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Biomass yield and energy balance of fodder galega in different production technologies: An 11-year field experiment in a large-area farm in Poland

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A B S T R A C T

This article presents the results of an 11-year field experiment (2008–2018) conducted in Poland to investigate the biomass yield and energy efficiency of fodder galega (*Galega orientalis* Lam.) in high-input and low-input production technologies. The demand for energy in the production of fodder galega biomass ranged from 13.0 to 14.2 (year of plantation establishment) to 6.4–8.2 GJ ha^{-1} (years 2–11). Agricultural intensification increased energy inputs by 11% on average. Dry matter yield (DMY) and energy output peaked in years 4 and 5 (14.7–15.3 Mg ha^{-1} and 122.4–131.1 GJ ha^{-1}, respectively). In the high-input production technology, DMY was 0.62 Mg ha^{-1} y^{-1} higher, energy output was 4.9 GJ ha^{-1} y^{-1} higher, the maximum DMY was achieved one year later, and the rate of decrease in biomass yield and energy output in the last years of the experiment (years 9–11) was 30% lower in comparison with the low-input system. The energy efficiency ratio of fodder galega ranged from 2.28 to 2.42 (year 1) to 8.04–16.53 (years 2–11). Productivity was 4% higher in the low-input than in the high-input technology. Fodder galega biomass was characterized by higher energy efficiency in the high-input technology (by approx. 2–12%) only in the last years of the experiment (years ≥10).

1. Introduction

Economic growth of any magnitude requires a steady supply of energy. Therefore, the energy sector is one of the main pillars of a modern economy that promotes the growth, development and competitiveness of businesses [1]. The growing demand for energy has prompted the search for alternative and environmentally-friendly sources of energy to reduce the share of fossil fuels in energy production [2,3]. In this context, the promotion of technologies that reduce carbon dioxide emissions poses a challenge to the global economy (decarbonized economy) [4]. A number of the EU countries generated 60–72% of electricity (Austria, Sweden, Denmark), 55–69% of cooling and heating energy (Sweden, Finland, Latvia) and 10–39% of transport energy (Sweden, Finland, Austria) from renewable sources already in 2017 [5]. In many European countries, solid biomass is a renewable resource with the highest energy potential due to local environmental and weather conditions [6]. Until recently, biomass for energy generation was harvested mainly in forests [7]. At present, agriculture is regarded as the key potential supplier of biomass for energy production [8,9]. Sustainable production of agricultural biomass poses one of the major challenges to the development of the European bioeconomy [5,10]. In Poland, agricultural land is not used intensively; therefore, yields can be substantially increased by increasing production inputs and modifying the production technology, and the vacated land can be dedicated to the production of energy crops [6]. The production of biomass for energy and food can only be reconciled by limiting the competition for agricultural land [10].

The major sources of biomass are lignocellulosic plants [11], including (i) woody plants such as willow (*Salix* spp.), poplar (*Populus* spp.) and black locust (*Robinia pseudoacacia* L.); (ii) herbaceous crops such as Virginia fanpetals (*Sida hermaphrodita* (L.) Rusby), Jerusalem artichoke (*Helianthus tuberosus* L.), cup plant (*Silphium perfoliatum* L.) and willowleaf sunflower (*Helianthus*

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salicifolius A. Dietr.); and (iii) grasses such as giant miscanthus (*Miscanthus* × *giganteus* Greef and Deuter), Amur silver grass (*Miscanthus sacchariflorus* (Maxim.) Hack), switchgrass (*Panicum virgatum* (L.) Poiret), prairie cordgrass (*Spartina pectinata* Link), giant reed (*Arundo donax* L.), and big bluestem (*Andropogon gerardii* Vitman) [12,13]. The popularity of lignocellulosic plants has increased in various sectors of the bioeconomy on account of its abundance and potentially sustainable supply [11]. Biomass has a variety of uses as (i) a direct source of energy, (ii) industrial material, and (iii) feedstock for integrated biorefineries. The integration of biorefinery technologies for converting waste-derived lignocellulosic biomass into biofuels and biopolymers is an important step towards a sustainable future [14]. Lignocellulosic biomass is used in the production of solid, liquid and gaseous fuels that are converted to heat, electricity and transport fuels. Biomass is also garnering increasing popularity in bioproduct and biochemical industries [13]. Efficient production and management of biomass energy sources on agricultural farms promote the sustainable development of agriculture and social structures that rely on agriculture [15]. Small-scale gasification systems and biogas plants, which are convenient and proven technologies for the generation of heat and/or electricity, provide a good example of biomass use for energy purposes on farms [16,17]. Biomass processing in the energy sector and industry delivers economic, environmental and social benefits [2]. In 2018, the renewable energy sector created around 11 million direct and indirect jobs, including around 3.2 million (29%) jobs associated with bioenergy generation (biomass, biofuels, biogas) [18]. Biomass production and bioenergy management generate high levels of employment because numerous businesses participate in the logistics chain, including the production, acquisition, storage, transport, preparation, conversion and utilization of biomass [2].

Energy generation during biomass fermentation/digestion is one of the most energy efficient processes [19]. Biogas can be produced from various types of biomass. Nearly all organic substrates of plant and animal origin can be fermented [7,20-27]. A substrate's suitability for conversion to biogas is determined by biomass yield per unit area, in particular dry matter yield and organic dry matter yield [28]. For this reason, plant species characterized by a high content of chemical energy in biomass and a positive energy balance (difference between the amount of energy accumulated in biomass and energy inputs in the production process) are particularly suited for energy generation [8]. Such crops guarantee stable substrate supplies to biogas plants and effective production of biomass with high methane content [29].

Agricultural biogas plants in Western Europe rely mainly on maize silage (*Zea mays* L.) [25,30-33]. Maize has a high share of arable land in Europe [34]; it is characterized by high dry matter yield (DMY) (15–25 Mg ha^{-1} y^{-1}) [8,20,35,36], its fermentation/digestion process is stable, and it is highly efficiently converted into biogas [26,28,37]. Despite the above, alternative substrates for biogas production are needed to guarantee sustainable crop rotation [22,38], minimize soil erosion [26], compensate for the limited geographic range of maize and its high thermal requirements [39], and guarantee food security in the light of growing maize prices on the global market [22,26,40,41]. Maize monocultures for energy generation should be avoided because they pose a direct threat to the biological diversity of agricultural ecosystems [22,42].

In northern countries where the cultivation of crops with a C_4 photosynthetic pathway is restricted or impossible, grasses with a C_3 photosynthetic pathway, including reed canary grass (*Phalaris arundinacea* L.), tall fescue (*Festuca arundinacea* Scherb.) and cocksfoot (*Dactylis glomerata* L.), can be grown as alternative sources of renewable energy [43-46]. The dry matter yield (DMY) of these grasses ranges from 6 to 18 Mg ha^{-1} y^{-1}, depending on species and agricultural intensity [6,47]. Perennial legumes such as alfalfa (*Medicago sativa* L), red clover (*Trifolium pratense* L.) and fodder galega (*Galega orientalis* Lam.) pose interesting alternatives [6,48]. In Europe, the yield potential of these crops grown in various production technologies ranges from 6 to 16 Mg ha^{-1} y^{-1} DM [6,8,48]. In comparison with other agricultural crops (cereals and Brassica crops), the production of perennial legumes is not highly energy intensive due to the low fertilizer requirements of these plants which remain in a symbiotic relationship with nitrogen-fixing bacteria [20,49,50]. The post-harvest biomass of perennial legumes (aerial plant parts and roots) is also characterized by a relatively low C/N ratio [51], which contributes to the rapid decomposition of organic matter by soil microorganisms [52]. Rapid decomposition limits periodic immobilization of nitrogen by microorganisms [53] and reduces the inhibitory effect of decomposition products on the emergence and early development of successive crops [54].

