The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-024-02295-w

LCA FOR AGRICULTURE

Environmental performance of an autonomous laser weeding robot—a case study

Janusz Krupanek[1] · Pablo Gonzales de Santos[2] · Luis Emmi[2] · Merve Wollweber[3] · Hendrik Sandmann[3] · Karsten Scholle[4] · Duc Di Minh Tran[5] · Joachim Jietse Schouteten[5] · Christian Andreasen[6]

Received: 26 November 2023 / Accepted: 29 February 2024

Abstract

Purpose Challenges in sustainable development envisioned in the European Union for the agricultural sector require innovation to raise the efficiency of production and safety of farming processes for farmers and ensure food safety for consumers. One of the key productivity factors in plant production is effective weeding. The WeLASER project aimed to develop a high-power autonomous vehicle with lasers to control weeds. To be sustainable, the invention should have a high environmental performance in the whole life cycle perspective, including its production, use in agriculture, and end-of-life phase. In the publication, a life cycle assessment (LCA) of the WeLASER weeding robot is presented. The aim was to identify weak and strong aspects of the invention in environmental terms and provide suggestions for its improvement.
Methods The machinery was characterized based on technical data provided by the developers, relevant literature, Ecoinvent 3.8 database, and own calculations. The quantitative assessment of environmental impacts was performed using the Simapro tool. For interpretation Recipe 2016 method (egalitarian perspective) was applied.
Results The results show that the energy issue related to autonomous laser-based weeding machine operations is the most challenging. It is related to impacts on climate change indicators and fossil fuel depletion. Production phase is characterized with impacts on human toxicity and is related to extensive application of electronic and electric components in the robot.
Conclusion In comparison with other weeding techniques, the high-power autonomous vehicle with lasers to control weeds shows potential for environmentally efficient use of the machinery in practice. Achieving high performance in the life cycle perspective requires improvements in the design, operational features, and smart application in agricultural practice enhanced through expertise, guidance, and advice.

Keywords Farm robot · Laser weeding · Life cycle assessment · Non-chemical weed control · Precision agriculture

Communicated by Matthias Finkbeiner.

✉ Christian Andreasen
can@plen.ku.dk

1 Instytut Ekologii Terenów Uprzemysłowionych, Kossutha 6 St, 40-844 Katowice, PL, Poland

2 Centre for Automation and Robotics (UPM-CSIC), 28500 Arganda del Rey, Madrid, Spain

3 Laser Zentrum Hannover E.V. Hollerithallee 8, D-30419 Hannover, Germany

4 Futonics Laser GmbH, Albert-Einstein-Straße 3, 37191 Katlenburg-Lindau, Germany

5 Department of Agricultural Economics, Ghent University, 653 Coupure Links, 9000 Ghent, Belgium

6 Department of Plant and Environmental Sciences, University of Copenhagen, Højbakkegård Allé 13, 2630 Taastrup, Denmark

1 Introduction

From a European Union (EU) perspective, the agricultural sector poses social, economic, and environmental challenges. One of the key aspects is the widespread use of herbicides, which can have an unintentionally negative impact on living organisms and the environment (Rani et al. 2021; Silva et al. 2019). Therefore, strict regulations for pesticide application are implemented by the EU to reduce side effects of their use (Bonanno et al. 2017; Kudsk and Mathiassen 2020).

New ambitious goals for the sustainable use of pesticides are set in the *Farm to Fork Strategy*—one of the central pillars of the *European Green Deal.* One of the ambitions set by the European Commission is that by 2030, the use and risk of chemicals and more hazardous pesticides in the EU should be reduced by 50% (Silva et al. 2022). The EU has

Published online: 08 April 2024

implemented a set of policy instruments to achieve this goal, where the Common Agricultural Policy (CAP) plays a significant role.

The CAP supports the sustainable use of pesticides in agriculture. It aims to help farmers protect their crops from pests and maintain high yields while protecting the agricultural ecosystems. The CAP promotes sustainable agricultural systems in the EU, enabling farmers to (1) provide safe, healthy, and sustainably produced food for society; (2) earn a stable and fair income, considering the full range of public goods they provide; and (3) protect natural resources, enhance biodiversity, and contribute to the fight against climate change (Moschitz et al. 2021).

According to the European Commission, precision farming is a promising opportunity for safe crop production. It can help increase crop yields and animal husbandry performance, reduce costs, and optimize the use of material inputs (Balafoutis et al. 2017). Precision agriculture can also help with the problem of manual labor shortage for weeding operations.

In Europe, precision agriculture (PA) and the integration of digital technology are expected to become the most influential trends in the sector as a growing number of farmers start to adopt digital technologies (Degieter et al. 2023). Precision agriculture is gaining ground in Europe, with some solutions widely used in European countries (Daheim et al. 2019). It is already used in weeding processes, enhancing efficiency and reducing negative impacts of pesticide application. Besides the mechanical and precise chemical weeding, new weed control solutions based on lasers are already commercialized or under development (Degieter et al. 2023). This solution offers vast opportunities for improvement in further technological development in terms of laser types, energy sources, design, configuration, and practical application. Innovative weeding solutions are being researched under the European Union Research and Technical Development (RTD) programs to boost the development and implementation of the techniques. One is the project “Sustainable Weed Management in Agriculture with Laser-based Autonomous Tools” (acronym: WeLASER), funded by the EU Horizon 2020 Program. The project aims to develop and test an autonomous laser-based weeding machine.

Although precision agricultural techniques can contribute to reducing pesticide use, they may pose new problems for societies related to energy demand, impact on critical materials (e.g., rare metals) availability, and waste management challenges in post-service life. The environmental impact assessment of the processes related to agricultural production is essential in the farming transformation towards sustainability (Notarnicola et al. 2017; Lee et al. 2012). Several works focus on innovative machinery used in plant production. A few studies focused on the environmental performance of innovative tractors. An electric tractor prototype was compared with the conventional tractor, highlighting its advantages and disadvantages (Lagnelöv et al. 2021). The study performed by Lee et al. (2012) focused on the minimizing of the environmental impact introduced by agricultural machinery during their use. The greenhouse gases and the atmospheric pollutant emissions introduced annually by the farm machinery for rice production were estimated. Finally, a model oriented to identifying the optimal combination of agricultural machinery that minimizes the environmental impact of their use on the field was presented and applied to a case study. Mousazadeh et al. (2011) introduced a solar hybrid electric tractor and analyzed its life cycle, economic cost, and environmental profile. The electric tractor prototype was compared with the conventional tractor, highlighting its advantages and disadvantages. Moreover, new innovative implements were assessed such as balers (Bortolini et al. 2014).

