CORE Organic Cofund

"SCOOP: Developing intercropping systems with camelina to increase the yield and quality parameters of local underutilized crops"

Deliverable report

D 4.4. Report on energy efficiency and the life cycle costing (LCC)

Authors: Mariusz J. Stolarski (UWM), Ewelina Olba-Zięty (UWM), Michał Krzyżaniak (UWM), Kazimierz Warmiński (UWM), Federica Zanetti (UNIBO), Cristina Micheloni (AIAB), Reyhan Bagdat (CRIFIC),

Olsztyn, Poland
2025

Contents

1. Introduction

The cultivation of various crop species, including the older and currently less common ones, in various combinations including sole-cropping, intercropping, mixed cropping, double-cropping and relay-cropping, or grown as intermediate crops, contributes to a reduction in monocultures of typical cereal and oil-bearing crop species, reduces the need for fertilizers and plant protection products, limits the development of diseases and pests, and can therefore offer an interesting alternative to farmers. Consequently, there has been growing interest in the production of niche plant species and the multidirectional use of their biomass. Research work and implementations regarding the production and use of this plants are promising. It should be stressed, however, that a very important aspect in assessing the validity of the production of these species is the assessment of energy inputs and energy efficiency of biomass yields. This is important because the energy inputs incurred in the production and energy efficiency are not affected by market turbulences related to changes in input prices (as is the case when assessing economic efficiency). For this reason, energy efficiency indices, such as energy input, energy output, energy ratio or energy intensity, are more stable in time and space and, therefore, offer reliable opportunities for comparing different technologies of the production of the crop species. The energy inputs related to biomass production are primarily determined by the crop species, the farming system and the cultivation technology applied, including mainly the inputs (fuels, mineral or organic fertilizers, plant protection products, seeds, etc.) and the agricultural operations used. In turn, the energy balance of the production of a particular crop species is determined, on the one hand, by the yield of biomass harvested and the energy accumulated in it and, on the other hand, by the inputs incurred. Another important aspect of assessing the validity of production and the possibilities of implementing new species or technologies is the economic evaluation of cultivation, including organic farming. Life Cycle Costing (LCC) is an economic analysis method that allows estimating the total costs associated with a product or service, as in the case of organic production. The analysis provides valuable information and enables more informed production decisions, allowing the selection of options that will be more profitable in the long run, even if initial costs are higher. Additionally, it helps identify areas for cost reduction. In the market conditions in which agriculture also operates, profitability assessment, identification of all possible sources of income, and evaluation of potential earnings are crucial, as economically viable solutions have a greater chance of implementation. It is also important not to forget the challenges of sustainable development. For this reason, economic analysis should consider not only internal costs directly and indirectly related to cultivation but also external costs, i.e., the environmental impact of this cultivation, expressed in monetary value.

2. Methods

Energy input and energy efficiency indices

The crop production and logistics chain up to the farm gate was adopted as the system boundary. The steps within the system boundaries for each intercropping system and crop are presented in Figure 1 and Tables 1–3. Additionally, Table 4 contains the seed/grain and straw yields used in the present analyses. Most of the data on machinery and yields were collected from field trials conducted as part of the project. These data were subsequently used to modify existing or similar processes available in the EcoInvent database included in the SimaPro software. Data that could not be obtained from the large-scale trials were supplemented with information from other literature sources. The energy input calculations per hectare were performed using the SimaPro 10.1.02 software, applying the Cumulative Energy Demand 1.12 method.

The total energy inputs (GJ ha^{-1}) for the production of the species under the sole-cropping system and under the intercropping system were determined based on the sum of inputs from four basic energy sources, i.e., direct energy carriers (diesel fuel), consumption of materials (manure, lime, seeds). The total energy input for the production of seeds of the species was calculated based on the quantity of materials consumed and the energy intensity of their production.

At the time of harvesting the crops, the seeds collected were weighed, and the obtained yield was converted into an area of 1 ha (Mg ha^{-1}). The laboratory determined the moisture content (%) in a dryer and the higher heating value (HHV) using a bomb calorimeter for the seeds. Based on the yield of seeds and straw (Mg ha^{-1} d.m.) as well as their HHV (GJ Mg^{-1} d.m.), the total biomass yield energy value (GJ ha^{-1}) was calculated. In the next step, based on the difference between the total biomass yield energy value and the total input for their production, the accumulated energy gain (GJ ha^{-1}) was calculated. Another index was the energy intensity (GJ Mg^{-1} d.m. seeds), which was calculated as the ratio of total energy input to the yield of seeds. Another index was the energy efficiency ratio of seeds production, which was calculated as the ratio of the yield energy value (energy output) to total energy input for its production (energy input).

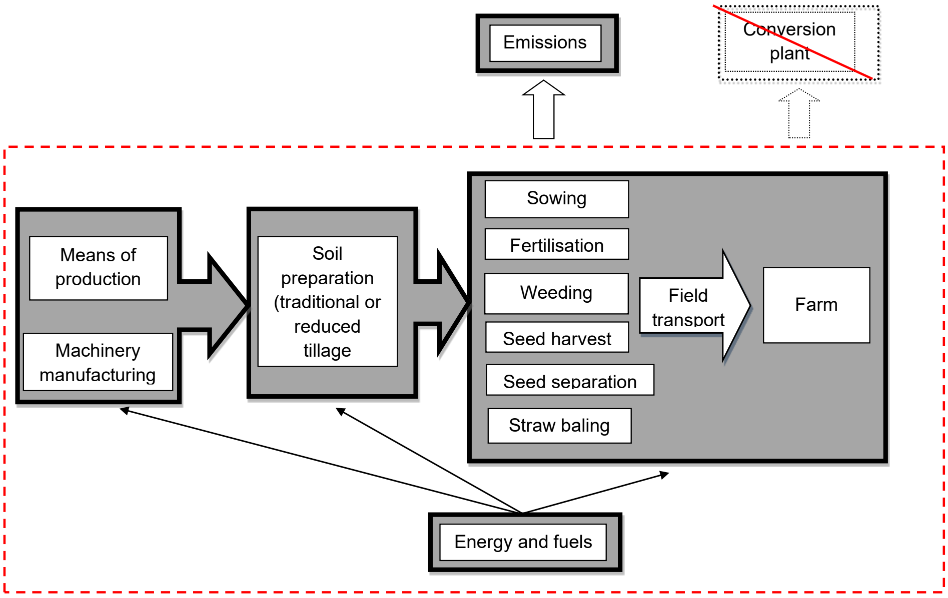

Fig. 1. System boundaries for crops cultivation

Table 1. Data from field operations for sole camelina, sole spelt and camelina and spelt intercropping systems in Poland