Fodder galega is characterized by the highest environmental adaptability in the group of perennial legume plants [6]. This crop is native to the Caucasus [55]. Similarly to other plants introduced from regions with a severe climate, fodder galega easily adapts to the environmental and climatic conditions in Europe, and its plantations are characterized by high field persistence and high productivity [56]. Biomass yields range from 5 Mg ha^{-1} y^{-1} DM in Finland [57] to 9.3–13.5 Mg ha^{-1} y^{-1} DM in Lithuania and Estonia [48,58], and even 11.0–16.3 Mg ha^{-1} y^{-1} DM in Poland [59–61]. Fodder galega is highly effective in fixing atmospheric nitrogen [62]. In a study by Symanowicz et al. [63], fodder galega fixed 312 kg N ha^{-1} y^{-1} on average. The crop's remarkable nitrogen-fixing ability can be attributed to its symbiotic relationship with *Rhizobium galegae* root nodule bacteria and an extensive root system composed of a well-developed tap root and numerous side roots [64]. The thickest part of the tap root penetrates soil to a depth of 30 cm. Stolons grow from the root crown and form adventitious roots. Stolons initially develop horizontally on soil surface, and they form vertical shoots in successive stages of growth. Stolons are the main nutrient reservoirs in fodder galega. They promote vegetative reproduction and enable plants to occupy free spaces between rows in the stand [65].

Fodder galega is grown for fodder in the severe climate of northern and eastern Europe (Estonia, Lithuania, Finland, Latvia, Russia) [55] as well as in France [66] Fodder galega is fed to livestock as green fodder, silage, dry feed, hay and protein concentrate. It is abundant in essential amino acids, in particular proline and arginine [55]. Fodder galega is also a source of nectar for pollinating insects [56]. This crop plant can be effectively cultivated in regions with a climate similar to northern Europe and Scandinavia [56]. According to Fairey et al. [67], fodder galega can also be grown in many regions of Canada. This cold-hardy plant is highly resistant to drought [68,69]. Fodder galega is more persistent in the field than red clover and alfalfa [70]. Its plantations have a life cycle of 10–13 [69] to 16–18 [71] or even 25 years [72] on account of the plant's considerable winter hardiness. This crop can survive temperatures as low as −25 °C without snow cover and −40 °C with snow cover [73]. Yields peak in the 2nd and 3rd year of cultivation [69] and remain high until the 7th and 8th year of growth [59,69]. Fodder galega is usually cut 2–3 times per year, and the first cut is characterized by an abundance of leaves that can be harvested already in May. In Poland, fodder galega can be cut 3 times in growing seasons with ample precipitation: I – in late May, II – in late July/early August, III – in September [60]. This persistent crop can also be used in prolonged land fallowing because it protects soil against erosion, increases soil fertility and limits weed succession [74].

Fodder galega is one of the most suitable plant species for energy generation [59]. Long and tough stems can be directly burned, and young plants can be converted to biogas [75]. The energy yield of fodder galega biomass per hectare ranges from 150 [36] to 270 GJ [76]. In a study by Budzyński et al. [6], the biogas yield of fodder galega silage was determined at 454 N dm^3 kg^{-1} organic DM, and it was equivalent to 131% of the biogas yield of alfalfa silage and 76% of the biogas yield of maize silage. In the work of Dubrovskis et al. [62], biogas yield increased by 6% when cow manure was supplemented with 25% fodder galega. The addition of 50% and 75% of fodder galega to cow manure increased biogas yield by 30% and 53%, respectively.

Agriculture is the most energy-intensive branch of the food industry, and it consumes nearly one-third of the total energy in the food production chain [15]. Technological process, modern crop management and renewable energy generation, including biomass production, will play an important role in maximizing the energy efficiency of agriculture and reducing its dependence on fossil fuels [77].

Previous research into fodder galega focused mainly on agronomic aspects (productivity under various agroecological conditions and responses to agronomic factors). The productivity and energy efficiency of fodder galega biomass in production technologies characterized by various intensity of agricultural inputs in long-term plantations remain insufficiently investigated. This article presents the results of an experiment conducted in a large-scale farm in north-eastern (NE) Poland. The biomass yield, energy inputs and energy efficiency of fodder galega grown in two production technologies were determined directly during the experiment. The compared production technologies differed in raw material and energy inputs. The aim of the study was to identify the most effective technology for the production of fodder galega biomass in terms of agricultural (fresh and dry biomass yield) and energy efficiency (energy inputs, energy output, energy efficiency ratio) parameters in large-area farms deploying heavy-during agricultural machines and equipment.

2. Materials and methods

2.1. Field experiment

A field experiment was carried out in 2008–2018 in the Agricultural Experiment Station in Bałcyny in NE Poland (53°35′46.4″ N, 19°51′19.5″ E, elevation 137 m). The station covers around 2000 ha of arable land, and it is owned by the University of Warmia and Mazury in Olsztyn. The experimental variables were two technologies for the production of fodder galega (*Galega orientalis* Lam.): (i) a high-input technology and (ii) a low-input technology (Table 1). The experimental field had an area of 2.5 ha (125 by 200 m), and the experiment had a randomized block design (RBD) with three replications. The experimental field was situated at a distance of approximately 1200–1500 m from the center of the station. Each year, the experiment was established on Haplic Luvisol originating from boulder clay [78].

2.2. Energy input analysis

The energy inputs in production of fodder galega biomass were determined based on direct measurements of diesel fuel consumption, labor and the field capacity of farming machines and equipment (Table 2). Energy inputs were divided into categories based on the respective energy fluxes (labor, energy carriers, farming machines and equipment, materials) (Equation (1)). The energy inputs associated with labor, operation of tractors and machines, consumption of diesel fuel and raw materials (seeds, pesticides and fertilizers) were determined based on literature data and summarized in Table 3. To estimate fuel consumption, each farming operation was started with a full fuel tank which was refilled at the end of the operation.

$$\text{Energy inputs} = E_{i\ \text{diesel}} + E_{i\ \text{fixed assets}} + E_{i\ \text{materials}} + E_{i\ \text{human labor}} \quad (1)$$

where:

Energy inputs - total energy inputs for fodder galega production (GJ ha^{-1}),
$E_{i\ \text{diesel}}$ - energy input for diesel fuel consumption (GJ ha^{-1}),
$E_{i\ \text{fixed}}$ - energy input for fixed assets (GJ ha^{-1}),
$E_{i\ \text{materials}}$ - energy input for materials (GJ ha^{-1}),
$E_{i\ \text{human labor}}$ - energy input for labor (GJ ha^{-1}).

2.3. Biomass processing experiment

Fodder galega was harvested in the budding phase when biomass is most suitable for conversion to biogas [61]. Fresh matter yield (FMY) was determined by weighing the harvested biomass immediately after harvest. Dry matter (DM) content was estimated by drying a subsample of 1 kg at 105 °C in a ventilated oven (FD 53 Binder GmbH, Germany) to constant weight (Equation (2)). Dry matter yield (DMY) was calculated with the use of equation (3):

$$\text{Dry matter } (\%) = 100 - \frac{(M_w - M_d)}{M_w} \times 100 \quad (2)$$

where:

M_w – wet sample weight, before drying (g),
M_d – dry sample weight, after drying (g).

Table 1
Production process of fodder galega.

Farming operation		Production technology: High-input	Production technology: Low-input
Tillage[a]		skimming (5–8 cm); fall ploughing (18–22 cm); cultivation unit (5–8 cm)	
Sowing[a]		15 kg seeds ha^{-1}, 75 cm inter-row spacing, cv. Risa	
Mineral fertilization	before sowing[a]	30 kg N ha^{-1}; 60 kg P_2O_5 ha^{-1}; 90 kg K_2O ha^{-1}	30 kg N ha^{-1}; 40 kg P_2O_5 ha^{-1}; 60 kg K_2O ha^{-1}
	during growing season[b]	90 kg P_2O_5 ha^{-1}; 120 kg K_2O ha^{-1}	60 kg P_2O_5 ha^{-1}; 90 kg K_2O ha^{-1}
Weed control	before sowing[a]	chemical 960 g ha^{-1} bentazon in 3-leaf stage	mechanical 1 cut
Harvest[b]		three cuts at the beginning of flowering (May/July/September)	

[a] Agricultural operation performed only in the year of plantation establishment.
[b] agricultural operation performed each year of the study.

