CORE Organic Cofund

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

Deliverable report

D 4.3. Report on the life cycle assessment (LCA) of selected intercropping systems

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

Olsztyn, Poland
2025

Content

1. Introduction

All agricultural production, including organic, affects the environment. Therefore, within the SCOOP project we tried to answer, through multi-criterial analysis, to the question: how intercropping systems with camelina influence the sustainability in terms of energy, environmental and economic categories. The scope of the research included analysis of energy efficiency, life cycle assessment (LCA) and life cycle cost (LCC) assessment, including external environmental cost. In the SCOOP project, focused on innovative and diversified organic intercropping systems, we aimed to test new intercropping systems based on camelina combined with locally selected underutilized crops (e.g., pulses, pseudocereals, ancient cereals, etc.) in Poland, Bulgaria and Türkiye. The goal was to develop high-performing intercropping systems for organic farming while simultaneously providing multiple environmental services (e.g., reduced nitrogen leaching, reduced soil erosion, and decreased pest and weed pressure). One of the research directions involved assessing the environmental impact of camelina cultivation in intercropping systems using life cycle assessment (LCA). While LCA studies on camelina have been conducted, they have primarily focused on its sole cultivation (Bacenetti et al., 2017; Ceriani et al., 2024; Krzyzaniak & Stolarski, 2019).

In SCOOP project, based on analyses and discussions with stakeholders during regional living labs, various companion crops were proposed: spelt in Poland, chickpea in Italy and fenugreek in Türkiye. Therefore, the aim of this research was to answer the question: How does the intercropping system with camelina and companion crops, cultivated in organic farming, influence the environment compared with the sole cultivation of each crop?

2. Methods

Aim and scope of the LCA

A life cycle assessment methodology of cropping systems was conducted according to ISO 14040 "Environmental management – Life cycle assessment – Principles and framework" (Standardization, 2006a) and ISO 14044 "Environmental management – Life cycle assessment – Requirements and guidelines" (Standardization, 2006b). The aim of this simplified life cycle assessment was to evaluate the impact of camelina cultivation in an intercropping system with companion crops under organic farming practices. For comparison, a life cycle assessment of the sole cultivation of camelina and companion crops was also performed. An attributional approach was used for the analysis, with system boundaries defined as "from cradle to farm gate". Figure 1 presents the general system boundaries of the study for the cultivation of camelina and companion crops in Poland, Turkey, and Italy. A detailed description of the trial locations and the conditions and under which they were conducted is presented in Deliverables D2.2. Report on SCOOP intercropping trials and D2.3. Report on farm scale trials.

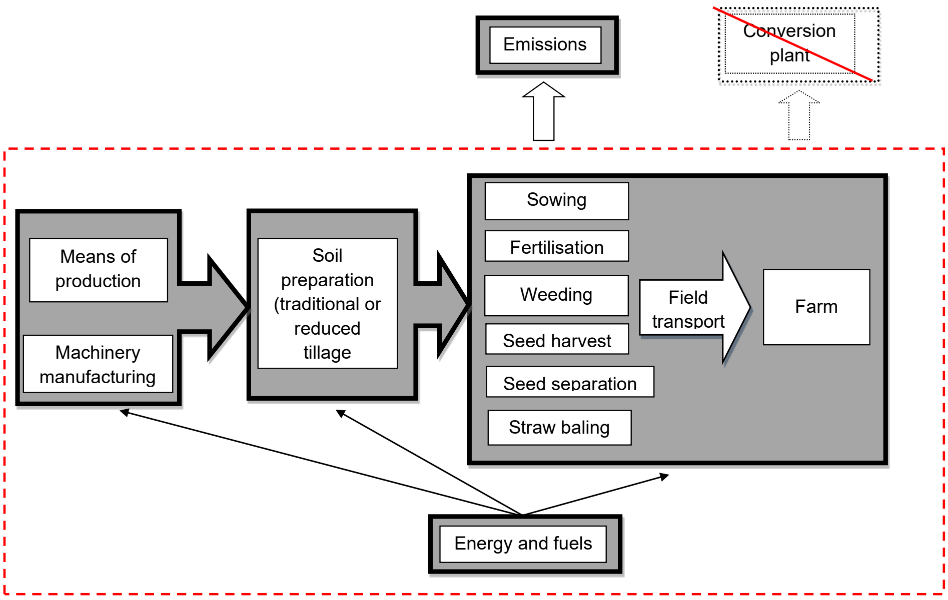

Fig. 1. System boundaries for crops cultivation

The main purpose of cultivating camelina and companion crops in the intercropping system was to produce seeds for high-quality oil, flour, spices and food, respectively from camelina, spelt, fenugreek and chickpea, respectively. In the case of crops in Poland and Italy, the straw was left on the field, whereas in Türkiye it was collected and used, for example, as feed or bedding. Since the functions of these crops vary, not only 1 Mg of seeds was used as a functional unit but and the energy content of seeds (1 GJ as higher heating value (HHV)) as well. Additionally, 1 hectare of sole crop and intercropping systems was used as a base functional unit. This unit provides stable values regarding crop production compared with product functional units.