Operation	Cropping system	Amount of processes	Machinery	Machinery power (kW)	Machinery mass (kg)	Means of productions	Diesel use (kg/ha)	Comments
Ploughing	C/S/CSI	1	Case Maxum 140 + plough 4 furrows Maschio Gaspardo	140	5845+1270	diesel	19.9	
Manure application	C/S/CSI	0.25*	Tractor Case Maxum 140 + spreader Pichon M945	140	5845+5300	cow manure 40 Mg, diesel	7.57	*Applied every 4 years (means of production divided per 4 years)
Limestone application	C/S/CSI	0.25*	Tractor Case Maxum 140 + spreader Pichon M945	140	5845+5300	lacustrine lime 7 Mg, diesel	3.60	
Tillage, cultivation unit	C/S/CSI	1	Tractor Case Maxum 140 + cultivation unit Batyra	140	5845+1500	diesel	13.2	
Sole sowing	C/S	1	Tractor Case Maxum 140 + combi drill unit Kverneland Amazone	140	5845+900	seeds : 8.3 kg (C), 200 kg (S), diesel	17.9	
Camelina & spelt sowing	CSI	1	Tractor Case Maxum 140 + combi drill unit Kverneland Amazone	140	5845+900	seeds : 6.2 kg (C), 140 kg (S), diesel	37.9	
Mechanical weeding	C/S/CSI	2	Tractor Case Maxum 140 + weeding harrow Pressius	140	5845+1450	diesel	18.9	
Harvest	C/S/CSI	1	Class Mercator 75	105	6000	diesel	19.3	
Transport	C/S/CSI	1	Tractor Case Maxum 140 + trailer Gromar	140	5845+1870	diesel	7.3 (C),11.4 (S), 8.8 (CS) tkm*	*units tkm (tonnes transported per amount of kilometres)
Separation of seeds	CSI	1	Petkus cleaning and separation line	40	8530	unprocessed seeds, electric energy	2.5	

C: camelina sole cropping; S: spelt sole cropping, SCI camelina and spelt intercropping

Table 2. Data from field operations for sole camelina, sole chickpea and camelina and chickpea intercropping systems in Italy

Operation	Cropping system	Amount of processes	Machinery	Machinery power (kW)	Machinery mass (kg)	Means of productions	Diesel use (kg/ha)	Comments
Mowing with flail mower	C/Ch/CChI	1	Fendt 724 + flail mower tmc cancela 8 m	181	7200+3800	diesel	8.40	
Tillage, tine cultivator	C/Ch/CChI	1	Fendt 514 + UST 4500 4,5 m	110	6100+3700	diesel	16.80	
tillage, tine harrow	C/Ch/CChI	2	Fendt 514 + Lemken 6 m vibrocultor	110	6100+1800	diesel	6.72	
Sole Sowing	C/Ch	1	Fendt 413 + Kuhn Premia 3 m	140	5000+740	seeds: 12 kg (C), 140kg (Ch) , diesel	5.88	
Camelina and chickpea sowing	CChI	1	Fendt 413 + Kuhn Premia 3 m	140	5000+740	6 (C)+170 (Ch) diesel	11.76	
Weeding, straw harrow	C/Ch/CChI	1	Fendt 413 + 6 mt Kockerling straw harrow	140	5000+600	diesel	5.04	
harvest	C/Ch/CChI	1	Combine harvester Class Lexion 7700	404	16700+2800	diesel	33.60	
Loading and transport	C/Ch/CChI	1	Fendt 514 + CUM 16T	110	6100+4500	diesel	6.71 (C),8.55 (Ch), 7.30 (CS) tkm*	*units tkm (tonnes transported per amount of kilometres)
Seed cleaning and separation	CChI	1	Petkus cleaning and separation line	40	8530	unprocessed seeds, electric energy	2.07	

C: camelina sole cropping; Ch: chickpea sole cropping, CChI camelina and chickpea intercropping

Table 3. Data from field operations for sole camelina, sole fenugreek and camelina and fenugreek intercropping systems in Türkiye

Operation	Cropping system	Amount of processes	Machinery	Machinery power (kW)	Machinery mass (kg)	Means of productions	Diesel use (kg/ha)	Comments
Tillage+cultivation	C/F/CFI	1	New Holland	135	8000+1000	diesel	14.28	
Sowing sole crop	C/F	2	New Holland Td 65+Köymak 2022	48	5000+500	seeds: 10.0 kg (C), 30.0 kg (F), diesel	9.53	
Sowing intercropping	CFI	1	New Holland Td 65+Köymak 2022	48	5000+500	seeds: 5.0 kg (C), 15.0 kg (F), diesel	19.07	
Seed harvest	CFI	1	New Holand 5,80	167	5800	diesel	16.80	
transport (seed)	C/S/CSI	1	BMC Professional	215	8000	diesel	3.1 (C),4.3 (F), 4.23 (CFI) tkm*	*units tkm (tonnes transported per amount of kilometres)
transport (straw)	C/S/CSI	1	BMC Professional	215	8000	diesel	6.54 (C), 7.35 (F), 7.96 (CFI) tkm*	
Straw baling+loading	C/S/CSI	1	New Holland Td 65+Sgorbati 350	48	5000+2200	diesel	Amount of straw bales 4.4 (C), 4.9 (F), 5.3 (CFI)	
Separation of seeds	CSI	1	Petkus cleaning and separation line	40	8530	unprocessed seeds, electric energy	1.20	

C: camelina sole cropping; F: fenugreek sole cropping, CF: camelina and fenugreek intercropping

Life cycle costing

The costs of camelina, spelt, chickpea, fenugreek production comprised the cost of operation done for cultivation of the crops. Direct cost also included the cost of purchase of materials, i.e. seeds for sowing, and diesel fuel. The economic analysis was based on the real market prices of goods, services, labour in years 2022-2024. The indirect cost included crop insurance. The direct and indirect cost together composed the internal cost of production.