Table 2
Technical parameters, performance and fuel consumption of agricultural machines in the production of fodder galega biomass.

Farming operations	Parameters of self-propelled machine	Parameters of accompanying machine	Service life (h)		Weight (kg)		Performance of self-propelled machine and accompanying machine (ha h^{-1})[a]	Fuel consumption (l h^{-1})[a]
			self-propelled machine	accompanying machine	self-propelled machine	accompanying machine		
Skimming (5–8 cm)	136 kW	7 (number of furrows)	12000	2000	9285	2600	4.0	32.5
Fall ploughing (18–22 cm)	136 kW	7 (number of furrows)	12000	2000	9285	3360	2.4	60.0
Tillage-cultivation unit (5–8 cm)	246 kW	4 m (working width)	12000	2000	13003	2150	4.4	32.9
Disking	114 kW	6 m (working width)	9000	1600	5635	3100	3.1	23.6
Row seeding	246 kW	6.0 m (working width)	12000	1440	13003	8900	4.4	34.8
Mineral fertilization	114 kW	30 m (working width)	9000	1200	5635	300	15.8	16.8
Chemical weed protection	53 kW	20 m (working width)	9000	1050	3550	1350	7.0	5.7
Harvest	44 kW/5.5 m (working width)	–	3000	–	3500	–	1.8	13.5
Tedding[a]	53 kW	5.2 m (working width)	9000	2500	3550	530	2.5	6.4
Raking[a]	53 kW	4.6 (working width)	9000	2000	3550	695	3.0	6.4
Harvest	232 kW/3.0 m (working width)	–	3000	–	3500	–	1.0–2.0[b]	22.5–37.5[b]
Biomass transport	97 kW	12 Mg (carrying capacity)	9000	1600	5200	3900	–	7.7
Loading	55 kW/2500 kg (load capacity)	–	4800	–	4922	–	–	8.0

[a] Average for the 11-year experiment.
[b] Differences resulting from variations in biomass yield.

Table 3
Energy equivalence of inputs associated with the production of fodder galega biomass.

Source	Unit	Input	References
Labor	MJ $hour^{-1}$	80	Wójcicki [80]
Tractors	MJ kg^{-1}	125	Wójcicki [80]
Machines	MJ kg^{-1}	110	Wójcicki [80]
Diesel oil	MJ kg^{-1}	48	Wójcicki [80]
Seeds	MJ $seeds^{-1}$	20.5	Povilaitis et al. [48]
N	MJ kg^{-1}	77	Wójcicki [80]
P_2O_5	MJ kg^{-1}	15	Wójcicki [80]
K_2O	MJ kg^{-1}	10	Wójcicki [80]
Herbicides	MJ kg^{-1} active ingredient	300	Wójcicki [80]

$$\text{Dry matter yield}\left(\text{Mg ha}^{-1}\right) = \frac{\text{Fresh matter yield}\left(\text{Mg ha}^{-1}\right)\times\text{Dry matter}\ (\%)}{100} \quad (3)$$

2.4. Energy output analysis

The unit energy value (higher heating value, HHV) of biomass was determined by adiabatic combustion in a calorimeter (IKA C 2000, USA) with the use of a dynamic method. The lower heating value (LHV) of biomass was expressed in terms of moisture content determined at harvest [79] (Equation (4)). The energy value of biomass (energy output) was determined as the product of LHV and FMY (Equation (5)).

$$LHV = \frac{HHV\times(100-W)}{100} - W\times 0.0244 \quad (4)$$

where:

LHV - lower heating value of fresh biomass (MJ kg^{-1})
HHV - higher heating value of dry biomass (MJ kg^{-1})
W - biomass moisture content (%)
0.0244 – correction coefficient for water vaporization enthalpy (MJ kg^{-1} per 1% moisture content)

$$\text{Energy output (GJ ha}^{-1}) = \text{LHV (GJ Mg}^{-1}) \times \text{FMY (Mg ha}^{-1}) \quad (5)$$

2.5. Energy efficiency analysis

The energy efficiency of fodder galega biomass was determined based on energy gain (Equation (6)) and the energy efficiency ratio (Equation (7)).

$$\text{Energy gain (GJ ha}^{-1}) = \text{Energy output (GJ ha}^{-1}) - \text{Energy inputs (GJ ha}^{-1}) \quad (6)$$

$$\text{Energy efficiency ratio} = \frac{\text{Energy output}\left(\text{GJ ha}^{-1}\right)}{\text{Energy inputs}\left(\text{GJ ha}^{-1}\right)} \quad (7)$$

2.6. Statistical analysis

Biomass yield (FMY, DMY), DM, HHV, LHV and the energy value

Table 4
ANOVA *F*-test statistics.

Parameter	Years	Production technology	Years × production technology
Fresh matter yield (Mg ha^{-1})	1917.813**	118.701**	3.532**
Dry matter content (g kg^{-1})	10.981**	0.931ns	0.284ns
Dry matter yield (Mg ha^{-1} DM)	630.228**	155.740**	2.097*
Higher heating value (MJ kg^{-1})	2.646**	3.339ns	0.213ns
Lower heating value (MJ kg^{-1})	10.894*	0.003ns	0.245ns
Energy output (GJ ha^{-1})	118.175**	20.414*	0.758ns

*significant $P < 0.05$; **significant $P < 0.01$; *ns* – not significant.

of biomass (energy output) were processed by repeated measures analysis of variance (ANOVA), where the production technology was the fixed grouping factor, and 11 harvest years were the repeated measurement factor. Treatment means were compared by Tukey's honestly significant difference (HSD) test at P < 0.05. All analyses were performed in the Statistica 13.3 program [81]. The *F* values of ANOVA are presented in Table 4.

3. Results

3.1. Weather conditions

The weather conditions during the experiment (2008–2018) are presented in Fig. 1. The long-term (1981–2015) average for total annual precipitation in NE Poland was 588 mm. Very high precipitation levels were noted in 2016 (750 mm) and 2017 (940 mm), whereas 2013, 2014 and 2015 were the driest years (454–515 mm). In the remaining years of the experiment, precipitation levels were similar (2008, 2009, 2011, 2018) or somewhat higher (2010, 2012) than the long-term average (1981–2015).

The long-term (1981–2015) mean annual temperature in the studied region was 7.9 °C. During the experiment, annual temperature was below the long-term average only in 2010, 2012 and 2013, mainly due to low temperatures during winter dormancy (−8.8 °C in 2010, -7.2 °C in 2012, and -4.4 °C in 2013). In the remaining years of the study, annual temperatures exceeded the long-term average by 0.4–1.5 °C (Fig. 1).

3.2. Energy inputs

The energy inputs associated with the establishment of the fodder galega plantation ranged from 13.0 in the low-input production technology to 14.2 GJ ha^{-1} in the high-input technology. In both technologies, fertilizers (41–47%) and fuel (39–46%) were the prevalent energy inputs in the first year of the study. In the remaining years of the experiment (years 2–11), the demand for energy was 42–49% (high-input technology) to 43–51% (low-input technology) lower. Beginning from the second year of the experiment, the key energy inputs in the production of fodder galega biomass were fuel (50–57%) and fertilizers (26–36%) (Table 5). An analysis of the energy inputs associated with agricultural operations revealed that mineral fertilizers (42–48%), followed by harvest and transport (28–30%) and tillage (16–17%) were the most energy-intensive processes. In years 2–11, the predominant energy inputs were harvest and transport operations (66–73%) and mineral fertilization (27–34%) (Fig. 2).