The WeLASER weeder is an autonomous mobile robot using high-power laser to eliminate weeds. It is a complex solution using autonomous systems, artificial intelligence (AI), and advanced geo-positioning (Emmi et al. 2023). The invention is developed, integrated, and tested in the project “Sustainable Weed Management in Agriculture with Laser-based Autonomous Tools—WeLASER” (https://welaser-project.eu/).

It comprises a mobile autonomous platform, a high-power laser weeding unit, and supportive components. In the WeLASER project, a weeding system with two lasers was tested to achieve the Technology Readiness Level 7 (TRL 7). To be commercialized, the product must attain Technology Readiness Level 9 (TRL 9). The commercialization product will be equipped with four high-power lasers. The WeLASER weeder has four baseline components: 1. autonomous mobile platform, 2. a weed meristem perception system, 3. a smart central controller, and 4. a laser-based weeding tool with a high-power laser source and a meristem targeting system. An overview of the WeLASER weeding system structure and functionality is presented in Fig. 1.

The aim of the WeLASER invention is to eliminate weeds in a variety of crop production systems (Andreasen et al. 2022). The key functional parameters are presented in Table 1.

Although WeLASER weeder is an invention focused on efficient and chemical-free weeding, apart from the obvious benefits, a prospective analysis of the environmental performance from the life cycle perspective can provide insight into the main factors determining its environmental performance in practice (van der Giesen et al. 2020). From the perspective of engineers, producers, and users, it is crucial to identify and assess environmental pros and cons, and to identify the most impactful components and appropriately improve the design of the commercialized product. Therefore, the life cycle phases, the production phase, the use phase, and the post-service phase, including the machinery dismantling and utilization of the wastes, must be addressed.

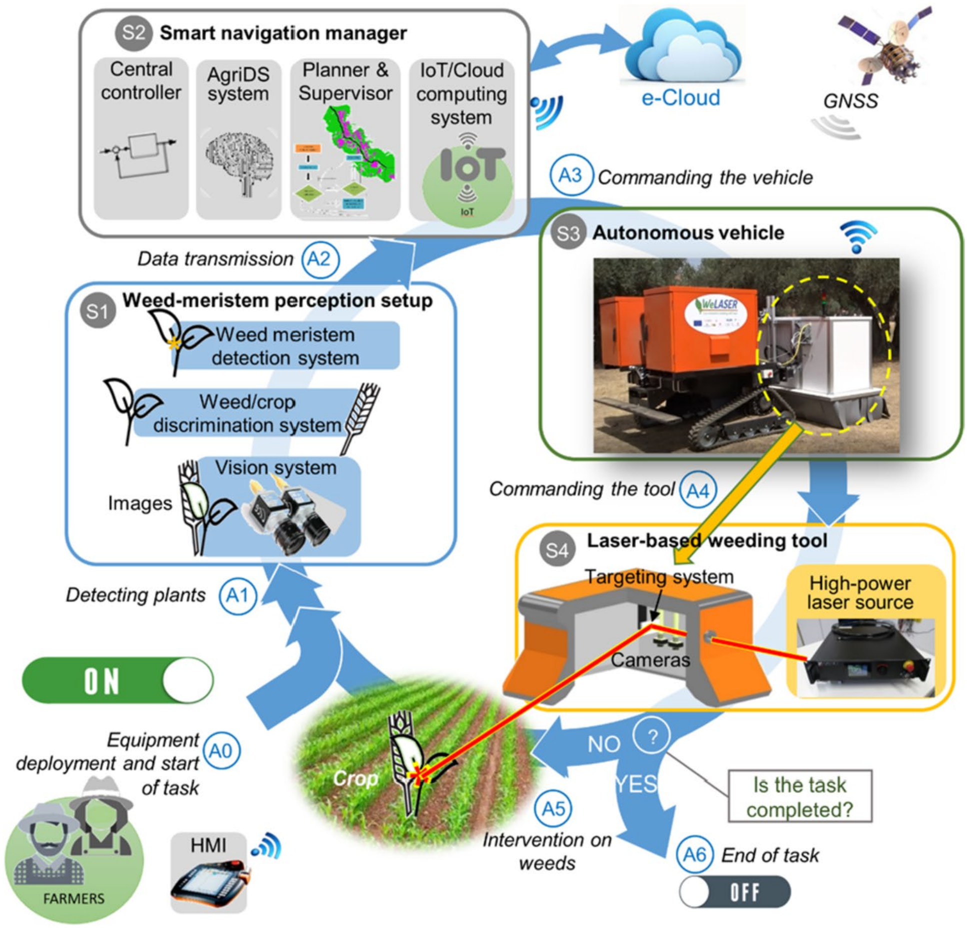


Fig. 1 Overview of the WeLASER technology (Emmi et al. 2023)

Moreover, comparison with other techniques related to weeding can provide an essential argument for developing and optimizing environmentally friendly weeding strategies with the application of WeLASER weeder.

To assess the environmental performance of the WeLASER technique, the analysis of the impacts in its full life cycle was carried out. In the life cycle assessment (LCA) study, the results of an autonomous vehicle with two lasers were extrapolated to a version with four lasers, which is intended as the final commercial product. The flexibility of the design to meet the end-users' requirements was considered. The WeLASER technique was also compared with other weed control methods, including chemical weeding and mechanical means, to understand the opportunities in practical applications. It should be noted that the qualitative benefits such as the lower impact on soil, no contamination of the produce, better occupational health conditions for the farmers, safety of operations, and opportunities for replacement of labor in weeding are important in undertaking decisions regarding enhancement of sustainability of agricultural production. Ecological aspects considered in the study of the laser-based weeding system are important also from social and economic perspectives including improvement of health conditions for farmers and improved quality of food for consumers. Dismantling and disposal of the machinery and its components can intensify the burdens related to waste processing. These aspects are not studied in details but the results of the study provide an indication of potential benefits and risks related to a wide use of the laser-based weed control systems. The economic aspects are not discussed because the price of the autonomous laser weeding

Table 1 WeLASER key functional parameters

Parameter	Value
Total weight	1714 kg
Effectiveness of weeding process	65 – 90%[1]
Weeding machinery speed	~2 km/h
Weeding performance (intended)	9.6 ha/day
Operational width	2 m
Accuracy of positioning	±3 mm
Interspacing of rows	> 25 cm
Speed of weeding process (maximum)	~2 km/h

[1] The weeding efficiency in practice will depend on many factors and the presented range has a tentative character

robot will depend on the number of units produced, and it is too early to predict the market for such machines. Social and economic aspects of the invention have been discussed by Tran et al. (2023).