Life Cycle Inventory

The crop production and logistics chain until the farm gate was adopted as the system boundary. The steps of 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 analysis. Most of the data regarding machinery and yields were collected from field trials conducted in the project. Subsequently, the data were 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 from other literature sources.

The boundaries included field emissions resulting from the application of fertilisers and soil organic carbon (SOC) changes from soil management. It also considers the environmental impact of the production of agricultural machines, the buildings in which they are kept.

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

Table 4. Seed/grain and straw 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	41.0
camelina sole IT	1.34	37.6
camelina sole TR	0.62	17.4
spelt sole	2.28	42.0
chickpea sole	1.71	31.3
fenugreek sole	0.86	16.8
camelina+spelt	1.76	38.0
camelina + chickpea	1.46	32.2
camelina+fenugreek	0.846	20.6

Modelling of field emissions

The field emission model included greenhouse gases (GHG) emissions and atmospheric pollutants, as well as the leakage of nitrates and phosphates into groundwater. The greenhouse gases balance accounted for CO_2 and N_2O emissions. Loss of SOC (soil organic carbon) was considered a positive CO_2 emission, while SOC sequestration was considered a negative CO_2 emission. N_2O was produced as a byproduct of nitrification and denitrification processes occurring in the soil of the field trials (direct emissions) as well as outside the cultivated area (indirect emissions).

Organic carbon from crop residues was calculated using the C-TOOL model, which accounts for the deposition of aboveground crop residues, including straw, as well as underground organic matter, originating from roots and root exudates (Taghizadeh-Toosi et al., 2014). The balance also included applied organic fertilizer as an additional carbon source. Only a portion of SOC is sequestered within a 100-year time horizon. In this study, it was assumed that 9.7% of the net OC input was sequestered (Petersen et al., 2013). Nitrous oxide emissions were calculated using the method recommended by the Intergovernmental Panel on Climate Change (IPCC) (Eggleston et al., 2006).

Nitrate leaching was calculated using the nitrogen balance method, based on the nitrogen input from manure application, atmospheric nitrogen deposition, annual net nitrogen mineralization in the soil, nitrogen content in harvested biomass, and nitrogen gas emissions from the soil (NH_3, NO_x, N_2O, N_2) (Alaphilippe et al., 2016; Krzyżaniak et al., 2018; Parajuli et al., 2017a; Parajuli et al., 2017b). Emissions of NH_3, NO_x, Particulate Matter (as PM_{10}, $PM_{2.5}$) and Non-Methane Volatile Organic Compounds were estimated using the indicator method recommended by the European Environment Agency (2023), while phosphate leaching from fertilizers was calculated based on the study by Iriarte et al. (2010).

Life Cycle Impact Assessment

A life cycle assessment was performed with SimaPro 9.6 software. The environmental impact of the analysed production system (LCIA) was assessed with the ReCiPe 2016 v1.10 method. Impact categories were defined using the ReCiPe midpoint (H) method, and damage categories were defined using the ReCiPe endpoint (H) method. In the midpoint method, environmental impacts were represented by 18 categories: global warming, stratospheric ozone depletion, ionising 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, and water consumption. Environmental damage was assessed in three categories: human health, ecosystems, and resources.

3. Results

The life cycle impact assessment (LCIA) results based on the Recipe midpoint method reveal considerable differences in the environmental impacts of sole cropping and intercropping systems for camelina, spelt, chickpea, and fenugreek cultivated in Poland, Italy, and Turkey (per 1 hectare) (Fig. 2). Among sole cropping systems, fenugreek cultivated in Turkey exhibited the highest values in global warming category (1116 kg/ha CO_2 eq) but overall camelina+spelt intercropping showed the highest impact in most of the rest impact categories. Among sole crops, chickpea had the lowest global warming potential (442 kg CO_2 eq).

Intercropping systems such as camelina+spelt and camelina+chickpea resulted in elevated impacts in some categories, such as water consumption (4.52 and 3.70 m^3/ha respectively) and terrestrial ecotoxicity (2928 and 2593 kg 1,4-DCB), yet in others they achieved lower or moderate values.

Intercropping of camelina with fenugreek had the highest global warming potential of all systems, reaching 1174 kg/ha CO_2 eq, yet this system simultaneously showed relatively low marine eutrophication (0.01 kg/ha N eq) and low water use (0.90 m^3/ha).