3.3. Biomass yield

In NE Poland, the FMY of fodder galega peaked in the 4th year of production (69.1–71.0 Mg ha^{-1}) in both technologies (Fig. 3). The FMY of fodder galega decreased rapidly between the 4th and the 7th year of cultivation (by 47–49%) regardless of the applied production technology. The above parameter was stabilized in years 7–8 at 35.2–37.3 (low-input technology) and 37.8–38.0 Mg ha^{-1} y^{-1} (high-input technology). Between years 9 and 11, FMY decreased again by 31% (high-input technology) to 37% (low-input technology). The FMY of fodder galega was 6–7% higher (by 2.65 Mg ha^{-1} y^{-1}) on average, and the rate of decrease in biomass yield in the last years of the experiment (years 9–11) was slower in the high-input than in the low-input system. The FMY of fodder galega was not significantly affected by agricultural intensity only in the 1st and 2nd year of the experiment (Fig. 3).

The DM of fodder galega biomass was determined mainly by the age of the plantation (Fig. 4). In years 1–8, the DM content of the harvested biomass ranged from 210 to 221 g kg^{-1}, and a

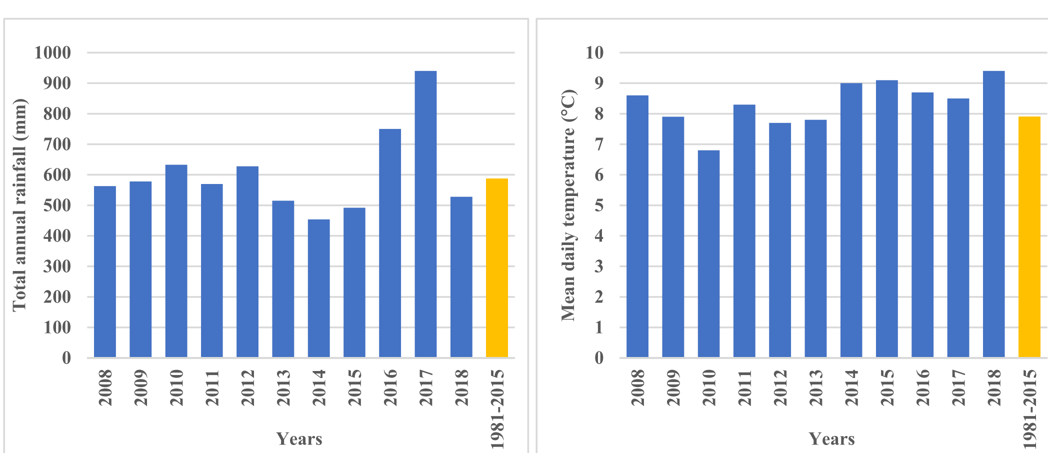

Fig. 1. Weather conditions in the experimental years (2008–2018) relative to the long-term average (1981–2015).

Table 5
Energy inputs associated with the production of fodder galega biomass by energy fluxes (2008–2018).

Specification		High-input technology					Low-input technology				
		Year 1[a]		Years 2–11[b]			Year 1[a]		Years 2–11[b]		
		MJ ha^{-1} y^{-1}	%	MJ ha^{-1} y^{-1}		%	MJ ha^{-1} y^{-1}	%	MJ ha^{-1} y^{-1}		%
				min[c]	max[c]				min[c]	max[c]	
Labor		207	1.5	174	211	2.4–2.6	223	1.7	174	188	2.7–2.8
Tractors and machines		1197	8.4	858	1043	12.0–12.8	1243	9.6	858	932	13.4–13.7
Fuel		5589	39.2	3583	4350	50.0–53.4	5910	45.5	3583	3890	55.9–57.1
Materials	total, including:	7256	–	2550	2550	–	5618	–	1800	1800	–
	seeds	308	2.2	0	0	0.0–0.0	308	2.4	0	0	0.0–0.0
	fertilizers	6660	46.7	2550	2550	35.6–31.3	5310	40.9	1800	1800	28.1–26.4
	herbicides	288	2.0	0	0	0.0–0.0	0	0.0	0	0	0.0–0.0
Total		14248	100.0	7164	8154	100.0	12993	100.0	6414	6810	100.0

[a] 2008.
[b] 2009–2018.
[c] Differences resulting from variations in biomass yield and the energy inputs associated with harvest and transport across experimental years.

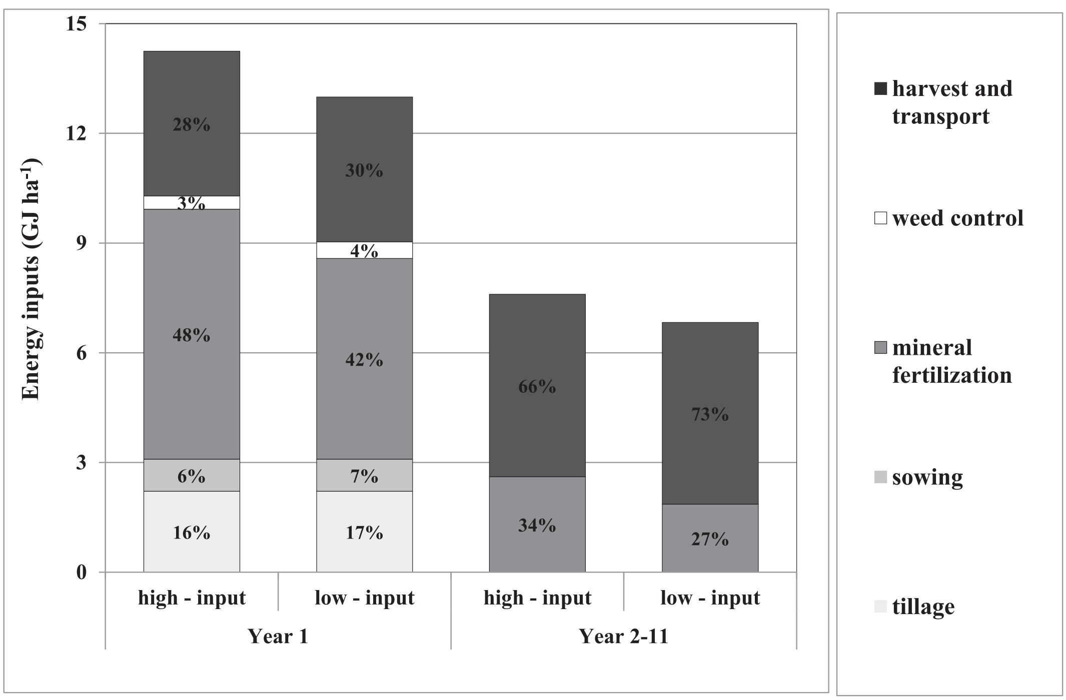

Fig. 2. Estimated energy inputs associated with the production of fodder galega biomass in high-input and low-input technologies by operations (average for 1 and 2–11 years of growth).

considerable increase (9–13%) in this parameter was observed beginning from the 9th year of the experiment (Fig. 4).

The DMY of fodder galega peaked in year 4 in the low-input technology (14.7 Mg ha^{-1} DM) and in year 5 in the high-input technology (15.3 Mg ha^{-1} DM) (Fig. 5). This parameter decreased rapidly at 2.3–3.5 Mg ha^{-1} y^{-1} between the 4th (5th) and 7th year of the experiment in both production technologies. In years 7–8, DMY was stabilized at 7.79–8.16 in the low-input technology and at 8.21–8.29 Mg ha^{-1} y^{-1} in the high-input technology. Beginning from the 9th year of the study, the DMY of fodder galega decreased by 0.6 Mg ha^{-1} y^{-1} in the high-input technology and by 0.9 Mg ha^{-1} y^{-1} in the low-input technology. In the high-input production technology, DMY was 0.62 Mg ha^{-1} y^{-1} higher, the maximum DMY was achieved one year later, and the rate of decrease in biomass yield in the last years of the experiment (years 9–11) was 30% lower in comparison with the low-input system (Fig. 5).