Estimation of the external environmental cost of camelina, spelt, chickpea, fenugreek production in the solo and intercropping systems was based on results of a Life Cycle Assessment. The LCA was carried out according to the ReCiPe 2016 Midpoint (H) method. This method enabled us to determine the size of the environmental impact according to the impact categories. The next step was to assess the monetary value of the impact on the environment using the monetary values proposed by Ponsioen et al., (2020) in the particular impact categories for ReCiPe 2016 Midpoint (H). External cost was calculated for the impact categories: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation, human health, fine particulate matter formation, ozone formation, terrestrial ecosystems, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, human carcinogenic toxicity, human non-carcinogenic toxicity, land use, mineral resource scarcity, fossil resource scarcity, water consumption.

The final step in the cost analysis was to estimate the total cost of camelina, spelt, chickpea, fenugreek production, which represented the sum of internal and external cost. Based on this analysis Life Cycle Cost of camelina, spelt, chickpea, fenugreek production was calculated.

Income analysis

The next step in the research was to estimate revenue (gross income) possible to be obtained from camelina, spelt, chickpea, fenugreek production. The analysis took into account two streams of revenue: from selling seeds, and from subsidies. The sum of these two streams constituted the total gross income. Revenue from selling seeds was estimated according to the volume of seed harvest obtained in the field trials converted to yield per 1 ha, and the market prices of camelina, spelt, chickpea, fenugreek from organic farming in analysed countries. The income from subsidies was calculated according to the Common Agricultural Policy (CAP) scheme. Moreover, the following were taken into account in the sole cropping system: revenue from organic farming. This type of subsidies was unavailable in the intercropping system.

Profitability analysis

The profitability analysis of the camelina, spelt, chickpea, fenugreek production in the different variants was conducted on the basis of the income analysis, in which different cost and income components were included. The first income indicator, closest to the market conditions, was the net income excluding subsidies including internal cost, which took into account only the revenue from selling seeds and the sum of direct and indirect costs but did not consider subsidies or externalities. The next indicator, i.e. the net income including subsidies including internal cost, in addition to the former one, included revenue from subsidies, although it still excluded the external cost. The third indicator, i.e. the net income excluding subsidies including total cost, took into consideration the total cost, that is the sum of internal and external cost but did not include revenue from subsidies. The last indicator, called the net income including subsidies including total cost, comprised all the analysed streams of costs and revenues. The last step of the economic analysis consisted of a comparison of income from production of species depending on the production system.

Statistical analysis

The statistical analyses based on multi-dimensional cluster analysis. Agglomeration was carried out using Ward's method, with Euclidean distance as the measure of dissimilarity. The cut-off significance was determined set at levels of 50%.The statistical analyses of the results obtained from cluster analysis were conducted based on the one-factor variance analysis (ANOVA), with the F and p-values being determined. The dependent variable was cluster, and independent variables were direct cost, indirect cost, internal cost external cost, total cost, sales income, subsidies income, gross income, net income excl. subsidies incl. internal cost, net income incl. subsidies incl. internal cost, net income excl. subsidies incl. total cost, net income incl. subsidies incl. total cost All statistical analyses were conducted using STATISTICA 13 software (TIBCO Software Inc., Palo Alto, CA, USA).

3. Results

3.1. Energy Efficiency of sole and intercropping systems

Yield and its energy value

The highest seed yield was recorded for spelt from sole cropping in Poland: 2.28 Mg ha^{-1} d.m. (Table 4). The seed yield of camelina from sole cropping in Poland was lower and amounted to 1.46 Mg ha^{-1}

d.m. In turn, the yield from intercropping of these two species was 1.76 Mg ha^{-1} d.m. The yield of camelina in sole cropping in Italy amounted to 1.34 Mg ha^{-1} d.m., while in Turkey it was only 0.62 Mg ha^{-1} d.m. The seed yields of chickpea and fenugreek under sole cropping were 1.71 and 0.86 Mg ha^{-1} d.m., respectively. In intercropping systems of camelina with chickpea or camelina with fenugreek, the yields were 1.46 and 0.85 Mg ha^{-1} d.m., respectively.

Similar relationships were found for the energy value of the yield (Table 4). The energy value of the seed yield of spelt from sole cropping in Poland was 42.0 GJ ha^{-1} (Table 4). The energy value of the camelina seed yield from sole cropping in Poland amounted to 41.0 GJ ha^{-1}. In the case of intercropping of these two species, the value was 38.0 GJ ha^{-1}. The energy value of the camelina yield in sole cropping in Italy was 37.63 GJ ha^{-1}, and in Turkey it was only 17.41 GJ ha^{-1}. The energy values of the seed yield of chickpea and fenugreek from sole cropping amounted to 31.29 and 16.77 GJ ha^{-1}, respectively. In intercropping of camelina with chickpea or camelina with fenugreek, these values were 32.20 and 20.60 GJ ha^{-1}, respectively.

Table 4. Seed/grain yields from sole crop cultivation and the intercropping systems.

Cultivation system	**Seed Yield (Mg ha^{-1})**	**Energy Yield (GJ ha^{-1})**
camelina sole PL	1.46	41.00
camelina sole IT	1.34	37.63
camelina sole TR	0.62	17.41
spelt sole	2.28	42.00
chickpea sole	1.71	31.29
fenugreek sole	0.86	16.77
camelina+spelt	1.76	38.00
camelina + chickpea	1.46	32.20
camelina+fenugreek	0.846	20.60

Energy inputs

The highest energy inputs were associated with the cultivation of spelt in Poland, amounting to 8.38 GJ ha^{-1} (Fig. 2). Slightly lower inputs were recorded for camelina in Poland (8.35 GJ ha^{-1}). The energy inputs for camelina cultivation in sole cropping in Italy amounted to 6.52 GJ ha^{-1}, while in Turkey they were only 3.89 GJ ha^{-1}. The energy inputs for chickpea and fenugreek cultivation in sole cropping amounted to 6.53 and 3.94 GJ ha^{-1}, respectively. In each case, typical cultivation practices specific to each country were applied for each species; therefore, the structure of energy inputs varied accordingly.