When recalculated per 1 tonne of harvested seeds, the highest global warming potential was observed for sole camelina cultivation in Türkiye, reaching 1786 kg CO_2 eq per tonne, followed by camelina+fenugreek intercropping (1388 kg/ha CO_2 eq) and sole fenugreek (1298 kg/ha CO_2 eq) (Fig. 3). In contrast, the lowest emissions were recorded for sole chickpea (258 kg/ha CO_2 eq) and sole spelt (319 kg/ha CO_2 eq).

Among intercropping systems, camelina+chickpea and camelina+spelt resulted in moderate emissions of 556 and 489 kg/ha CO_2 eq, respectively. Camelina+fenugreek intercropping remained among the highest-emission option (1388 kg/t CO_2 eq).

In other categories, such as terrestrial ecotoxicity, the highest burdens per tonne of seeds were observed for sole camelina cultivation in Türkiye (2023 kg/ha 1,4-DCB), while sole chickpea (1270 kg) and sole spelt (1166 kg) had lower toxicity impacts. Intercropping generally resulted in increased water consumption, compared to sole cropping systems. Marine eutrophication remained low for all systems.

The LCIA results calculated per 1 GJ of energy contained in seeds show that the lowest GHG emission were recorded for sole chickpea cultivation (14.1 kg CO_2 eq/GJ) while the highest was observed for sole fenugreek sole (66.6 kg) (Fig. 4). Among intercropping systems, camelina+spelt intercropping systems had the lowest GHG emission (22.6 kg CO_2 eq/GJ), whereas camelina+fenugreek exhibited the highest carbon footprint (57.0 kg CO_2 eq/GJ).

In other midpoint categories, emissions remained low but varied noticeably between systems. For example, terrestrial ecotoxicity ranged from 57.6 to 80.5 kg 1,4-DCB eq/GJ, and marine ecotoxicity was the highest from camelina+chickpea intercropping (1.23 kg 1,4-DCB/GJ). Human toxicity (carcinogenic) values ranged from 1.36 to 1.96 kg 1,4-DCB eq/GJ. In contrast, marine eutrophication and stratospheric impact were very low.