3.4. *Energy output*

The HHV and LHV of fodder galega biomass were determined at 17.1 and 1.94 MJ kg^{-1}, respectively. Different levels of agricultural intensity did not differentiate the HHV and LHV of fodder galega biomass (Fig. 6, Fig. 7). It should also be noted that the LHV of fodder galega biomass continued to increase with the plantation's age, and the greatest increase was observed in years 9–11 (Fig. 7).

The energy output of fodder galega biomass was determined by agricultural intensity (production technology) and the plantation's age (Table 6, Fig. 8). The average energy output of fodder galega biomass during the 11-year experiment ranged from 76.3 in the low-input technology to 81.2 GJ ha^{-1} y^{-1} in the high-input technology (Table 6). Energy output was lowest in the first year of the study (31.5–32.5 GJ ha^{-1}) (Fig. 8). The energy output of fodder galega biomass peaked in year 4 in the low-input

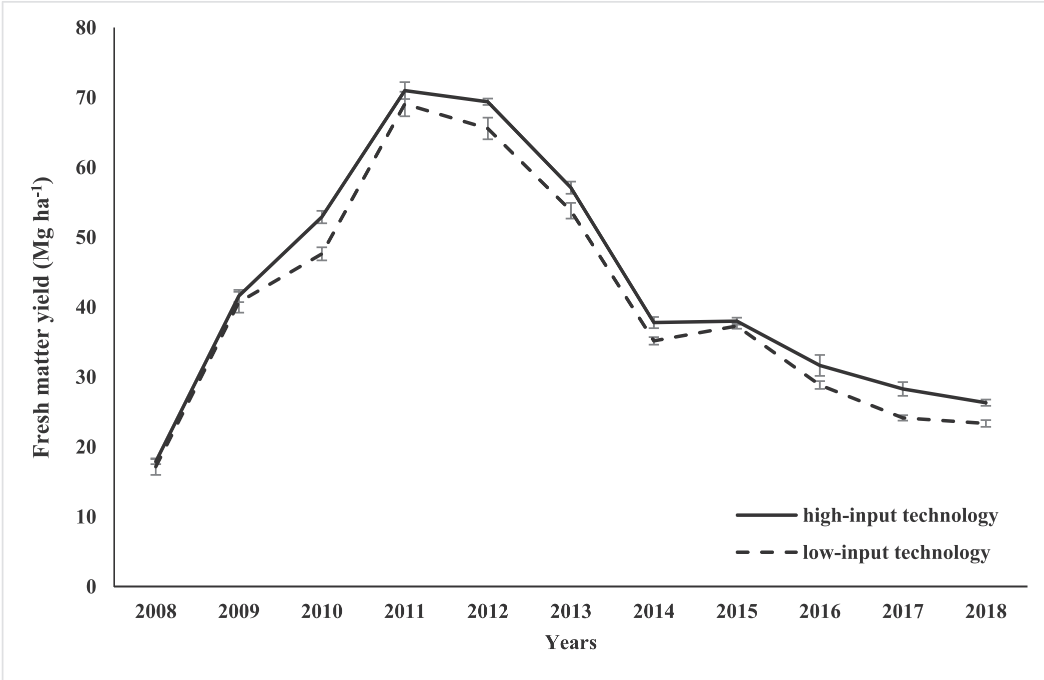

Fig. 3. Fresh matter yield of fodder galega in high-input and low-input technologies (growing seasons of 2008–2018).

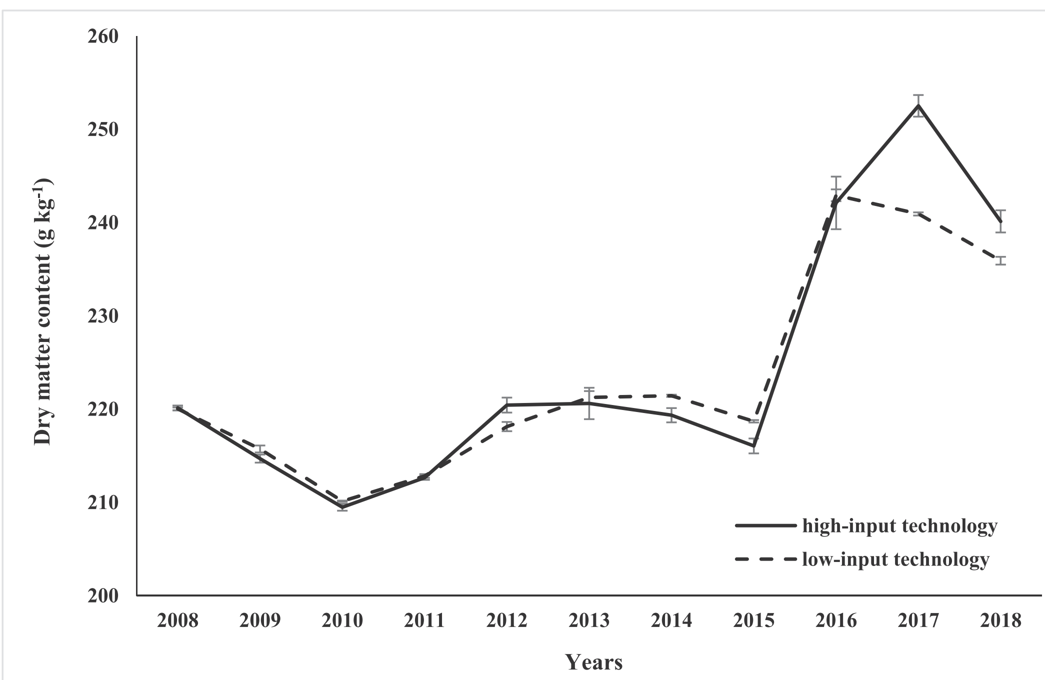

Fig. 4. Dry matter content of fodder galega in high-input and low-input technologies (growing seasons of 2008–2018).

technology (122.4 GJ ha^{-1}) and in year 5 in the high-input technology (131.1 GJ ha^{-1}). The analyzed parameter decreased at a rate of 18.9–20.9 GJ ha^{-1} y^{-1} between the 4th (5th) and 7th year of the experiment in both production technologies. In years 7–9, the energy output of fodder galega biomass was stabilized at 65.7–67.8 Mg ha^{-1} y^{-1} in the low-input technology and 67.6–72.7 Mg ha^{-1} y^{-1} in the high-input technology. In years 9–11, energy output decreased by 19% in the high-input technology and by 24% in the low-input technology. In general, agricultural intensification increased the energy output of fodder galega biomass by 6% on average (by 4.91 GJ ha^{-1} y^{-1}), prolonged the achievement of maximum values by 1 year, and slowed down the decrease in energy output (from 8.1 to 6.9 GJ ha^{-1} y^{-1}) in the last years of the experiment (years 9–11) (Fig. 8).

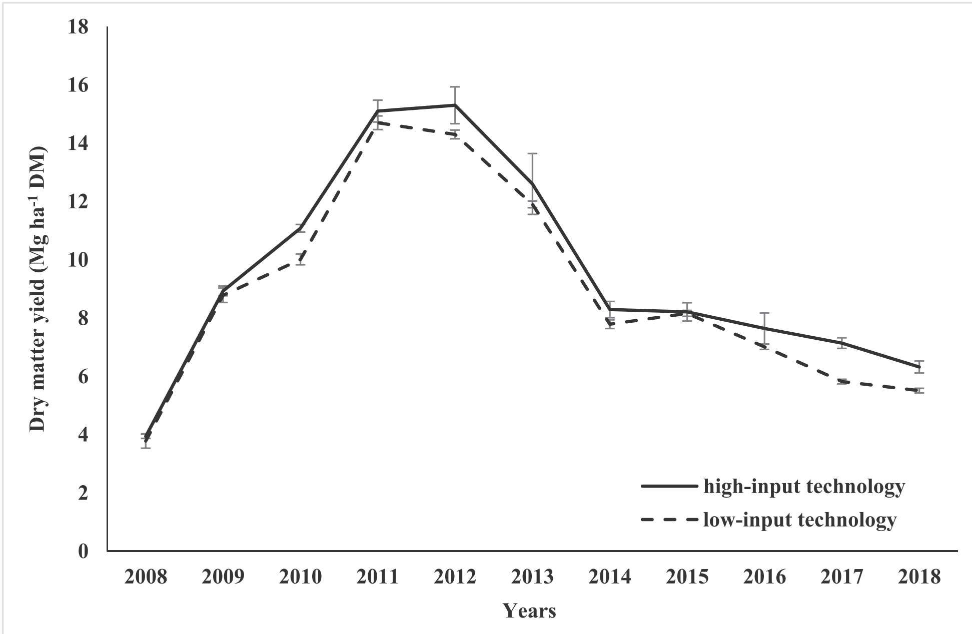

Fig. 5. Dry matter yield of fodder galega in high-input and low-input technologies (growing seasons of 2008–2018).