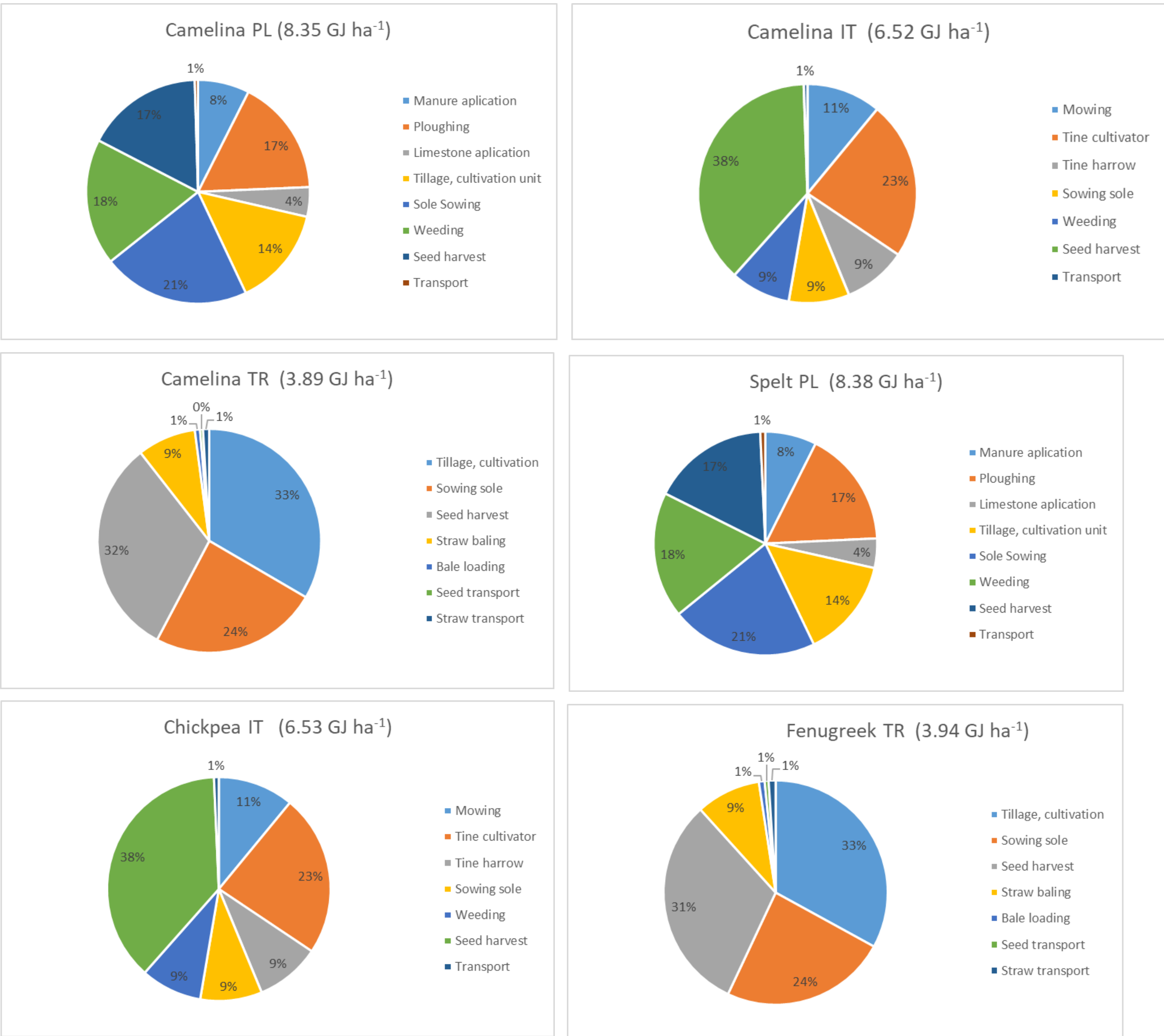

Fig. 2. Energy inputs and their structure in sole cropping of the studied species.

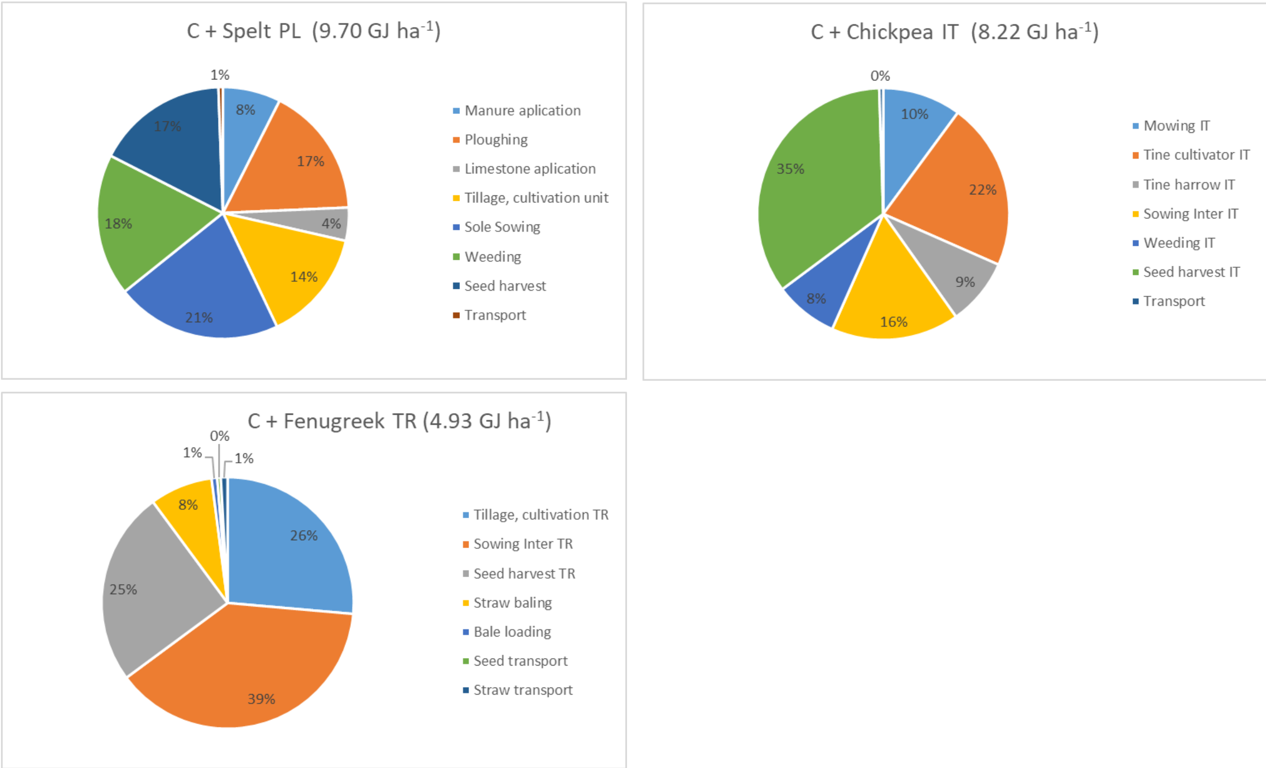

Fig. 3. Energy inputs and their structure in intercropping of the studied species

The energy input in intercropping of camelina and spelt in Poland amounted to 9.70 GJ ha^{-1} (Fig. 3). In turn, the energy inputs for intercropping of camelina with chickpea or camelina with fenugreek amounted to 8.22 and 4.93 GJ ha^{-1}, respectively. As in sole cropping, typical cultivation practices specific to each country were applied in each intercropping system; therefore, the structure of energy inputs varied. For example, in Poland, the largest share in the input structure was associated with sowing (21%), weeding (18%), and harvest (17%). In Italy, harvest dominated (35%), while in Turkey sowing accounted for the largest share (39%).