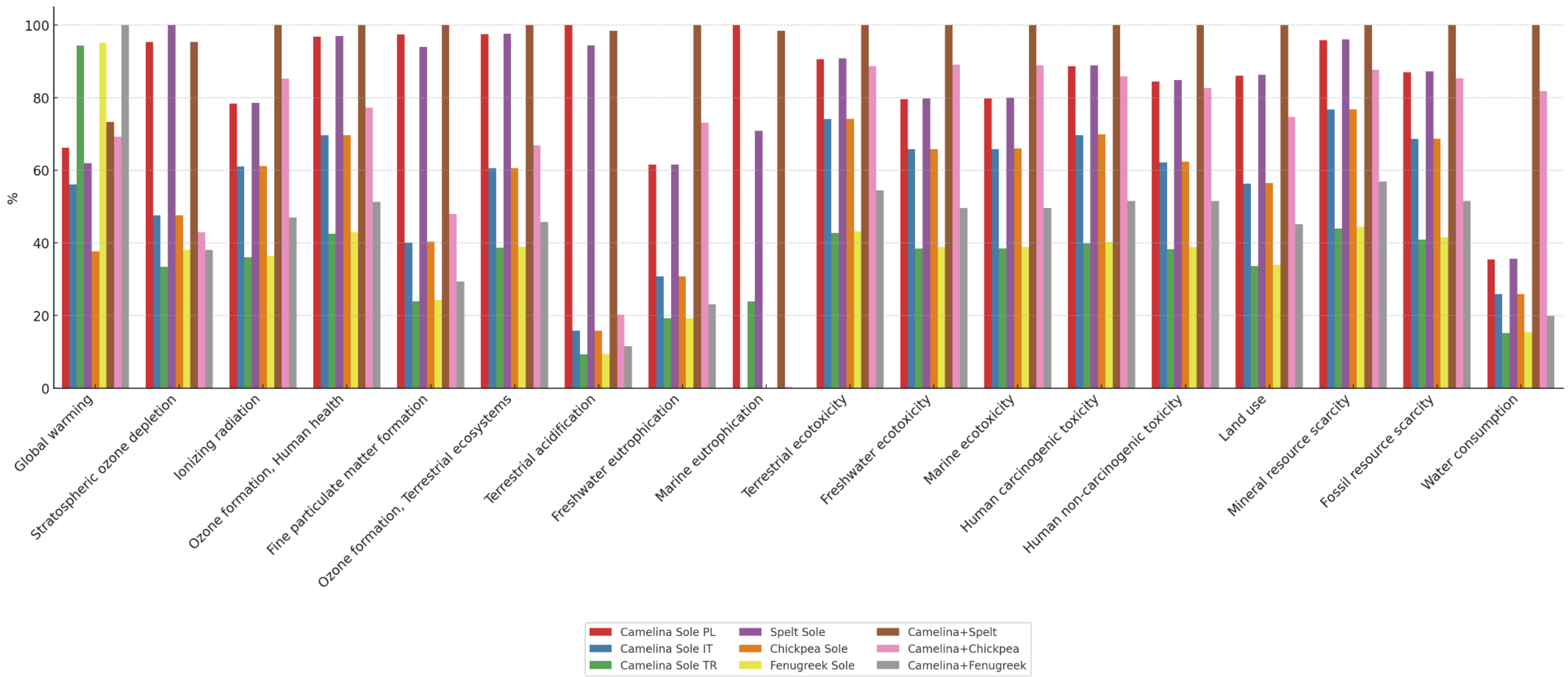

Fig. 2. Characterisation results of the environmental impact of sole cropping and intercropping systems (per 1 hectare) in Poland, Italy and Turkey, based on the midpoint method

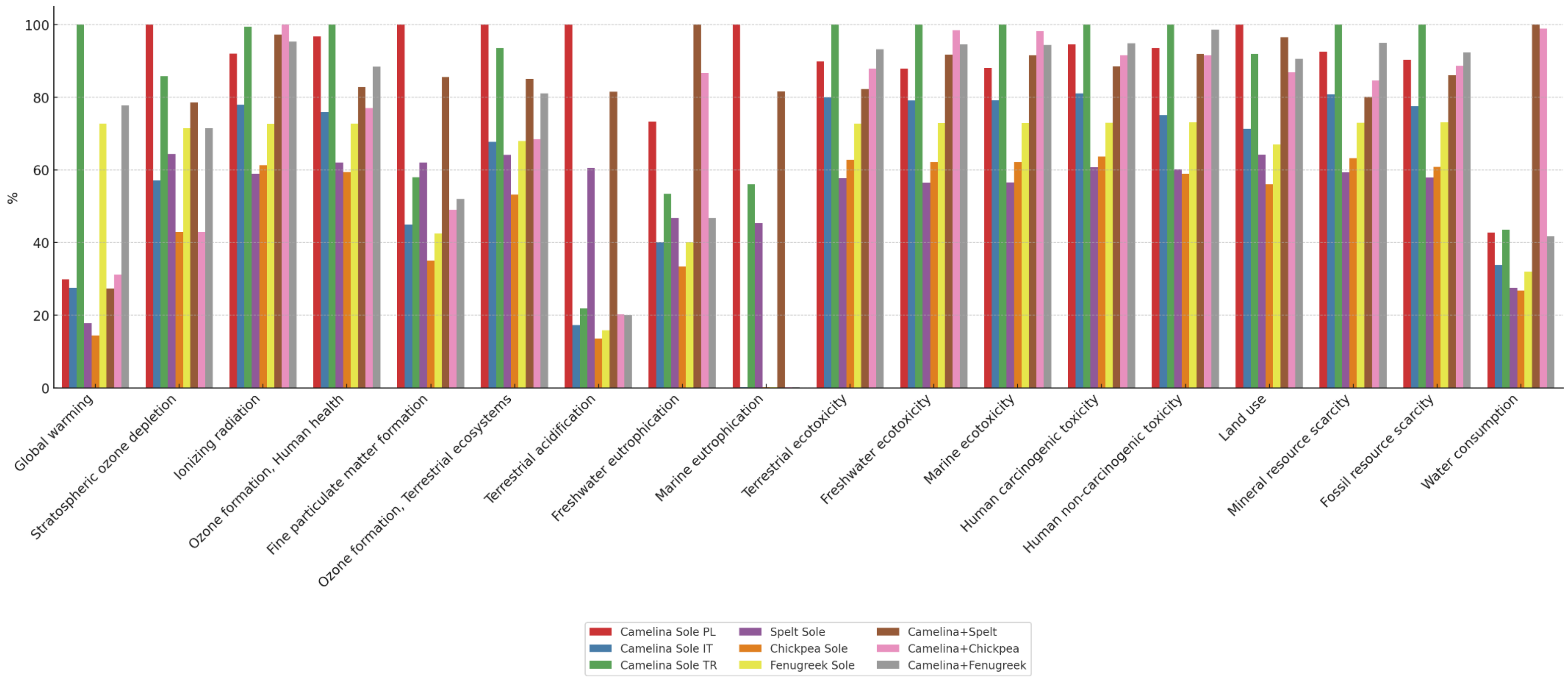

Fig. 3. Characterisation results of the environmental impact of sole cropping and intercropping systems (per 1 tonne of seeds) in Poland, Italy and Turkey, based on the midpoint method

