poplar and 9.9–14.1 kg Mg^{-1} DM for black locust [14]. It was determined in another study that the consumption of diesel fuel in the production of 1 Mg DM of willow chips was 9.3 kg Mg^{-1} DM for the highest-yielding cultivar and 14.2 kg Mg^{-1} DM for the lowest-yielding cultivar [23].

3.3.3. Energy intensity

The energy intensity of the production of 1 Mg FM of chips was differentiated significantly by the species and form and level of N fertilisation (Table 13). The total amount of energy consumed for the production of 1 Mg of fresh chips was the lowest in the cultivation of *Helianthus salicifolius* on the control plot (0.34 GJ Mg^{-1} FM). Its value for the other species on the control plots was also the lowest, but it was higher by 9%, 24% and 85% for HT, MG and SH, respectively, than for HS. The form and level of fertilisation increased the energy intensity of the production of 1 Mg FM of chips of all species. The values were 1.6–5.4 times

Table 13
Energy intensity for PHC chips production depending on the form and level of fertilisation, mean values for the first three years of cultivation.

Species of PHC	Form and level of fertilisation								
	WD 85	WD 170	DD 85	DD 170	TD 85	TD 170	MF 85	MF 170	C
Helianthus tuberosus									
GJ Mg^{-1} FM	0.58	0.62	0.95	1.51	1.45	2.01	0.60	0.75	0.37
GJ Mg^{-1} DM	2.10	2.23	3.36	5.28	4.89	6.57	1.92	2.52	1.27
Sida hermaphrodita									
GJ Mg^{-1} FM	1.58	1.61	2.24	3.27	4.95	7.56	1.11	1.52	0.63
GJ Mg^{-1} DM	2.49	2.57	3.53	5.17	7.75	11.91	1.73	2.36	0.99
Helianthus salicifolius									
GJ Mg^{-1} FM	0.52	0.66	1.00	1.30	1.73	2.37	0.52	0.68	0.34
GJ Mg^{-1} DM	1.28	1.67	2.50	3.24	4.35	5.80	1.28	1.69	0.81
Miscanthus × giganteus									
GJ Mg^{-1} FM	1.41	2.11	2.57	3.64	3.96	5.61	0.94	1.28	0.42
GJ Mg^{-1} DM	3.25	4.92	5.88	8.33	9.03	13.01	2.31	3.11	0.98