2 Materials and methods

The environmental assessment of the WeLASER innovative weed control technique was performed using the life cycle assessment method according to ISO 14040:2009 (2021) standard published by the International Organization for Standardization. According to ISO 14040:2009 (2021), LCA is an effective tool designed to assess existing products, technologies, and services, and to identify the weakest and strongest points in the whole life cycle from the environmental perspective (Thonemann et al. 2020). The primary LCA objective is to consider all direct and indirect aspects that could affect the environment and are associated with a product or a service. The analysis was performed using the SimaPro 8 software which is widely recognized LCA tool (Su et al. 2020).

2.1 Goal and scope of the analysis

In this study a preliminary assessment of a prospective commercial product that can be applied in future weeding practices was carried out. The main goal of the study was to assess the environmental performance of the WeLASER weeding technique and specifically (1) to identify key environmental benefits and impacts which can be stimulators or barriers to its wide implementation in crop production, (2) to identify the relevance of particular components for environmental performance in a life cycle perspective, and (3) to compare the environmental performance of WeLASER weeder with other weeding techniques. Based on the results, indications of its key advantages and disadvantages are provided and recommendations for improving the invention's sustainability. The results are meant to guide the developers and prospective producers in the second phase of commercialization, which can help improve the weeding tool's environmental performance and help farmers optimize its use.

To fulfil the goal, the default/Allocation at the Point of Substitution (APOS) system model was used to describe how datasets representing materials and processes related to particular life phases of the weeder are linked to form product systems in the Ecoinvent 3 database. It follows the attributional approach in which environmental burdens are attributed proportionally to specific processes. In the model, the responsibility over wastes (burdens) is shared between producers and subsequent users benefiting from the treatment processes by using valuable products generated in these processes. The APOS model expands the allocation system to include all treatment processes required for any byproducts whether they are waste or recyclables. The model is suitable for studies where the question of waste disposal methods is important (Wernet et al. 2016). This method was selected in the study as one of the issues considered was the disposal of the advanced technique, including the opportunities for prolonging the lifetime of its or its components' reuse and facilitating design for efficient recycling of the materials.

2.2 System boundary definition

The LCA system boundaries separate the system of WeLASER weeder from the general environment. In this study, the assessment was performed in the first place as a cradle-to-grave analysis. The analysis includes the following phases: 1. the production of WeLASER components and the WeLASER integrated robot; 2. its application in weed control; and 3. the post-service dismantling of the WeLASER machinery and treatment of waste. The system boundary is presented in Fig. 2. To have a better insight of the production and use phase, a cradle to gate analysis was performed for these phases.

2.3 Functional unit

The functional unit in LCA assessment enables different scenarios of the life cycle of the weeder to be treated as a functionally equivalent to permit direct comparison between various WeLASER technological variants and other agricultural techniques related to weed control. The functional unit considered for the WeLASER technique in this study corresponds to its basic weeding function. It is defined as 1 ha of field treated in one passage regardless of crop type and cultivation. The laser system can, in principle, be implemented in all crop types, but it requires the development of a recognition tool that can distinguish between the crop and the weeds. The WeLASER project only developed such a tool for sugar beets and maize.

This simplified approach was considered because of the lack of data on the weeding system performance in practical, specific operational settings. For that reason, it allows only for an indicative assessment of environmental performance of the invention and comparison with other techniques related to weeding.

2.4 Life cycle inventory

In the WeLASER project, a prototype machine with a limited operational capacity (half of the intended capacity) was developed, integrated, and tested. To perform a prospective assessment of the envisioned final design, a generalized model of WeLASER weeder was prepared according to the specifications provided by the technical designers and literature data on the agricultural machinery

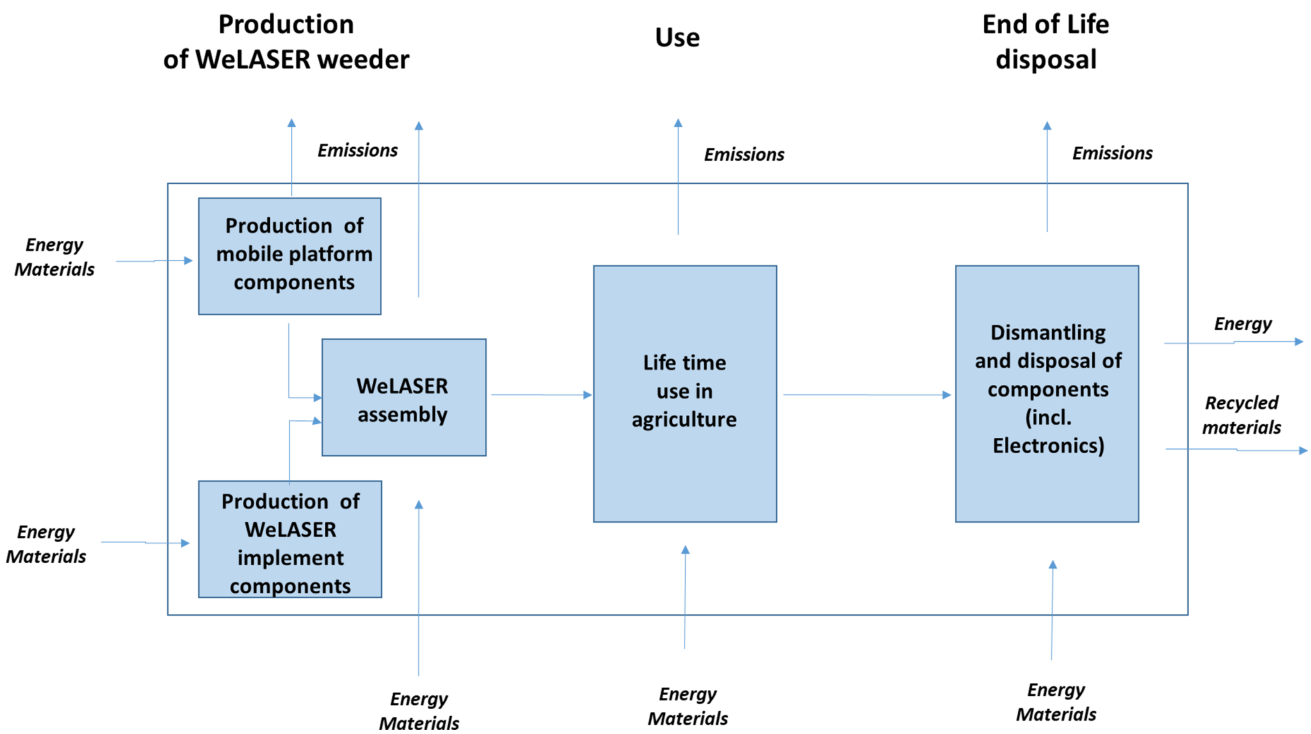


Fig. 2 Overview of the system boundary of LCA of WeLASER weed control technique

and its components. The WeLASER technique was characterized by its performance and construction features (Table 2) of the following subsystems:

- Autonomous mobile platform
- Weeding implement consisting of three subsystems:
  - A laser-based weeding tool including two key components:
    - High-power laser source
    - Laser targeting unit
  - Meristem perception set-up
  - Smart central controller

In the first step, the functionality of the WeLASER technique was profiled based on information, provided by the

Table 2 General overview of the WeLASER weeder key systems—WeLASER pilot data extrapolated for the commercial four-laser system based on the testing design

Component	Description	Weight (kg)
Autonomous WeLASER weeder		**1714**
Mobile autonomous platform integrated with the laser weeding implement		
Autonomous mobile platform		**980**
Power train, drivetrain	Diesel-electric system: diesel engine, electric generator, batteries, electric engines, gear system, electric components, wheels, and caterpillar	202
Body structure	Chassis, frame, suspension, and auxiliary systems	778
High power laser system implement		**734**
Weed-meristem perception	Front Stereo Camera and artificial lighting, recognition RGB cameras, and image recognition computers	30
High-power laser source	High power laser system, DC/DC converters, chillers, collimators	359
Laser targeting system	Enclosure with safety curtains, 4 units of linear axis, scanner heads, visual processing units, and controllers	300
Central controller	Central controller and additional safety components	45

developers on key parameters, such as working speed, working width, service lifetime, energy use, and weeding capabilities. In the next step, the main components of the mobile platform and the laser weeding implement were characterized by material composition and production processes using information received from developers on component type, weight, and basic characteristics related to the two-laser system. In the next step, the four-laser system model was characterized using engineering knowledge, market data, literature on analogous inventions and components, and the Ecoinvent v3.8 database. Scalable life cycle inventories (LCIs) were used for some components including thermal and electric engines. The characterization covered production, use performance, and post-usage phases. It must be noted that the mobile platform designed in the project is basically used for testing, and other design schemes can also be envisioned in the future. Ecoinvent v3.8 data on agricultural processes related to weeding were applied to compare WeLASER weeder performance with other techniques.

It was assumed that the potential WeLASER weeder production is mainly realized in a European context (electricity and waste management processes). Transport of the components during the production phase within Europe, the final delivery to the consumer, and its disposal were not considered. The potential differences in soil types and climate conditions during operations in the field were also not considered. In the baseline scenario of the WeLASER weeder application, the key following assumptions were made:

- Average weed density to be removed in the field is 60 weeds per m^2 at the 2–4 leaf stage of weeds.
- The four-laser system covers the operational span of 2 m width (3–4 rows of maize, 4 rows of sugar beet, ~15 rows of cereals).
- Average conditions of the field are assumed: flat terrain, good movement conditions, and dry ground.
- The auxiliary process of robot transportation to the fields is included. The WeLASER weeder is owned by a farmer and the distance travel for transportation is 1 km between the field and the farm, assuming that the minimum field area is 1 ha.

2.5 Production phase

Characterization of the weeder production is based on the WeLASER weeder general technical scheme provided by the developers and literature data (Grimstad and From 2017; Hannemann 2016; Nordelöf et al. 2018). For characterization of the autonomous mobile platform, its key components, and materials, there were used data provided by the producer, literature data on analogous machinery, and Ecoinvent v3.8. Due to a lack of specific data characterizing autonomous vehicles, data for tractors and heavy-duty road vehicles were used. It was assumed that data relevant to the study on these vehicles could be scaled, adjusted, and fitted to characterize the autonomous system. Based on Lagnelöv et al. (2021), a universal model for the mobile platform was developed. It covered both the material composition and relevant machinery production processes. Literature data for the identified components were adjusted on a weight or electric and thermal power basis (Table 3). The model of the autonomous platform comprised five components: (1) wheels and caterpillar, (2) platform body structure including chassis and frame, (3) drivetrain and suspension, (4) powertrain, and (5) miscellaneous accessories and systems.

2.6 Laser implements

The key components of the weeding implement were characterized based on specific technical information provided by the developers of the WeLASER weed control robot. Literature data, information on commercially available products, and Ecoinvent v3.8 database (Table 4) were used to characterize material composition and production processes. The proxy data were scaled on a weight or energy basis according to the technical specifications of the WeLASER prototype model. It must be noted that in the testing design, the laser weed control implement is integrated with the mobile platform in two ways:

- On the mobile platform, the key electronic components: high-power laser source, computers, weed recognition subsystem, central control subsystem, and chillers are positioned.
- The weeding implement is mounted on the tow, including the laser scanners, cameras, and laser targeting subsystem.

2.7 Use phase characterization

Because the WeLASER weeder testing was limited during the project period, to characterize the use phase of the machine, an operational model was derived based on a set of parameters relevant to the WeLASER project prototype. The estimation of the parameters was based on the available technical data for robot's component characteristics, lab testing of the components, field demonstration of the prototype testing results, literature, and Ecoinvent v3.8 data. The key parameters of the model are presented in Table 5. These parameters were used to calculate the energy demand and operational time for given conditions. For key performance parameters, the baseline value, and range of values were determined to get an insight into uncertainty of the weeder assessment.

The amount of energy and materials calculated for the intended lifetime was recalculated for 1 hectare of weeded field. The maximum thermal energy generated in the diesel