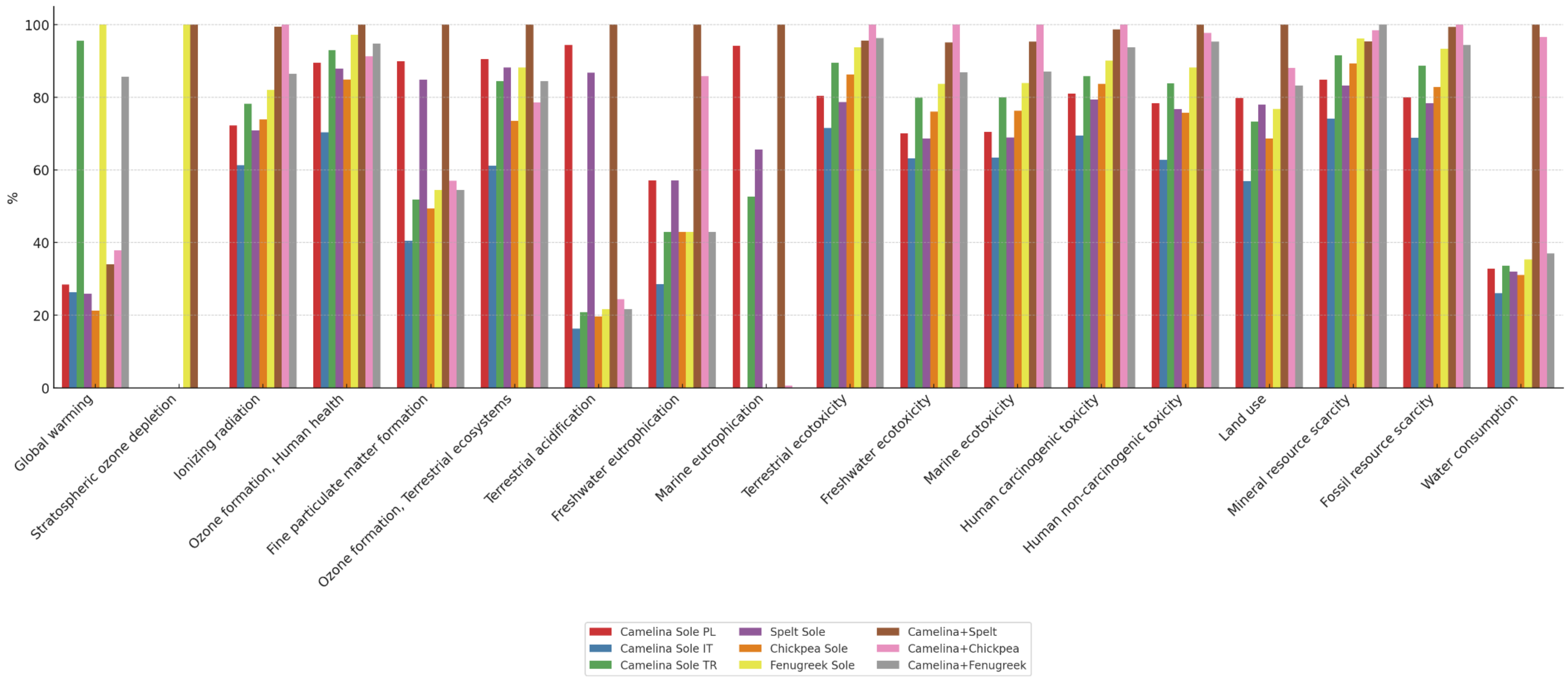

Fig. 4. Characterisation results of the environmental impact of sole cropping and intercropping systems (per 1 GJ of energy in seeds) in Poland, Italy and Turkey, based on the midpoint method

Damage-oriented assessment (endpoint results) shows that the environmental burden associated with all three cropping systems in Poland were higher in all three endpoint categories: human health, ecosystems, and resources while using 1 hectare as the functional unit (Fig 5). The highest impact on human health was recorded for camelina+spelt intercropping (0.00329 DALY/ha), while the lowest was observed for chickpea sole cropping (0.00151 DALY/ ha). In the ecosystem damage category, camelina+spelt intercropping again showed the highest value ($6.99×10^{-6}$ species.yr/ha), with sole chickpea being the lowest ($2.67×10^{-6}$ species.yr/ha). Regarding resource depletion, again camelina+spelt system had the highest damage (66.5 USD/ha), compared to only 30.2 USD/ha for camelina sole cultivation in Türkiye (the lowest value).

When converting to 1 tonne as the functional unit, the highest impact on human health was recorded for camelina sole cultivation in Türkiye (0.00272 DALY/t), while the lowest was associated with sole chickpea sole (0.00088 DALY/t) (Fig. 6). In the ecosystem damage category, camelina sole cultivation in Turkiye again exhibited the highest value ($6.40×10^{-6}$ species.yr/t), followed by camelina+fenugreek intercropping ($5.16×10^{-6}$ species.yr/t). The lowest impact was found for sole chickpea cultivation ($1.56×10^{-6}$ species.yr/t). Regarding resource depletion, sole camelina in Türkiye had the highest damage (48.73 USD/t), while sole spelt showed the lowest (28.15 USD/t) per functional unit.