Energy gain, energy intensity and energy ratio

The energy gain from sole cropping of spelt in Poland amounted to 33.62 GJ ha^{-1} (Table 5). The energy gain from sole cropping of camelina in Poland was 32.65 GJ ha^{-1}. In turn, the value of this indicator for intercropping of these two species was 28.30 GJ ha^{-1}. The energy gain from sole cropping of camelina in Italy amounted to 31.11 GJ ha^{-1}, while in Turkey it was only 13.52 GJ ha^{-1}. The energy gain from sole cropping of chickpea and fenugreek was 24.76 and 12.83 GJ ha^{-1}, respectively. In intercropping of camelina with chickpea or camelina with fenugreek, the values were 23.98 and 15.67 GJ ha^{-1}, respectively.

Table 5. Energy efficiency indicators for sole crop cultivation and the intercropping systems.

Cultivation system	Energy gain (GJ ha^{-1})	Energy intensity (GJ Mg^{-1} d.m.)	Energy ratio
camelina sole PL	32.65	5.72	4.91
camelina sole IT	31.11	4.87	5.77
camelina sole TR	13.52	6.27	4.48
spelt sole	33.62	3.67	5.01
chickpea sole	24.76	3.82	4.79
fenugreek sole	12.83	4.58	4.25
camelina+spelt	28.30	5.51	3.92
camelina + chickpea	23.98	5.63	3.92
camelina+fenugreek	15.67	5.82	4.18

The energy intensity of spelt seed production in sole cropping in Poland was the lowest, amounting to 3.67 GJ Mg^{-1} d.m. (Table 5). The energy intensity of camelina seed production in sole cropping in Poland was 5.72 GJ Mg^{-1} d.m., while for intercropping of these two species it was 5.51 GJ Mg^{-1} d.m. The energy intensity of camelina seed production in sole cropping in Italy was 4.87 GJ Mg^{-1} d.m., and in Turkey it was as high as 6.27 GJ Mg^{-1} d.m. The energy intensity of chickpea and fenugreek seed production in sole cropping was 3.82 and 4.58 GJ Mg^{-1} d.m., respectively. In intercropping systems of camelina with chickpea or camelina with fenugreek, the values were 3.92 and 4.18 GJ Mg^{-1} d.m., respectively.

The highest energy ratio of camelina seed production in sole cropping was recorded in Italy, at 5.77 (Table 5). In Poland, this indicator for camelina under sole cropping was 4.91, and in Turkey it was 4.48. The energy ratio of spelt seed production in sole cropping in Poland amounted to 5.01. The energy ratio of chickpea and fenugreek seed production in sole cropping was 4.79 and 4.25, respectively. In intercropping systems, the energy ratio for camelina + chickpea and camelina + spelt was 3.92, while for camelina + fenugreek it was 4.18.

3.2. Life cycle cost analysis of sole and intercropping systems

Life cycle costing

The highest costs directly related to cultivation were recorded in the intercropping system in Poland and Italy in the camelina and spelt and camelina and chickpea cultivation and amounted to € 869.71 ha^{-1} and € 868.50 ha^{-1} (table 6). On the other hand, the lowest production costs were recorded in Turkey in the sole cropping of camelina and fenugreek (€ 249.97 ha^{-1} and € 260.07 ha^{-1}). Direct costs of cultivation in the intercropping system were higher and amounted to € 389.93 ha-1, but it was 50% lower than in the other countries. Indirect costs ranged from € 10 ha^{-1} to € 32 ha^{-1}. The highest internal cost was related to the intercropping camelina and spelt in Poland (€ 901.94 ha^{-1}). The highest external cost was also obtained in Poland in all analysed crop variants. The highest sales income was obtained from chickpea cultivation in Italy in the sole cultivation system and amounted to € 2906.96 ha-1. High sales income was also obtained in the case of intercropping camelina and chickpea in Italy and camelina sole cultivation in Poland (€ 1974.22 ha^{-1} and € 1945.43 ha^{-1}). The lowest sales income was obtained in Turkey, especially in the case of camelina sole cultivation and amounted to € 265.71 ha^{-1}. Subsidies income for organic farming was significantly higher in the case of cultivation in sole systems, therefore in intercropping crops subsidies were not a source of additional income. Moreover, in Turkey, subsidies income was lower than in Poland or Italy. Analysis of net income excl. subsidies incl. internal cost allowed to establish that the highest net income was obtained in Italy from chickpea cultivation in sole system and amounted to over € 2000 ha^{-1}. Net income above € 1000 ha^{-1} was obtained in case of camelina sole cultivation in Poland (€ 1229.75 ha^{-1}) and camelina and chickpea in Italy (€ 1095.72 ha^{-1}). Sole spelt cultivation in Poland was unprofitable (€ -103.83 ha^{-1}) and camelina sole cultivation in Turkey was on the verge of profitability (€ 0.74 ha^{-1}). Including subsidies allowed to obtain higher net income mainly in sole systems. Including external cost caused that additionally camelina sole cultivation in Turkey, camelina and fenugreek in Turkey and camelina and spelt in Poland became unprofitable. The highest Nnet income incl. subsidies incl. total cost was obtained for chickpea in Italy (€ 2521.27^{-1}), camelina sole in Poland (€ 1522.89 ha^{-1}) and camelina sole in Italy (€ 1025.75 ha^{-1}).