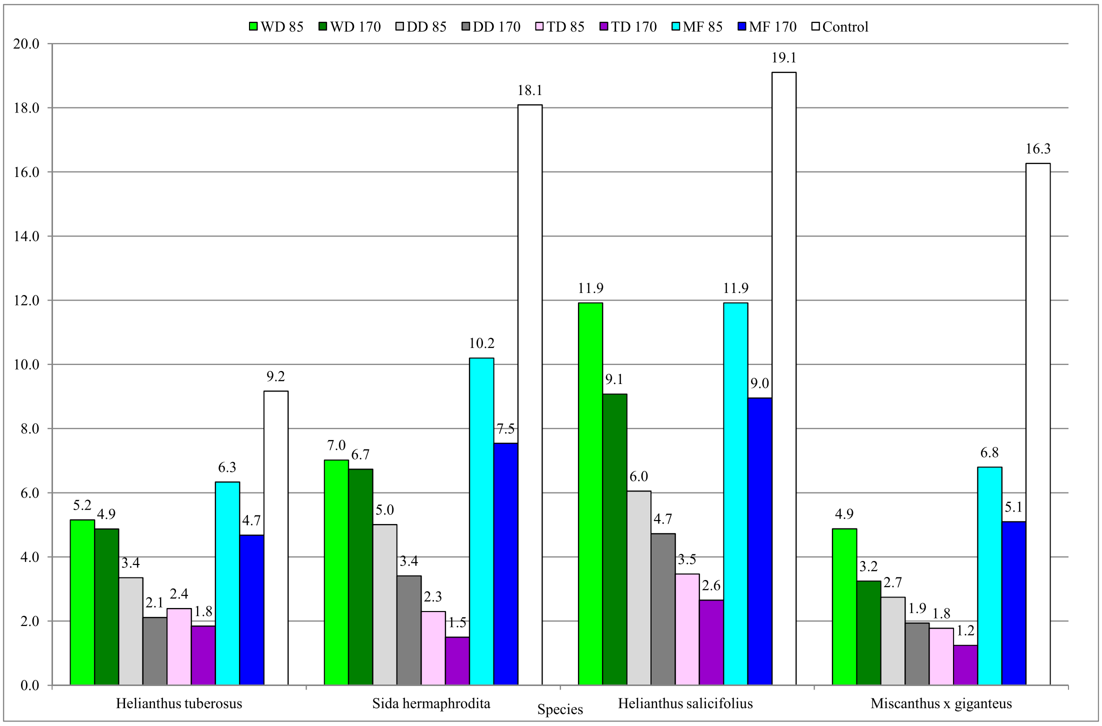

Fig. 2. Energy efficiency ratio for the production of HT, SH, HS and MG chips depending on the form and level of fertilisation; mean values for the first three years of cultivation.

higher for HT and 1.5–7.0 times higher for HS. An increase in the energy intensity of the production of 1 Mg FM of chips of lower-yielding species was even higher within the ranges of 1.8–12.0 and 2.2–13.4 than on control plots for SH and MG, respectively. Furthermore, the energy intensity of production of 1 Mg DM of the PHC species under study was also determined for control plots and was below 1 GJ Mg^{-1} DM for HS, MG and SH, and 1.27 GJ Mg^{-1} DM for HT (Table 13). Obviously, the form and level of fertilisation increased the energy intensity of the production of 1 Mg FM of chips of all the species to a similar extent as for the energy intensity of fresh biomass production. The production of PHC biomass was found to be the most energy-consuming on plots in which TD was applied as a fertiliser at an increased rate and the highest value of this index was determined for MG (13 GJ Mg^{-1} DM).

The energy intensity determined for the production of SH biomass in another study ranged between 0.9 and 2.1 GJ Mg^{-1} DM [33,34]. However, the value determined in a large-area experiment was higher (2.7 GJ Mg^{-1} DM) [13]. Therefore, it can be concluded that similar values of the index were obtained in this study on the control plot and when it was fertilised with MF and WD. The application of DD and TD increased the energy intensity significantly compared to other data. On the other hand, very low energy intensity was obtained in the production of MG biomass in Europe, ranging from 0.24 to 0.74 GJ Mg^{-1} DM [13,19,21]. For comparison, the energy intensity in the production of short rotation woody biomass crops in Poland was: 0.59–0.79 GJ Mg^{-1} DM for willow, 0.65–0.85 GJ Mg^{-1} DM for poplar and 0.80–1.55 GJ Mg^{-1} DM for black locust [14]. For black locust in Italy it was 0.93 GJ Mg^{-1} DM [35], and ca. 1.1 GJ Mg^{-1} DM for poplar [36]. On the other hand, the energy intensity of cultivation of oily plants of the *Brassicaceae* family, which are used in the production of first generation biofuels, expressed as the energy needed to produce 1 Mg of seeds, is much higher and ranges from 4.8 to 7.2 GJ (for winter oilseed rape and white mustard) [13,37–40] and 15.3–17.9 GJ (for spring oilseed rape and Indian mustard) [38]. Therefore, the energy intensity observed in this study in the production of lignocellulosic biomass of PHC in most fertilisation options was much lower and was beneficial from the point of view of the energy input for the production of 1 Mg DM compared to the production of seeds of *Brassicaceae* family plants. However, they were worse than the values obtained for short rotation woody crops.