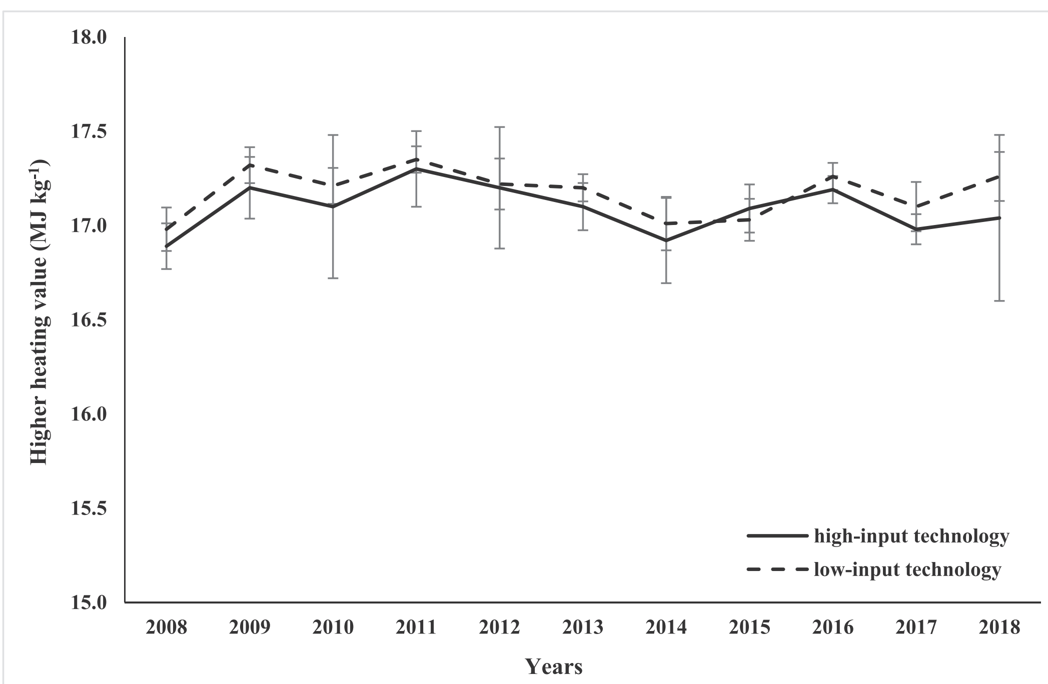

Fig. 6. Higher heating value of fodder galega in high-input and low-input technologies (growing seasons of 2013–2018).

3.5. *Energy efficiency ratio*

The energy gain/net energy yield ratio (calculated as the difference between energy output and energy input per hectare) and the energy efficiency ratio (calculated as the ratio of energy output to energy input per hectare) were calculated to evaluate the performance of fodder galega (Table 6). The values of both energy efficiency indicators (energy gain and energy efficiency ratio) were lowest in the first year of the experiment at 18.2–18.5 and 2.28–2.42 GJ ha^{-1}, respectively. Energy gain was highest in year 4 in the low-input technology (115.0 GJ ha^{-1}) and in year 5 in the high-input technology (122.9 GJ ha^{-1}). In successive years, energy gain decreased at a rate of 10.0–11.9 GJ ha^{-1} y^{-1}. The high-input technology was characterized by the highest average energy gain (73.0 GJ ha^{-1} y^{-1}) during the 11-year experiment. This parameter was approximately 6% lower (by 4.1 GJ ha^{-1} y^{-1}) in the low-input technology (Table 6).

The energy efficiency of fodder galega biomass was considerably

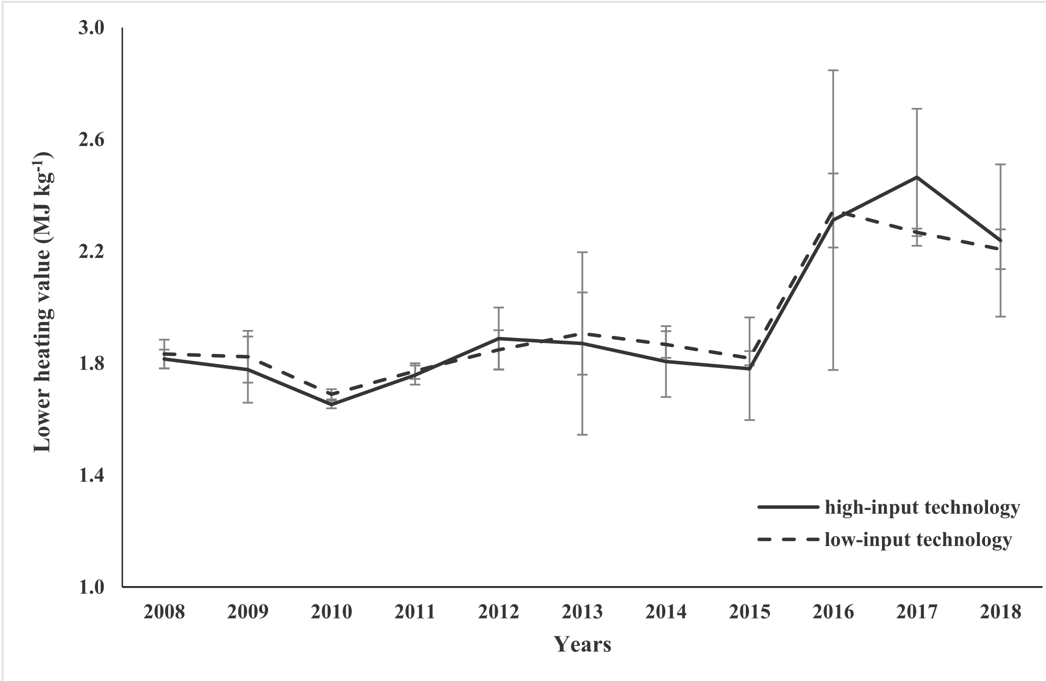

Fig. 7. Lower heating value of fodder galega in high-input and low-input technologies (growing seasons of 2008–2018).

Table 6
Energy analysis of the production process of fodder galega biomass (2013–2018).

Years	High-input technology				Low-input technology			
	Energy inputs (GJ ha^{-1} y^{-1})	Energy output (GJ ha^{-1} y^{-1})	Energy gain (GJ ha^{-1} y^{-1})	Energy efficiency ratio	Energy inputs (GJ ha^{-1} y^{-1})	Energy output (GJ ha^{-1} y^{-1})	Energy gain (GJ ha^{-1} y^{-1})	Energy efficiency ratio
2008	14.2	32.5	18.2	2.28	13.0	31.5	18.5	2.42
2009	7.6	73.9	66.3	9.77	6.8	74.1	67.3	10.89
2010	7.8	87.4	79.7	11.27	6.8	80.5	73.7	11.82
2011	8.2	124.8	116.7	15.31	7.4	122.4	115.0	16.53
2012	8.2	131.1	122.9	16.07	7.4	121.1	113.7	16.36
2013	7.8	106.9	99.1	13.78	7.0	102.4	95.4	14.62
2014	7.6	68.3	60.7	9.03	6.8	65.7	58.9	9.65
2015	7.6	67.6	60.1	8.95	6.8	67.8	61.0	9.96
2016	7.2	72.7	65.5	10.15	6.4	67.7	61.3	10.55
2017	7.2	69.6	62.5	9.72	6.4	54.8	48.4	8.54
2018	7.2	58.9	51.7	8.22	6.4	51.6	45.1	8.04
∑	90.2	893.6	803.4	9.90	81.3	839.6	758.3	10.30
Per year of cultivation	8.2	81.2	73.0		7.4	76.3	68.9	

higher in the low-input technology (10.30). Agricultural intensification decreased this parameter by around 4%. The energy efficiency of fodder galega biomass was higher (by approx. 2–12%) in the high-input than in the low-input technology only in the last years of the experiment (years ≥10) (Table 6). The above can be attributed to the slower rate of decrease in FMY, DMY and energy output in the high-input technology in years 9–11 (Figs. 3, 5 and 8).