When considering results per 1 GJ of seed energy content, the highest impact on human health occurred in the sole fenugreek system (0.000101 DALY/GJ), while the lowest was observed for sole camelina in Italy (0.0000454 DALY/GJ). Notably, chickpea and camelina in Italy exhibited favourable values below 0.00008 DALY/GJ.

Fenugreek sole cropping in Türkiye ($1{,}01×10^{-4}$ species·yr/GJ) showed the highest impacts per 1GJ, while chickpea sole (8.52×10-4 species·yr/GJ) again showed the lowest damage. For resource depletion, camelina+fenugreek intercropping (1.84 USD/GJ) and fenugreek sole cropping (1.83 USD/GJ) showed the highest damage, while the lowest damage was associated with camelina sole cultivation in Italy (1.34 USD/GJ).

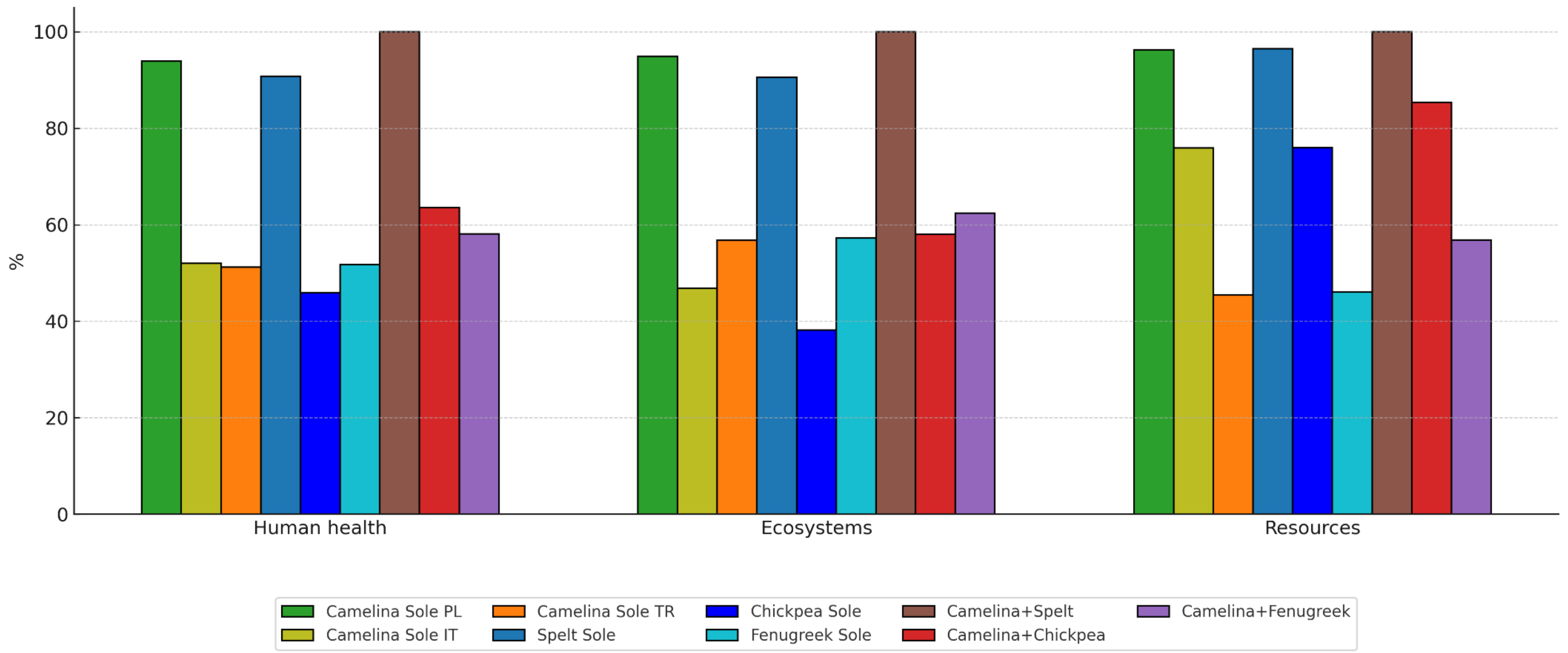

Fig. 5. Characterisation results comparing environmental damage for sole cropping and intercropping systems (per 1 hectare) in Poland, Italy, and Turkey using the endpoint method.