Table 6. Economic indicators of camelina, spelt, chickpea, fenugreek production per 1 ha

Indicators	Camelina Sole PL	Camelina Sole IT	Camelina Sole TR	Spelt Sole	Chickpea Sole	Fenugreek Sole	Camelina +Spelt	Camelina +Chickpea	Camelina+ Fenugreek
Direct Cost	683.45	568.50	249.97	758.10	806.50	260.07	869.71	868.50	389.93
Indirect cost	32.23	10.00	15.00	32.23	10.00	15.00	32.23	10.00	15.00
Internal cost	715.67	578.50	264.97	790.32	816.50	275.07	901.94	878.50	404.93
External cost	315.63	200.75	231.09	299.58	168.19	228.94	343.95	248.96	253.03
Total cost	1031.30	779.25	496.06	1089.90	984.69	504.01	1245.89	1127.46	657.97
Sales income	1945.43	1206.00	265.71	686.49	2906.96	614.28	1125.71	1974.22	504.85
Subsidies income	608.76	599.00	77.14	608.76	599.00	77.14	240.04	169.00	77.14
Gross income	2554.19	1805.00	342.85	1295.26	3505.96	691.42	1365.74	2143.22	581.99
Net income excl. Subsidies incl. Internal cost	1229.75	627.50	0.74	-103.83	2090.46	339.21	223.77	1095.72	99.92
Net income incl. Subsidies incl. Internal cost	1838.52	1226.50	77.88	504.93	2689.46	416.35	463.81	1264.72	177.06
Net income excl. Subsidies incl. Total cost	914.13	426.75	-230.36	-403.41	1922.27	110.27	-120.18	846.76	-153.12
Net income incl. Subsidies incl. Total cost	1522.89	1025.75	-153.22	205.36	2521.27	187.41	119.85	1015.76	-75.98

Analysis of the production costs of 1 Mg of camelina seeds showed that the lowest direct costs and internal production costs were associated with the cultivation of camelina in the sole system in Turkey (€ 403.18 Mg^{-1} and € 427.37 Mg^{-1}) (Table 7). Slightly higher direct and internal production costs were obtained in Italy (€ 424.25 Mg^{-1} and € 431.72 Mg^{-1}). The lowest external costs were associated with the production of camelina in intercropping systems both in Italy (€ 85.26 Mg^{-1}) and in Poland (€ 97.72 Mg^{-1}). Taking into account the above, the lowest Life Cycle Cost including both internal and external cost of production of 1 Mg of grain was related to the production of camelina in the sole system in Italy and amounted to € 581.53 Mg^{-1} and the highest from camelina in the sole system in Poland € 943.60 Mg^{-1}. The highest market value of camelina seeds was in Poland (€ 1329.76 Mg^{-1}) lower in Italy (€ 900.00 Mg^{-}

[1]) and the lowest in Turkey (€ 428.56 Mg^{-1}). Intercropping generated higher production costs of 1 Mg of camelina in all countries.

Table 7. Economic indicators of camelina production per 1 Mg in different countries and production systems

Indicators	Camelina Sole PL	Camelina Sole IT	Camelina Sole TR	Camelina Inter PL	Camelina Inter IT	Camelina Inter TR
Direct Cost	475.28	424.25	403.18	815.62	675.14	560.25
Indirect cost	22.73	7.46	24.19	30.27	7.77	21.55
Internal cost	498.01	431.72	427.37	845.88	682.91	581.80
External cost	216.18	149.82	372.73	97.72	85.26	149.55
Total cost = Life Cycle Cost	714.19	581.53	800.10	943.60	768.17	731.35

Economic analysis of selected companion crops cultivation showed that the lowest direct cost of production of 1 Mg seed was associated with the production of fenugreek in Turkey and amounted to € 151.20 Mg^{-1}, while taking into account internal and external cost in Life Cycle Cost of 1 Mg fenugreek it amounted to € 426.13 (Table 8). If in market conditions external costs were included in costs, then at the market price of € 357.14 Mg^{-1} fenugreek cultivation would be unprofitable. The highest direct production costs were associated with the cultivation of chickpea in intercropping, but the high selling price (€ 1700 ha^{-1}) allowed profitable production of this species in both systems. Intercropping generated higher production costs of 1 Mg of all companion crops in all countries.

Economic analysis of selected companion crops cultivation showed that the lowest direct cost of production of 1 Mg seed was associated with the production of fenugreek in Turkey and amounted to € 151.20 Mg^{-1}, while taking into account internal and external costs in the Life Cycle Cost of 1 Mg Fenugreek it amounted to € 426.13. If in market conditions external costs were included in costs, then at a market price of € 357.14 Mg^{-1} fenugreek cultivation would be unprofitable. The highest direct production costs were associated with the cultivation of chickpea in intercropping, but the high selling price (€ 1700 ha^{-1}) allowed for profitable production of this species in both systems. Intercropping generated higher production costs of 1 Mg of all companion crops in all countries.

Table 8. Economic indicators of Spelt, Chickpea and Fenugreek production per 1 Mg in different countries and production systems.

Indicators	Spelt Sole	Spelt Inter	Chickpea Sole	Chickpea Inter	Fenugreek Sole	Fenugreek Inter
Direct Cost	428.25	494.60	235.82	529.06	151.20	391.50
Indirect cost	19.10	19.09	2.92	6.09	8.72	15.06
Internal cost	447.35	513.69	238.75	535.16	159.93	406.56
External cost	131.39	236.34	98.36	85.26	266.20	149.55
Total cost = Life Cycle Cost	578.74	750.02	337.11	620.42	426.13	556.11

The analysis of the similarity of the analysed crops, taking into account all economic indicators, allowed us to designate three groups (Fig. 4). The first group consists of plants whose cultivation did not require high direct and indirect costs but also did not allow for achieving high profitability indicators and these were all crops in Turkey, i.e. camelina grown in sole system, Fenugreek grown in sole system and camelina and fenugreek in intercropping. The second group consists of plants whose cultivation was associated with high production costs and low profitability indicators, i.e. spelt and camelina in the intercropping system and spelt in Poland. The third group consists of crops that were characterized by lower costs than in the second group and, above all, higher production profitability and these included camelina grown in sole system in Poland and Turkey, camelina together with chickpea in the intercropping system and chickpea grown in sole system in Italy.