4. Discussion

4.1. Energy inputs

Energy consumption in agriculture increased considerably after the Green Revolution had improved crop performance by introducing high-yielding plant varieties and farming operations characterized by a high demand for agricultural inputs (fertilizers, chemicals, diesel fuel and electricity). Energy inputs differ depending on farming systems, environmental and agronomic conditions during the growth and development of plants [82]. The energy efficiency of agricultural production is evaluated by analyzing the structure of energy inputs, where the proportions of energy-intensive materials and processes should be minimized. Analyses of the structure of energy inputs support the selection of the optimal production technology [6].

In Lithuania (NE Europe), the energy inputs associated with the production of fodder galega biomass were determined at 3.8 GJ ha^{-1} y^{-1} and were 8–9% higher than in alfalfa [48]. Agricultural machinery and diesel fuel were the predominant energy inputs (83–90%) in the production of both perennial legume crops. The demand for energy was 3.7-fold lower in the production of fodder galega than maize (reference biogas crop) biomass [48]. Energy inputs were lower in the production of alfalfa and fodder galega biomass than maize biomass mainly due to lower requirements for mineral fertilizers and chemical weed control [8]. In

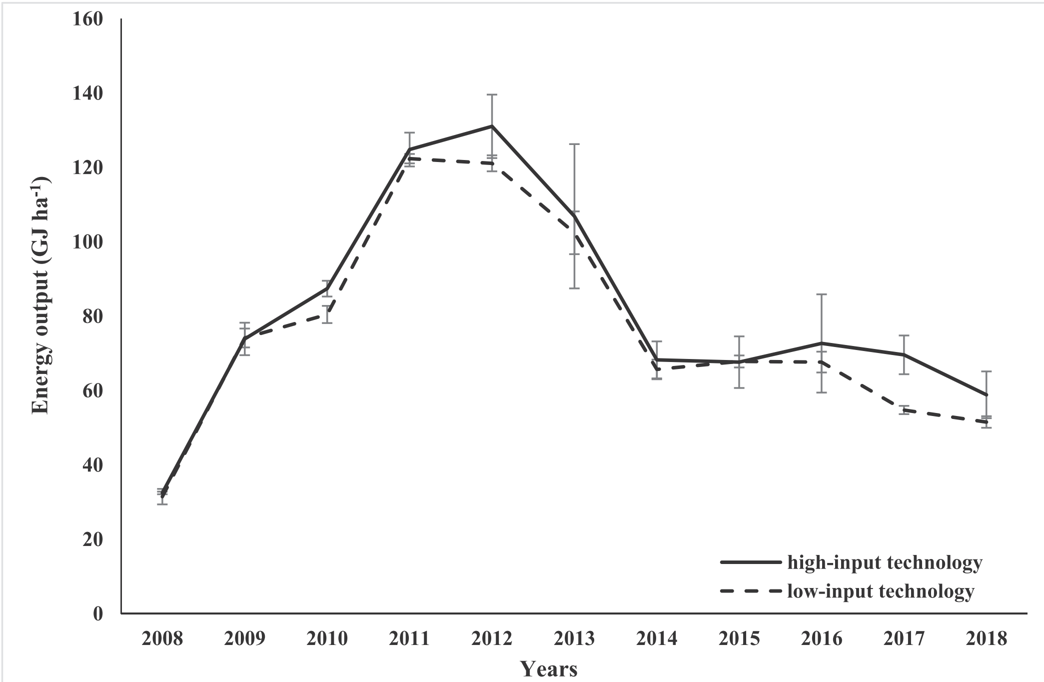

Fig. 8. Energy output of fodder galega in high-input and low-input technologies (growing seasons of 2008–2018).

the present study (NE Poland), the energy inputs associated with the production of fodder galega biomass reached 13.0–14.2 GJ ha^{-1} in the year of plantation establishment. In successive years, energy inputs were determined in the range of 6.4–8.2 GJ ha^{-1}. In a large-area farm, energy inputs were higher by 9% (year 1) to 11–15% (years 2–11) in the high-input technology. In the first year of the study, fertilizers (41–47%) and fuel (39–46%) were the predominant energy inputs in both production technologies. In years 2–11, the most energy-intensive agricultural inputs were fuel (50–57%) and fertilizers (26–36%).

4.2. *Biomass yield*

In studies evaluating the performance of perennial legume crops in NE Europe (Lithuania, Estonia), the biomass yields of fodder galega ranged from 7.6 to 8.0 in the year of plantation establishment to 9.3–13.5 Mg DM ha^{-1} y^{-1} in successive years of production [48,58]. In the cold climate of Lithuania, the DMY of fodder galega was similar to alfalfa and higher than in other herbaceous plants such as common sainfoin (*Onobrychis viciifolia* Scop.), mugwort (*Artemisia vulgaris* L.), Sakhalin knotweed (*Polygonum sachalinensis* F.W.Schmidt ex Maxim.), switchgrass (*Panicum virgatum* L.) (3.4–5.2 Mg ha^{-1} y^{-1}), cat grass (*Dactylis glomerata* L.), alfalfa (*Medicago sativa* L.), giant miscanthus (*Miscanthus* × *giganteus* Greef and Deuter), cup plant (*Silphium perfoliatum* L.) (6.1–7.3 Mg ha^{-1} y^{-1}), Jerusalem artichoke (*Helianthus tuberosus* L.), Virginia fanpetals (*Sida hermaphrodita* L. Rusby) and reed canary grass (*Phalaris arundinacea* L.) (8.6–9.9 Mg ha^{-1} y^{-1}). In Central-Eastern Europe (Poland), the biomass yield of fodder galega ranged from 11.0 to 16.3 Mg DM ha^{-1} y^{-1} [6,59-61]. In the current study (NE Poland), biomass yields were determined in the range of 3.8–3.9 Mg ha^{-1} y^{-1} DM in the year of plantation establishment to 9.4–10.1 Mg ha^{-1} y^{-1} DM in years 2–11. In the milder climate of Western Europe, the maximum biomass yield of fodder galega was 13 Mg ha^{-1} DM in the first year and 10 Mg ha^{-1} DM in the second year of production, and the crop was harvested five times per year before flowering [83].

Fodder galega plantations have a long life cycle on account of the plant's considerable winter hardiness and the absence of pests and pathogens targeting the species [70,84]. In a study by Symanowicz et al. [61], the biomass yield of fodder galega peaked in the 4th and 5th year of cultivation (16.8–16.9 Mg DM ha^{-1} y^{-1}). Meripőld et al. [58] reported maximum biomass yield (13.5 Mg ha^{-1} y^{-1}) in the 2nd year of fodder galega production. In an experiment conducted by Slepetys [74], the biomass yields of fodder galega were highest (11.9 Mg DM ha^{-1} y^{-1}) in years 10 and 11. In the present study, fodder galega produced the highest biomass yields (14.7–15.3 Mg ha^{-1} y^{-1} DM) in years 4 and 5. Biomass yields decreased rapidly at a rate of 2.3–3.5 Mg ha^{-1} y^{-1} DM between the 4th (5th) and 7th year of cultivation. Yields were stabilized at 7.79–8.29 Mg ha^{-1} y^{-1} DM in years 7 and 8, and a further decrease in DMY was noted in the remaining years of the experiment at a rate of 0.6–0.9 Mg ha^{-1} y^{-1}.