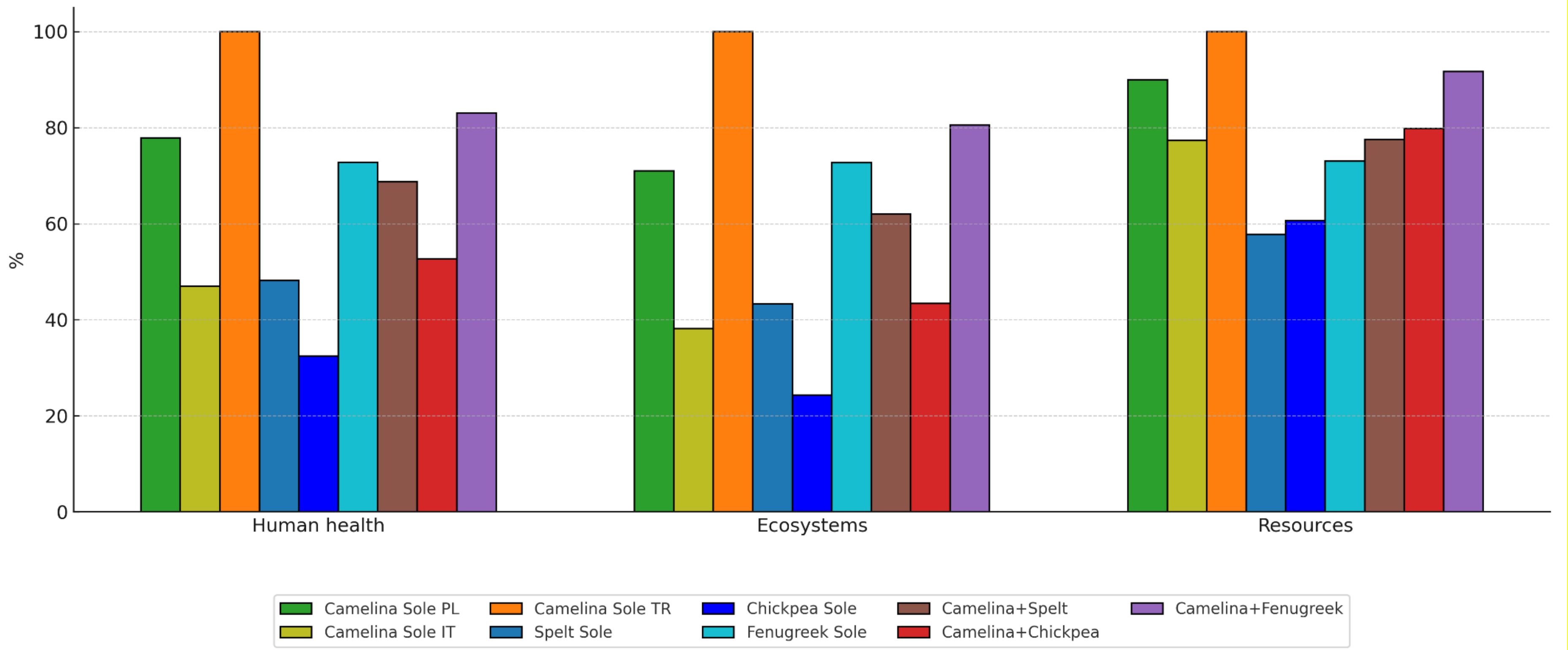

Fig. 6. Characterisation results comparing environmental damage for sole cropping and intercropping systems (per 1 tonne) in Poland, Italy, and Turkey using the endpoint method.