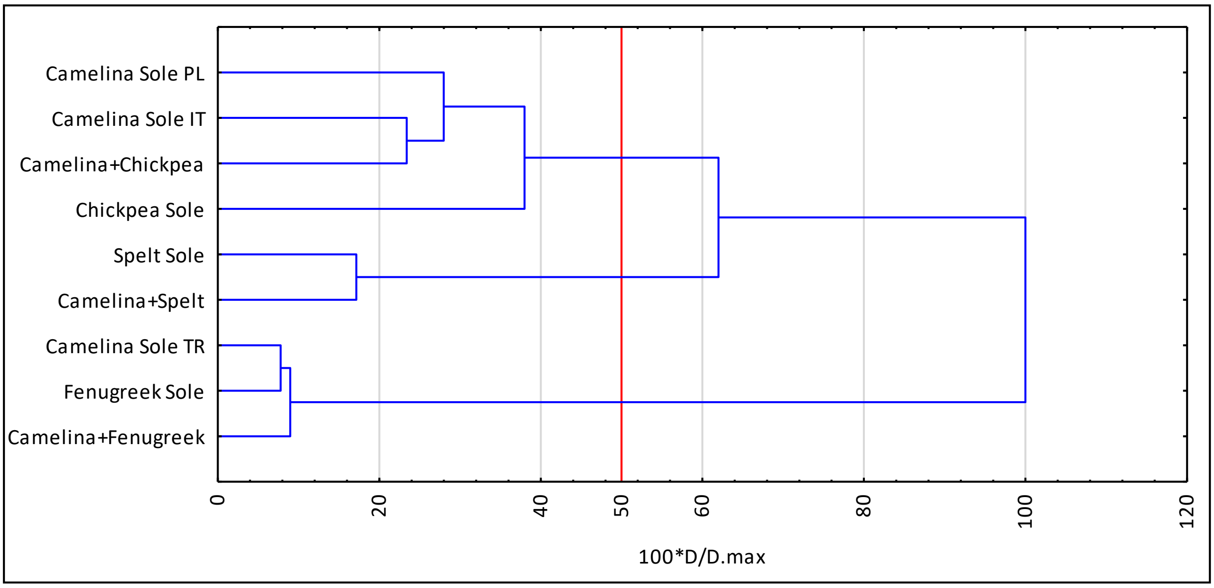

Fig. 4. Cluster analysis of crops cultivation

Analysis of variance of economic indicators in relation to cluster membership showed that production conditions differentiated internal cost the most, then direct cost, total cost and gross income, which were characterized by the lowest *p*-values (Table 9). Subsidies income, external cost and indirect cost did not differ significantly between cultivation systems, plants and countries and did not affect grouping, as the *p*-value was greater than 0.05.

Table 9. *p* – value of economic indicators in AVOVA analysis.

Variable	*p*
Internal cost	0.0024
Direct Cost	0.0029
Total cost	0.0033
Gross income	0.0078
Net income incl. subsidies incl. internal cost	0.013
Net income incl. subsidies incl. total cost	0.014
Sales income	0.019
Net income excl. subsidies incl. total cost	0.023
Net income excl. subsidies incl. internal cost	0.025
Subsidies income	0.064
External cost	0.094
Indirect cost	0.15

The highest external costs are related to global warming in all analyzed cultivation variants and ranged from € 66 ha^{-1} in chickpea sole cultivation to € 176.16 ha^{-1} in camelina and fenugreek intercropping (Figure 5). All variants generated high external costs in the categories of fossil resource scarcity, fine particulate matter formation and terrestrial acidification. Significant external costs were also generated in the categories of human carcinogenic toxicity and human non-carcinogenic toxicity and marine eutrophication. The structure of the share of costs in the individual impact categories was the same in the case of the analysis of external cost per 1 ha and 1 Mg (Fig. 5 and Fig. 6). In the case of the analysis of external cost per 1 ha, the highest external costs were related to camelina and spelt intercropping system, spelt sole and camelina sole in Poland. Whereas the assessment of the external cost of production of 1 Mg seeds showed that the highest external cost related to the production of camelina sole and camelina with fenugreek in intercropping system and fenugreek sole in Turkey.