The demand for energy in the production process (energy inputs) and the energy accumulated in biomass (energy output) are determined mainly by agricultural intensity [6,12,85]. In a study by Symanowicz et al. [61], the DMY of fodder galega increased in response to NP, NK, PK and NPKCa fertilization, from 7.81 Mg DM ha^{-1} y^{-1} (non-fertilized treatment) to 12.8–14.1 Mg DM ha^{-1} y^{-1} (NP, NK or PK fertilizers), and 16.3 Mg DM ha^{-1} y^{-1} (NPKCa fertilizer). According to Meripőld et al. [58], the DMY of fodder galega increased by 11% (1.0 Mg ha^{-1} y^{-1}) when the rate of nitrogen fertilization was increased by 50 kg ha^{-1}. In the current study, agricultural intensification increased the DMY of fodder galega biomass by 0.62 Mg ha^{-1} y^{-1} (7%), prolonged the achievement of maximum yields by 1 year, and slowed down the annual rate of decrease in biomass yield by 30% in the last years of the experiment (years 9–11).

4.3. *Energy output*

High DMY and high energy output are the key determinants of crops' suitability for energy production [8]. The energy output of fodder galega biomass reached 162 GJ ha^{-1} y^{-1} in the colder climate of NE Europe (Lithuania) [48]. In Central-Eastern Europe (Poland), this parameter ranged from 178 to 241 GJ ha^{-1} y^{-1} [6,59]. It should also be noted that fodder galega and alfalfa are characterized by similar energy output in Europe [6,48]. On average, this parameter is 38–43% lower in perennial legumes (fodder galega, alfalfa) than in maize [6,8,48]. In this study, conducted in NE Poland, the energy output of fodder galega biomass was lowest (31.5–32.5 GJ ha^{-1}) in the year of plantation establishment, and it peaked (122.4–131.1 GJ ha^{-1}) in the 4th and 5th year of cultivation. Energy output decreased at an annual rate of 10–12 GJ ha^{-1} y^{-1} between the 4th (5th) and 11th year of production. In the work of Symanowicz et al. [61], the energy output of fodder galega biomass was also lowest (129.28 GJ ha^{-1}) in the year of plantation establishment and highest (312–315 GJ ha^{-1}) in years 4–5.

The energy output of biomass is largely dependent on agricultural intensity [6,12,85]. In a study by Symanowicz et al. [61], the application of mineral fertilizers increased the energy output of fodder galega biomass by 65–90% (NP, NK or PK) to 117% (NPKCa) relative to the non-fertilized treatment. Budzyński et al. [6] reported an increase in the energy output of fodder galega (5%) and alfalfa (8%) biomass in response to agricultural intensification. The energy output of perennial legumes grown in combination with C_3 grasses was higher in the high-input production technology than in pure-sown stands. In perennial legumes cultivated with C_3 grasses, agricultural intensification increased energy output by 19% (red clover with timothy-grass *Phleum pratense* L.) to 55% (alfalfa with timothy-grass) [6]. In the present study, agricultural intensification increased the energy output of fodder galega biomass by 6% (4.91 GJ ha^{-1} y^{-1}) on average, prolonged the achievement of maximum energy output by 1 year, and slowed down the annual rate of decrease (from 8.1 to 6.9 GJ ha^{-1}) in energy output in the last years of the experiment (years 9–11).

4.4. Energy efficiency ratio

Plant species characterized by high biomass yield per unit area and a positive energy balance are particularly suited for energy generation. The process of converting biomass to energy is influenced mainly by the energy efficiency of the production technology [2,6,9]. Plant species with a high energy potential and a high energy efficiency ratio guarantee reliable supplies of feedstock for energy generation [8]. Perennial legumes have a higher energy efficiency ratio than most energy crops because their production entails high energy inputs only in the year of plantation establishment, and they do not have a high demand for nitrogen fertilizers [48]. In a study by Budzyński et al. [6], fodder galega was characterized by the highest energy efficiency ratio (11.6) in the group of the analyzed perennial legumes. This parameter was also relatively high in alfalfa (9.9). The lowest values of the energy efficiency ratio were noted in timothy-grass (6.6) and a mixture of red clover with timothy-grass (7.3). In the current study, the energy efficiency ratio of fodder galega biomass ranged from 2.28 to 2.42 in the year of plantation establishment to 8.04–16.53 in years 2–11. Productivity was 4% higher in the low-input than in the high-input technology. The energy efficiency of fodder galega biomass was higher (by approx. 2–12%) in the high-input technology only in the last years of the experiment (years ≥10).

5. Conclusions

The energy potential of fodder galega biomass cultivated in a low-input and a high-input production technology in NE Poland was evaluated. The average biomass yields in a large-area farm (2008–2018) ranged from 3.9 Mg ha^{-1} y^{-1} (year of plantation establishment) to 9.7 Mg ha^{-1} y^{-1} (years 2–11). Dry matter yields peaked in year 4 in the low-input technology (14.7 Mg ha^{-1}) and in year 5 in the high-input technology (15.3 Mg ha^{-1}). Beginning from the 4th (5th) year of production, biomass yields decreased at an annual rate of 2.3–3.5 ha^{-1} y^{-1} DM until year 7 and at a rate of 0.6–0.9 Mg ha^{-1} y^{-1} DM between years 9 and 11. The average energy output of fodder galega biomass was determined in a range of 31.5–32.5 GJ ha^{-1} (year 1) to 51.6–131.1 GJ ha^{-1} y^{-1} (years 2–11). Energy output peaked in year 4 in the low-input technology (122.4 GJ ha^{-1}) and in year 5 in the high-input technology (131.1 GJ ha^{-1}). A rapid decrease (by 47–48%) in the energy output of fodder galega biomass was noted between years 4(5) and 7. This parameter was stabilized in years 7–9 at 65.7–72.7 Mg ha^{-1} y^{-1}, and it decreased by 19–24% in years 9–11. Agricultural intensification increased the DMY of fodder galega biomass (by 0.62 Mg ha^{-1} y^{-1}) and energy output (by 4.9 GJ ha^{-1} y^{-1}); it prolonged the achievement of maximum yields by 1 year, and slowed down the rate of decrease in biomass yield and energy output (by 30%) in the last years of the experiment (years 9–11). The energy inputs associated with the production of fodder galega biomass ranged from 13.0 to 14.2 GJ ha^{-1} (year of plantation establishment) to 6.4–8.2 GJ ha^{-1} (years 2–11). The predominant energy inputs were fertilizers (year 1) and fuel (years 2–11). Agricultural intensification increased energy inputs by 11% on average. The energy efficiency ratio of fodder galega biomass ranged from 2.28 to 2.42 (year 1) to 8.04–16.53 (years 2–11). Productivity was 4% higher in the low-input than in the high-input technology. The energy efficiency of fodder galega biomass was higher (by approx. 2–12%) in the high-input technology only in the last years of the experiment (years ≥10). An analysis of energy gains and the energy efficiency ratio indicates that fodder galega biomass for energy generation should be produced in low-input technologies in farms where agricultural production is limited by access to energy resources rather than land (mainly in large-area farms). However, if the main limiting factor is the availability of land rather than energy (mostly small farms), the energy efficiency of fodder galega biomass is likely to be higher in high-input technologies. These production technologies are more energy intensive, but the resulting energy gain per hectare is 6% higher than in low-input technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Bogdan Dubis: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Krzysztof Józef Jankowski:** Conceptualization, Methodology, Investigation, Resources, Writing - original draft, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Mateusz Mikołaj Sokólski:** Investigation, Resources, Writing - original draft. **Dariusz Załuski:** Software, Formal analysis, Data curation. **Piotr Bórawski:** Formal analysis, Funding acquisition. **Władysław Szempliński:** Validation.

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