Table 3 Characteristics of the modeled key mobile platform components

Key component	Elements	Material/utility	Weight		Hypothesis on component characterization	Source
Wheels and caterpillar	• Rim wheels, caterpillar	Rim wheels—steel	3 kg	108 kg	Characterization based on data on analogous components and literature	(Lagnelöv et al. 2021)
		Caterpillar—rubber	35 kg			
	• Structural elements	Steel components	70 kg		Ecoinvent v3.8 processes for steel components	
Platform body structure	• Chassis, frame, and suspension	Steel	490 kg	527 kg	Allocation according to project data and literature, Ecoinvent v3.8 processes used for steel, rubber, and proxy data for High Impact Polystyrene	(Lagnelöv et al. 2021)
		Plastic	15 kg			
		Rubber	22 kg			
Drivetrain	• Wheel electric motors (2 units)	Electric utility	25 kg	50 kg	Project data on motor type and weight, inventory based on literature, adjusted on a weight basis	(Grimstad 2014; Lagnelöv et al. 2021)
	• Gear and transmission	Electric/mechanical utility	25 kg		Adjusted proxy data on truck components mechanical part—steel, and servomotor (electric utility) 3 kg	(Wolff et al 2020)
Powertrain Diesel-electric system	• Diesel engine 20 kW	Thermal engine	80 kg	177 kg	Proxy data for truck diesel engine adjusted on thermal power basis	Engine producer's specification (Wolff et al. 2020)
	• Electric generator 15 kW	Electric utility	21 kg		Own estimation based on data on electric engine and alternator, scaled on a weight basis	Electric engine (Nordelöf et al. 2016), alternator (Schau et al. 2011)
	• Batteries	Li-ion	15 kg		Ecoinvent v3.8 processes for Li-ion and NaCl batteries	Project data
		NaCl	12.5 10 kg			
	• Structural and mechanical components	Steel elements including tank 50 l	51 kg		Material allocation based on literature, Ecoinvent v3.8 processes for steel components	(Marinescu et al. 2012)
Miscellaneous accessories and systems	• Structural elements three-point hitch, beams, bumpers	Steel	46 kg	118 kg	Own estimation, Ecoinvent v3.8 processes for steel components	Project data
	• Smart navigation manager	Electronics: lidar, sensors	1.2 kg		Literature data adjusted (active—0.6 kg, passive – 0.6 kg components)	(Lagnelöv et al. 2021)
		Control and processing unit	2 kg		Ecoinvent v3.8 process for industrial control unit and mounted wiring board	Project data
		Cameras (2 units)	0.6 kg		Proxy data for general purpose electronic camera	(Hillerström and Troborg 2010)
		Steel structure	4 kg		Ecoinvent v3.8 processes for steel components	Project data
		Cables and plugs	2.2 kg		Ecoinvent v3.8 processes applied for data cables and plugs	Project data
	• Electric system	Electric relays	5 kg		Proxy EcoInvent v3.8 data for industrial control unit	Project data

Table 3 (continued)

Key component	Elements	Material/utility	Weight	Hypothesis on component characterization	Source
		Structural elements steel	6 kg	Own estimation, Ecoinvent v3.8 processes for steel components	Project data
		Cables and plugs	26 kg	Scaled truck components inventory, Ecoinvent v3.8 processes for electric cables (21 kg of copper) and plugs	(Nordelöf et al. 2014)
	• Electric jack	Electric utility	15 kg	Scaled and adjusted electric motor inventory	(Nordelöf et al. 2016), product specification
		Steel	10 kg	Ecoinvent v3.8 processes for steel components	
Total weight			**980**		

Table 4 Characterization of WeLASER weeding implement

Subsystem	Element	Material/utility	Weight		Characterization	Source
Weed meristem perception	• Enclosure and supporting structure	Steel	15.3 kg	30.2 kg	Ecoinvent v3.8 processes for non-alloyed steel and aluminum components	Commercial product specifications
		Aluminum	5.5 kg			
	• Image recognition computer	Electronic component	4 units, 1.58 kg each, 6.3 kg in total		Proxy Ecoinvent v3.8 process for laptop, modified (monitor, HDD and power supply unit excluded) and scaled on weight basis	Project data
		Data and network cables	1 kg		Ecoinvent v3.8 process for data and network cables	Project data
	• Recognition cameras stereo RGB	Electronic component	4 units, 0.15 kg each, 0.6 kg in total		Proxy data for general purpose electronic camera	(Hillerström and Troborg 2010)
	• Front camera stereo RGB	Electronic component	0.3 kg			

Table 4 (continued)

Subsystem	Element	Material/utility	Weight		Characterization	Source
	• Artificial lighting	Lighting utility	10 units, 0.12 kg, 1.2 kg in total		Literature data on lighting adapted and Ecoinvent v3.8 data	(Casamayor et al. 2018)
Laser targeting	• Laser scanners	Control units	3.6 kg (4 units)	85.2 kg	Estimation, proxy Ecoinvent v3.8 process for control unit electronics	Electronics' specifications
		Graphics data processing unit	6.6 kg (4 units)		Ecoinvent v3.8 process for PC computer, modified (HDD and power unit excluded, wiring board and integrated circuit included)	Commercial product' specification
		Scanner head	21.8 (4 units)		Own characterization of scanner head including servomotors and optics	Producers' technical information
		Optic system—aluminum, glass, graphite	10.6 kg (4 units)		Own characterization based on analogous components	Producer' technical information
		Cables and plugs, switches, jacks, connectors	10 kg (4 units)		Ecoinvent v3.8 data on cables, connectors and plugs (5.5 kg), switches and jacks (4.5 kg)	Project data
		Enclosure (aluminum) and ventilator	11 kg (4 units)		Ecoinvent v3.8 processes for aluminum product, ventilators 0.8 kg	Project data, example of ventilator EPD for commercial product
	• Linear axis	Aluminum runner and axis	10 kg (4 units)		Own estimation, Ecoinvent v3.8 processes for aluminum components	Commercial products' data
		Servomotor and electric gear utilities	8 kg (4 units)		Own characterization of electric utilities based on products' technical characteristics	
		Caterpillar neoprene, aluminum	3.6 kg (4 units)		Estimated, Ecoinvent v3.8 processes for aluminum (0.9 kg) components and rubber (2.7 kg)	Commercial products' data
Enclosure with safety curtains	• Structural elements	Aluminum frame	40 kg	215 kg	Estimation based on products' technical characteristics, Ecoinvent v3.8 processes for aluminum, steel, and rubber components	Commercial products' data
		Steel plates	170 kg			
		Double safety flaps (rubber)	5 kg			

Table 4 (continued)

Subsystem	Element	Material/utility	Weight		Characterization	Source
Control Management	• Central controller	Controller including communications, sensors, and ventilation	15 kg	45 kg	Proxy Ecoinvent v3.8 data for industrial controller electronics for communication Wifi/5 g router (0.23 kg), sensors (0.6 kg), ventilation (0.3 kg)	Commercial products'specification (Lagnelöv et al. 2021)
	• Enclosure	Steel structure	5.4 kg		Estimated, based on rack' technical description	Project data, commercial product' data
		Aluminum	1.6 kg			
	• Fibers and cables	Electric, data, and network cables	18 kg in total		Ecoinvent v3.8 process for coated copper cables, data, and network cables	
						Project data
	• Additional safety components	Safety controller	5 kg		Proxy Ecoinvent v3.8 process for industrial controller electronics	
					Own characterization on ventilation, power system and enclosure based on products' technical information	Commercial products' information
High power laser source	• DC/DC converters	Electric/electronic utility	4 units, 5.6 kg each, 22.4 kg in total	359.4 kg	Proxy Ecoinvent v3.8 process for electric car converter	Project data
	• Thulium laser high power sources	Power supply	5.2 kg		Ecoinvent v3.8 process for transformer	Commercial lasers technical information (Fuhrberg et al. 2020)
		Fibers	1 kg		Proxy Ecoinvent v3.8 process for glass fiber	
		6 laser diodes	12 kg		Estimation based on products technical characteristics	
		Control unit, electronics	8 kg		Estimation, proxy Ecoinvent v3.8 processes for industrial control unit and wiring board	
		Cables, fiber connectors, collimators	13 kg		Estimation, Ecoinvent v3.8 processes for network, data and electric cables, collimators (steel, aluminum and glass)	