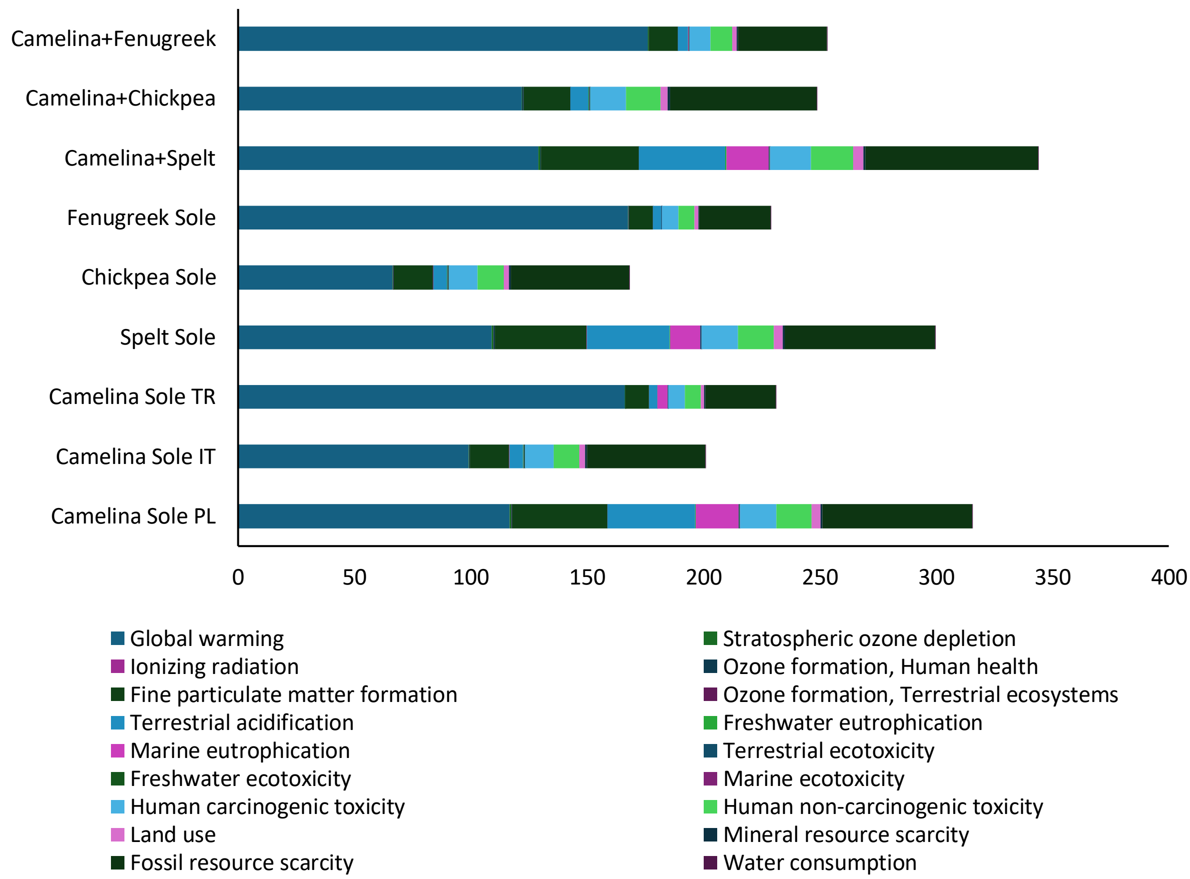

Fig. 5 External cost of camelina, spelt, chickpea, fenugreek production in impact categories per 1 ha

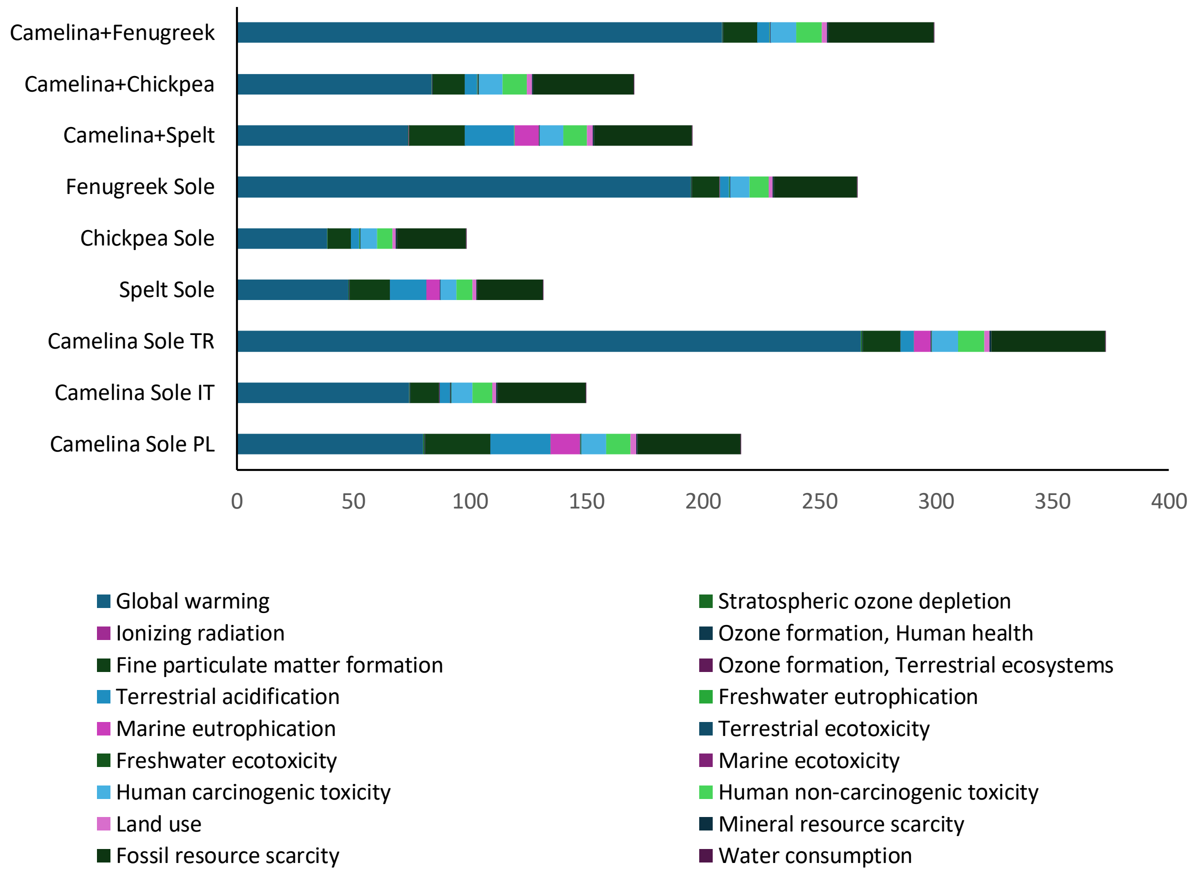

Fig. 6. External cost of camelina, spelt, chickpea, fenugreek production in impact categories per 1 Mg of seeds.

4. Conclusion

The highest energy inputs were recorded for the cultivation of spelt and camelina in Poland, while the lowest were observed in Turkey. Intercropping systems generally required higher energy inputs than sole cropping. The greatest energy gains and the lowest energy intensity were achieved in sole cropping of spelt in Poland. Sole cropping systems were generally more energy-efficient than intercropping systems. The highest energy ratio was observed for camelina grown in sole cropping in Italy. Overall, the results demonstrate that energy efficiency in crop production depends on the species, cropping system, and local cultivation practices.

The lowest cultivation costs were obtained in Turkey, but due to low yields and low market prices, the highest external costs were also obtained there. Cultivation in Poland was associated with the highest internal costs, but due to higher yields, the external cost of production of 1 Mg seeds was lower. The market value of camelina seeds in Poland was high, which had a positive impact on the profitability of its production in the sole system and improved profitability in the intercropping system. The low market value of spelt caused this cultivation was unprofitable in the sole system and significantly reduced profitability in the intercropping system. The most favorable economic conditions were in Italy. High subsidies in sole cropping and the market value of Chickpea influenced the highest profitability of cultivation in sole systems. Intercropping cultivation generated higher production costs per 1 ha and 1 Mg of all analyzed species in all countries. Sole cultivation allowed for higher profitability of production of all species and in all countries, except for sole spelt cultivation in Poland, which was associated with a low market value of spelt.

Production conditions differentiated the most internal cost, direct cost, total cost and gross income. The largest external costs are related to global warming, followed by fossil resource scarcity, fine particulate matter formation and terrestrial acidification in all analyzed cultivation variants.

5. References

Ponsioen, T., Nuhoff-Isakhanyan, G., Vellinga, T., Baltussen, W., Boone, K., Woltjer, G. 2020. Monetisation of sustainability impacts of food production and consumption. Wageningen: Wageningen Economic Research.