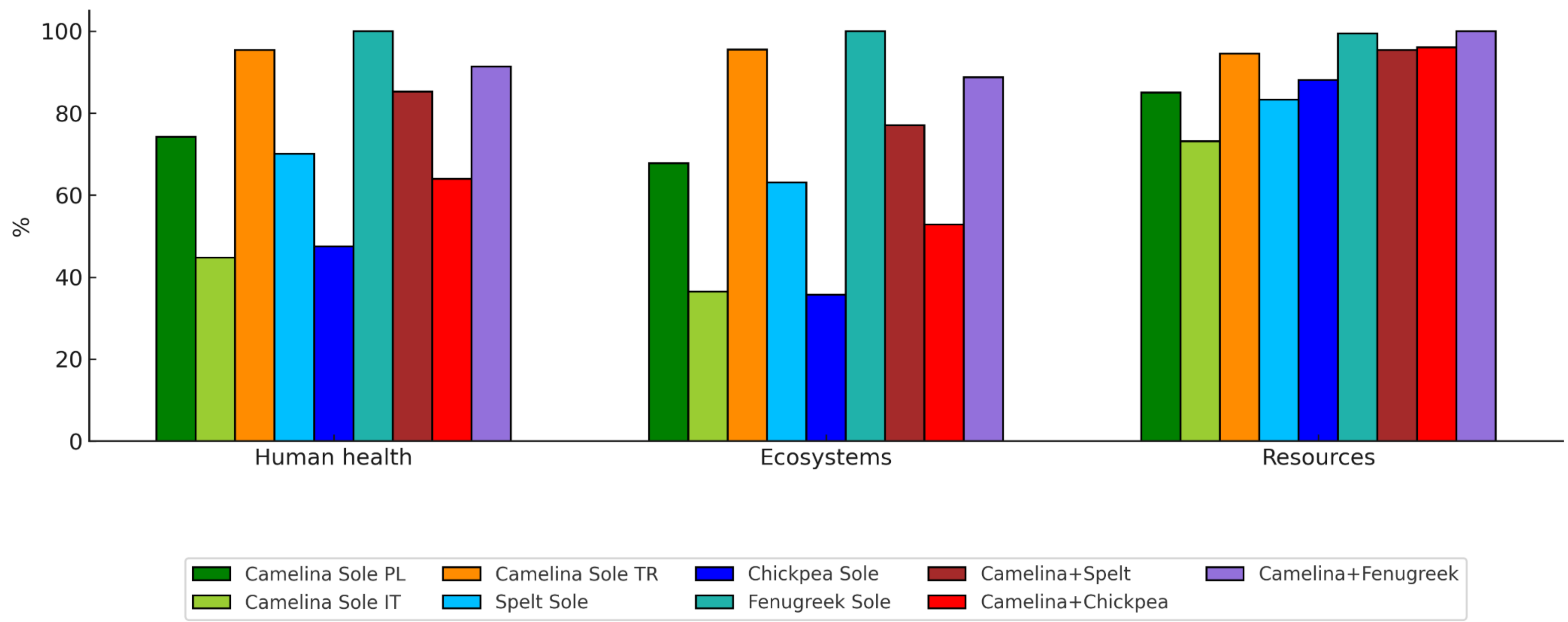

Fig. 7. Characterisation results comparing environmental damage for sole cropping and intercropping systems (per 1 GJ) in Poland, Italy, and Turkey using the endpoint method.

4. Discussion and conclusion

The environmental impact of camelina cultivation, companion crops, and intercropping systems varied considerably depending on the plant species, but above all on the applied production inputs and the resulting yields. In general, cropping systems in Poland involved more intensive management and higher input levels, which translated into high environmental impact and damage, especially when expressed per 1 hectare. However, in Turkey, despite lower input levels, low yields and due to reduced carbon sequestration—mainly due to straw removal for feed—led to the highest greenhouse gas emissions across all systems. In contrast, in Italy and Poland, straw was retained in the field and incorporated as organic fertiliser, contributing to higher carbon sequestration. Nevertheless, this comparison is not entirely straightforward. It must be noted that both straw incorporation and its removal for animal feed have downstream effects. Applying a system expansion approach in LCA, where the environmental impact of producing equivalent fertiliser or fodder are included, could provide a more accurate picture of emissions and system impacts.

When the results were recalculated per 1 tonne of harvested seeds, the differences in environmental impact between cropping systems and countries shifted. Polish cropping systems, despite their high inputs, often ranked more favourably due to relatively high yields. For example, the global warming potential (GWP) of camelina sole cropping in Turkey, which had low yield and low carbon sequestration, reached the highest value, compared to chickpea sole and spelt sole cultivation. Intercropping systems such as camelina+spelt and camelina+chickpea had intermediate emissions, while camelina+fenugreek remained among the most emission-intensive systems, largely due to low yield and low carbon sequestration. Similar patterns were observed in other categories. For instance, terrestrial ecotoxicity remained highest for camelina sole cropping in Turkey, while lowest values were found for chickpea and spelt sole cropping. Water consumption generally increased in intercropping systems, but marine eutrophication remained low for all systems due to no input of phosphorus or nitrogen fertilisers (except manure use in Poland).

When the functional unit was further converted to 1 GJ of energy content in the seeds, the results again shifted, now placing greater weight on the energy density of different seeds and seed mixtures. Here, sole chickpea achieved the lowest GWP, while fenugreek sole cropping had the highest. Among intercropping systems, camelina+spelt performed best (despite the highest inputs used), and camelina+fenugreek the worst (despite low input but also due to low energy yield).

Endpoint indicators largely confirmed the trends observed in midpoint categories: systems with lower yields, especially in Turkey, tended to have higher environmental burdens per tonne and per GJ, despite lower input levels. Per hectare, camelina+spelt intercropping showed the highest damage in all categories, but when converted to yield or energy, cultivation sytems in Türkiye had the highest damage. Chickpea sole cropping consistently remained the most favourable system across functional units. Italian systems, particularly camelina sole, were the most efficient per GJ, aligning with midpoint results.

In conclusion, the choice of functional unit strongly influences the interpretation of environmental impact results. While higher input systems in Poland appeared least favorable per hectare, their performance improved markedly when adjusted to yield- or energy-based units. Conversely, low-input systems in Turkey, which initially seemed environmentally benign, emerged as less efficient when seed and energy yields were considered. Moreover, a drawback that could be improved is the limited amount of data collected in these systems for LCA purposes. Therefore, it is worth continuing similar studies on camelina intercropping to enable more accurate analyses and reduce uncertainty in the results.

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