Table 4 (continued)

Subsystem	Element	Material/utility	Weight	Characterization	Source
		Chassis for electronics	16 kg	Estimation, Ecoinvent v3.8 process for chassis for network unit	
		Steel structure	56 kg	Estimation, Ecoinvent v3.8 processes for steel component	
	• Chillers	Cooling equipment	4 units, 42 kg each, 172 kg in total	Own model based on producers' specifications	(Rossi et al. 2021) and commercial product EPD data
	• Rack cabinets (two units)	Steel structure	39,5 kg	Ecoinvent v3.8 processes for non-alloyed steel and aluminum	Commercial product specification
		Aluminum	14,2 kg		
Implement total			**734.7 kg**		

engine for a given operation was calculated using data on specific fuel consumption, diesel engine power, and time of operation (Eq. 1). The maximum energy that can be produced by the diesel engine, which is available for the robot operations per given area, was determined by the fuel consumption and the diesel oil heat value (Eq. 2).

$$Q_{diesel\ oil} = SFC_{diesel\ engine} * P_{diesel\ engine} * t_{weeding} * {}^{1}/_{D_{diesel\ oil}} \tag{1}$$

$$E_{thermal} = HV_{diesel\ oil} * Q_{diesel\ oil} \tag{2}$$

where:

$E_{\ thermal}$—thermal energy generated by the diesel engine [MJ].

$SFC_{diesel\ engine}$—specific fuel consumption [g kWh^{-1}].

$D_{\ diesel\ oil}$—diesel oil density [kg l^{-1}].

$P_{diesel\ engine}$—diesel engine power [kW].

$t_{weeding}$—time of weeding operation [h].

$HV_{diesel\ oil}$—heat value of diesel oil [MJ l^{-1}].

$Q_{\ diesel\ oil}$—diesel fuel consumption [l].

Available electric energy per ha in the diesel and electric system was calculated according to the following formula (Eq. 3):

$$E_{electric} = E_{thermal} * C_{thermal\ engine} * C_{electric\ generator} \tag{3}$$

where.

$E_{\ thermal}$ —thermal energy generated by the diesel engine [MJ].

$E_{\ electric}$—electric energy generated in the diesel-electric system [MJ].

$C_{\ thermal\ engine}$—thermal efficiency of the diesel engine [%].

$C_{\ electric\ generator}$—efficiency of electricity generation and mechanical losses [%].

Calculation of the electric demand for the high-power laser subsystem was calculated according to Eqs. (4) and (5). For other subsystems, the electric power of a given subsystem (see Table 5) was multiplied by the time of active laser system operation (Eqs. 6 and 7). Standby mode was considered for the laser targeting and high power-laser subsystems as their operation is dependent on actual presence of the weeds. For central control unit and the weed meristem perception, a continuous work was assumed. The sum of the thermal energies required for the subsystems was used to calculate the fuel demand.

$$Ee_{high-power\ laser} = E_{optical} * D_{plants} * 10^{5} * \frac{Pe_{high-power\ laser\ system}}{P_{laser\ optical}} \tag{4}$$

$$Ee_{high-power\ laser\ source} = Ee_{chiller} + Ee_{chiller\ standby\ mode} + Ee_{converter\ standby\ mode} + Ee_{high-power\ laser} \tag{5}$$

Table 5 Key operational parameters of WeLASER weeder application

Parameter	Unit	Value	Range	Source of information/comments
Time of operation of each laser	s	0.04	0.08 – 0.04	WeLASER project[a]
Laser optical power	W	500	250 – 500	WeLASER project
Power of each laser system	kW	3.6	1.8 – 3.6	WeLASER project
Laser optic energy used per weed meristem	J per weed	20	5 – 20	WeLASER lab testing (e.g., Andreasen et al. 2024; Coleman et al. 2021; Heisel et al. 2001)
Electric energy of high-power laser	J per weed	133	66 – 133	WeLASER project
Thermal energy demand for high power laser operations	J per weed	462	229 – 462	Own calculations based on electric-diesel engine efficiency—baseline case
Energy per treated area	J mm^2	63	16 – 63	2 mm beam diameter
Weed meristem perception subsystem power	W	522	-	WeLASER project
Laser targeting subsystem power	W	1104	-	WeLASER project
Central controller power	W	650	-	WeLASER project
Diesel engine power	kW	20	19 – 21	WeLASER project, adjusted value
Specific fuel consumption	g of fuel kWh^{-1}	250	230 – 300	Data for commercial engines for specific working conditions (Zhao et al. 2023; Zhu et al. 2022)
Heat value of diesel oil	MJ l^{-1}	38	35.8 – 38.6	Energy Efficiency & Renewable Energy[b] (Eriksson and Ahlgren 2013)
Diesel oil density	kg l^{-1}	0.85	0.82–0.85	(Schaschke et al. 2013; Kohler engines[c])
Electric generator	kW	15	14 – 16	Project data for specific engine type
Time of operation of the robot	hours $hectare^{-1}$	2,5	1.2 – 5	Depending on the variance of weeds density, their statistical distribution and energy availability
Time of laser operation	hours $hectare^{-1}$	1.7	0.14 – 5	WeLASER project
Time of standby operation	hours $hectare^{-1}$	0.8	0.6 – 1.2	Own calculation based on WeLASER project data
Density of weeds (average)	Weeds m^{-2}	60	5–120 (180)	Literature (Adeux et al. 2019; Borgy et al. 2012; Gerhards et al. 2017; Kulan and Kaya 2023) and WeLASER project data
Number of lasers	number	4	-	WeLASER project
Width of operation	M	2	-	WeLASER project
Robot operational velocity	km h^{-1}	2	1 – 4	WeLASER project
Fuel consumption per ha	l ha^{-1}	14.6	10.7 – 28.3	Own calculations—see below (Woong et al. 2019; Moitzi et al. 2013; Plizga 2021)
Fuel allocated to weeder's traction per ha	l ha^{-1}	5	4 – 7	WeLASER project, literature (Lacour et al. 2014; Parsons 1980; Downs and Hansen 1998; ISU 2001; Lovarelli et al. 2016; Wilfong 2019; Ueka 2013; Mousazadeh et al. 2011)
Fuel allocated to laser implement per ha	l ha^{-1}	9.6	6.7 – 21.3	WeLASER project data and components characterization, values depend on the variance of weeds density, their statistical distribution and energy availability
Thermal efficiency of the diesel engine	%	32	30 – 35	Engine producers' information and literature data (Grisso 2004; Lajunen et al. 2023)

[a]Time correlated with optical power

[b]https://afdc.energy.gov/fuels/properties

[c]https://engines.kohlerenergy.com/en/press-release/2022/february/kohler-engines-approves-use-of-hvo-for-all-its-diesel-engines-in-europe

where.