3.3.4. *Energy efficiency ratio*

The energy efficiency ratio in the production of chips, like other indexes, varied depending on the PHC species and the form and level of N fertilisation (Fig. 2). An analysis of the cultivation options applied showed that the highest energy efficiency ratio for all species was achieved on the control plots (with no fertilisation). The highest energy efficiency ratio in the whole experiment (19.1) was obtained for HS in the no-fertilisation option. Its value for the other species in the control plots was lower by 5%, 15% and 52%, for SH, MG and HT, respectively. The energy efficiency ratios for HS depending on the form and level of N fertilisation, from the highest to the lowest were as follows: C–MF 85–WD 85–WD 170–MF 170–DD 85–DD 170–TD 85–TD 170. The form and level of N fertilisation had a similar effect on the sequence of energy efficiency ratios in the other species as in HS. However, their values for SH were lower by 5%–43% compared to HS obtained for the same fertilisation combinations applied in the experiment. Furthermore, the values in the production of HT were lower by 30%–57%, and lower by 15%–64% for MG. Very low levels of the index (below 4.0) were obtained for all the species at sites fertilised with TD and in the cultivation of HT and MG and fertilisation with DD.

The greatest drop in the energy efficiency ratio (by 92%) was found for MG and SH in plots fertilised with TD. In general, the greatest decrease in the energy efficiency ratios when fertilisation was applied, compared to the control plot, was observed in the cultivation of MG. Moreover, mineral fertilisation (MF) decreased the energy efficiency ratio by 31%–69% in all the PHC species under study. On the other hand, plant fertilisation with WD, DD and TD decreased the index by: 38%–80%, 63%–88% and 74%–92%, respectively.

A higher energy efficiency ratio, by 54% in the cultivation of MG, compared to its highest value in this study, was obtained in the production of the biomass of this species on a large-scale farm [13]. Furthermore, it can be estimated from data presented in other studies that the energy efficiency ratio in the cultivation of MG could be even higher than 40 [19,21,32,41]. This index for SH ranged from 8.7 to 20.2 depending on the type of planting material, planting/sowing density and cultivation technology [33,34]. Higher values of the index were obtained in a medium-input technology, which is in line with the trends presented in this study. On the other hand, the energy efficiency ratio obtained in the cultivation of SH on a large-scale farm was lower – 7.0 [13]. The energy efficiency ratio in the production of short rotation woody crops can also vary within a wide range from 10 to over 50 [14,23,35,36,42]. This depends on a number of biological, habitat-related, technological, agricultural and material-related factors. The energy efficiency ratio of annual crop production is also mainly influenced by the species and production technology which determines the demand for energy and the amount of energy accumulated in biomass [37,43]. Moreover, energy efficiency ratios in the production of annual plants intended for the production of first generation biofuels are much lower. For example, the energy efficiency ratio in the production of seeds of *Brassicaceae* plants ranged from 1.1 to 5.4 [38,39,44,45]; the ratio increased to 9–12 when the energy value of straw was included [38].

4. Conclusions

Our findings provide producers and end users of PHC biomass with valuable information and may be useful to decision makers in developing regulations governing the use of digestate for PHC crops and the use of this feedstock for energy generation or in industry. It has been shown that the growth of the yield (though sometimes small) of dry biomass justifies the use of biogas plant digestate in the cultivation of HT, SH and HS. However, no fertilisation should be used in the cultivation of MG. Energy efficiency analyses have shown that the use of biogas plant digestate or mineral fertilisers is not justified during the first years of cultivation of the PHC species under study; this applies especially to MG, HS and SH. This is a consequence of high energy intensity of fertiliser production and a small increase in biomass yield. As a result, better energy efficiency ratios were obtained in control plots than in options with fertilisation. Therefore, the efficiency and justifiability of the fertilisation options under study in PHC cultivation from the point of view of energy efficiency of biomass production cannot be demonstrated at this stage. However, the possibilities of reducing energy intensity in the fertiliser production process should be sought. Moreover, if the fertilisers are regarded as a by-product and are delivered to the field at no cost to a plantation owner, their use would be justified because it would be a method of their utilisation. Therefore, the production methods of PHC biomass should be verified in future research and analyses in terms of energy-related features involving comprehensive cost and benefit analyses (both economic and environmental).

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