$Ee_{\text{high power laser source}}$—electric energy required for the high-power source subsystem per ha [MJ ha^{-1}].

$Ee_{\text{high power laser}}$—electric energy required for high-power laser per ha [MJ ha^{-1}].

$Ee_{\text{standby mode}}$—electric energy required for standby mode (CD/CD converter, chiller) [MJ ha^{-1}].

E_{optical}—optical energy of the high-power laser required to kill one meristem [J].

D_{plants}—weed density per square meter [plants m^{-1}].

$Po_{\text{laser optical power}}$—optical power of the laser [W].

$Pe_{\text{high-power laser system}}$—total electric power of the high-power laser subsystem including DC/DC converter [W]

$$Ee_{subsystem} = P_{subsystem} * t_{weeding} * 0.0036 + E_{subsystem\ standby\ mode} \quad (6)$$

$$E_{subsystem\ standby\ mode} = P_{subsystem} * t_{subsystem\ standby\ mode} * C \quad (7)$$

where.

$Pe_{\text{subsystem}}$—electric power of a given subsystem [W].

$Ee_{subsystem}$—electric energy required for a given subsystem [MJ h^{-1}].

$Ee_{subsystem\ standby\ mode}$—electric energy required for a given subsystem in a standby mode [MJ h^{-1}].

C—coefficient of standby mode energy for a given subsystem, fraction of a given subsystem power 0.3 for chillers, 0.1 for DC/DC converter.

t_{weeding}—time of robot weeding operation for a given weed density [h].

$t_{subsystem\ standby\ mode}$—calculated as fraction of total time of robot operations which is not allocated for active lasers operations [h].

The engine efficiency was calculated by the corresponding amount of fuel used per unit of thermal energy produced. The engine power declared by the producer's information was adjusted to balance the overall energy. Maximum diesel consumption for a 20-kW power engine is set as the reference in the baseline scenario. The thermal energy was recalculated into electricity assuming 32% efficiency of the diesel engine (mechanical energy at the crankshaft/chemical energy embedded in diesel oil),[1] and 10% losses were assumed in the electric generator (Cummins 2023; Jamal et al. 2018; Benhammou et al. 2023).

Although the system is supported by batteries, their capabilities are limited, and they are charged by the same generator powered by the diesel engine. They stabilize the electric energy availability for the implement operations. The electric energy produced by the generator is spent on the mobile platform traction and the laser implement operation. The energy for traction is estimated based on project field tests and literature data on energy consumption of particular components of the mobile platform. Because the efficiency of electric motors is generaly high (Nagel 2023), and should be at least 90% according to eco-design rules (EC 2019; Thallapalli et al. 2021), an efficiency of 95% was assumed in the study. The gearbox mechanical losses were considered at the level of 3 – 8% (König et al. 2021).

The electric power distribution is managed flexibly between these two main subsystems. Actual energy consumption depends on many factors related to weeding performance and the conditions of the working environment. In the baseline scenario of a four-laser unit weeder, the thermal energy of 553 MJ ha^{-1} generated in the 20-kW engine is assumed as sufficient to achieve the working parameters: 2 km h^{-1} (working speed), 2 m operational width, and average weed density 60 weeds m^{-2}. The maximum energy required for the high-power laser operation was calculated based on the time of the laser operation corresponding to the power needed to destroy the weed meristem (20 J per weed), number of weeds, and the total power of associated subsystems and components.

In case of the baseline scenario and the variants of weed density, the time of laser operations is only a part of the whole duration calculated for respective robot movement velocities. Thus, in the energy model a partial stand-by mode was considered for the high-power laser subsystem, its supporting components (DC/DC converters and chillers), and laser targeting system. The energy consumption was calculated based on minimum required power of the components and standby time. For the autonomous platform and the weed recognition system, continuous work was assumed for the whole time of operation.

The speed of the robot is determined by the weed density and the energy demand for the operation of the high-power laser source. The maximum speed designed for the mobile platform is 6 km h^{-1}. In the baseline scenario, a fixed velocity of 2 km h^{-1} was assumed within the range of 1 – 4 km h^{-1} corresponding to weed density 5 – 120 weeds m^{-2}. In the high-density (120 plants) scenario, the velocity must be lowered roughly to 1.3 km h^{-1} in order to allow for sufficient energy generation for lasers' operation. In the baseline scenario, the energy requirements for the machine operation roughly meet the maximum energy supply of the thermal engine. Nevertheless, for the baseline architecture of the robot, it might still be possible to work efficiently for higher weed densities in the range of 120 – 200 weeds per m^2 in case the energy needed per weed can be reduced (10 – 15 J per plant). For higher weed densities, an engine of higher power is required. The energy required for traction was assumed at the level of 190 MJ ha^{-1} corresponding to 5 l of diesel oil consumed. It is a conservative value regarding other studies (e.g., 3 – 4 l h^{-1} in mechanical weeding operation (Martinelli et al. 2023)). The thermal energy in the baseline scenario and its variants generated in the system (20-kW diesel engine) distributed between the basic subsystems is presented in Table 6.

Among the features related to robot maintenance, besides fuel, there was considered replacement of lubricating, rubber traction parts, and engine oil (Table 7). In other studies (Lagnelöv et al. 2021), other features were also considered including hydraulic oil and spare parts for which additional 20% of production and energy was

[1] Engine producer's information.

Table 6 Characterization of thermal energy requirements for the main components in weeding operation expressed as MJ ha^{-1} (baseline scenario 60 weeds m^{-2})

Components	Thermal energy required for component operation (MJ ha^{-1})		
	5 plants m^{-2}	60 plants m^{-2}	120 plants m^{-2}
Mobile platform	190[a]	190	190
The laser implement total	58.8	363.6	700.9
Weed-meristem perception	7.8	16.3	21.8
Laser targeting system	1.9	23.0	46.0
Central controller including additional safety components (safety controller and sensors)	12.9	20.3	27.1
High-power laser source including chiller and DC/DC converter	36.2	304	606
Total WeLASER weeder maximum engine power	248.8[b]	553.6[3c]	890.9[4d]

[a] The energy required for the velocity range of the robot traction was assumed at the same level

[b] Time of robot operation 1.2 h, velocity around 4 km h^{-1}

[c] Time of robot operation 2.5 h, velocity 2 km h^{-1}

[d] Time of robot operation 4 h, velocity 1 km h^{-1}

allocated in relation to maintenance. The aspect of maintenance was further considered in the uncertainty analysis. Considering the relative long-life expectancy for the key components of the laser implement in the baseline design, the lifetime for all parts was assumed at the level

Table 7 Key exploitation features of WeLASER weeder

Parameter/process	**WeLASER weeder subsystems**				
	High-power laser source	**Meristem targeting**	**Weed meristem perception**	**Control system**	**Mobile platform**
Expected lifetime	5000 as minimum 25,000 on average–50,000 working hours (project expert information)	10 years for industrial scanners (proxy data[a])	10,000 working hours, industrial computer 5 – 15 years[b] 6 – 10 years for industrial cameras[c]	Industrial computer 5 – 15 years[b]	10,000 (3000 up to 20,000) assumption for agricultural tractors (Muñoz and Lianos 2012; Kowalczyk 2011; Nemecek and Kägi 2007; Pradel et al. 2022; Vahdanjoo et al. 2023) technical and expert information, Ecoinvent v3.8 data
Maintenance	Spare parts (not specified)	Specialized liquids, spare parts, and other materials not specified	Cleaning agents, spare parts not specified	Spare parts not specified	Lubricants 74 kg and rubber parts 55 kg, electric energy 2531 MJ in 10 year lifetime according to (Lagnelöv et al. 2021). Spare parts and hydraulic oil are not included—engine oil calculated based on oil consumption 0.013 l/h (engine' producer data)

[a] https://envysion.com/envysion/security-cameras-life-expectancy/

[b] https://ipc2u.com/articles/knowledge-base/how-is-an-industrial-mainboard-better-than-an-office-one/

[c] https://envysion.com/envysion/security-cameras-life-expectancy/

of 10,000 working hours as a minimum value. The same value characterizes the autonomous mobile platform.

2.8 Disposal phase characterization

The phase of disposal of the machinery was characterized based on material profiles (weight basis) of the mobile platform and the laser implement subsystems broken down into its main components. The content of main metal components and electronic elements was calculated. Specific reuse rates were assumed for key materials and specific transformation processes characterized according to Lagnelöv et al. (2021). The reuse for structural components was assumed at the rate of 100%. For electric components, 85% recovery was assumed for non-ferrous metals. For electronics recycling rates of computers, information from Eygen et al. (2016) was applied and Ecoinvent v3.8 data. The disposal mode of the remaining materials which are not reused is landfilling/incinerating (Table 8). It was assumed that the metals were preprocessed before reuse and were characterized by the average metal working processes for each of the main metals (aluminum, copper, steel) and a general metal working process for remaining metals. For batteries 100% recycling was considered.

2.9 Interpretation of the results

The Endpoint ReCiPe 2016 method with egalitarian perspective version 1.13 was used for the interpretation of the results. This method translates emissions and resource extraction into limited environmental impact scores. These indicator scores express the relative severity of each environmental impact category. The results are expressed in points (Pt) or millipoints (mPt). The point indicator is the total environmental load expressed as a single score. Characterization, damage assessment, normalization, and weighting are combined in the score. The egalitarian perspective is the most precautionary perspective that considers the longest timeframe and impact types that are not yet fully established but for which some indication is available. The reason for its application in the study was that health toxicity is an important impact researched in the study both for the current weeding methods (chemical spraying) and in the production phase of highly advanced precision machinery. A set of critical materials is needed to manufacture advanced robots, and they are predominantly produced outside of Europe under less strict environmental policy conditions. Moreover, in both cases the environmental burdens can be viewed as long standing, due to contamination of the environment (soil, sediments, biota). On the other hand, the continuous European Union policies implement stricter rules for chemicals use, but there are still uncertainties related to use of chemicals on farmers as well as consumer health.

2.9.1 Sensitivity analysis and data uncertainty

The sensitivity analysis addressed key aspects of the weeding robot's performance: weed density in the field, energy required to kill weed meristems, and lifetime working hours in relation to the environmental impact of production. Accordingly, the analysis as a one-at-a-time parameter change was performed for selected parameters (Table 9). Absolute change and absolute sensitivity were calculated. Weed density in a given area is an essential factor for energy use. In the analyzed model, the operational weed density is between 5 and 120 weeds m^{-2}. The distribution of energy can influence the lifetime of particular components and the machine as a whole. The energy required for plant meristem destruction was also considered because laboratory tests performed in the WeLASER project indicated a wide range of this parameter. Another issue considered is the transportation between the field and the storage place in relation to the business models of the WeLASER weeder implementation, e.g., leasing, ownership,

Table 8 Key parameters of reuse and disposal

Material/process	High-power laser source	Meristem targeting	Weed meristem perception	Control system	Mobile platform
Opportunity for reusing of the components	Yes	Yes	Yes	Yes	Yes[a]
Medium rate of material reuse/recycling[b]	71%	86%	86%	37%	80%
Landfilling[b]	16%	7%	8%	45%	5%
Incinerating[b]	13%	7%	6%	18%	15%

[a] Particular components/machine

[b] Weight basis

Table 9 Parameters studied in the sensitivity analysis

Parameter	Tested parameters
Lifetime of the components	3000 – 20,000 working hours
Transport of the vehicle for farms/farms area	1–50 km, range of farms' cultivated area 1–100 ha
Energy required for plant meristem destruction at fixed speed of 2 km h^{-1}	5–20 J $plant^{-1}$ (meristem)
Density of weeds m^{-2} at a fixed speed of 2 km h^{-1}	5–120 weeds m^{-2}

or weeding services determining the transportation needs. Sensitivity analysis scenarios were considered in relation to the unique baseline scenario.

3 Results and discussion

3.1 Environmental impacts in the WeLASER weeder life cycle

In the life cycle of the WeLASER weeder, the calculated impacts, in particular impact categories, differed significantly. Key impact categories that account for more than 98% (weighted and normalized values) of the total score calculated for the combined production phase and use phase are:

- human toxicity
- climate change human health
- climate change ecosystem
- climate change ecosystem
- fossil depletion
- metal depletion
- particulate matter

The remaining impacts account for less than 1% of the total score (weighted and normalized values). The relative importance of the environmental impacts in the cradle to gate (production and use phase) analysis of the WeLASER weeder (Endpoint Recipe 2016) for the baseline scenario calculated for the functional unit is presented in Fig. 3. It should be noted that in this approach, the significance of particular impacts depends on the key parameters that characterize the baseline and the sensitivity scenarios.

The highest environmental impact is allocated to the WeLASER weeder use phase, and account for around 70% of the total score (weighted values, excluding the impacts in post-service phase). The crucial factor in this phase is the generation of electric energy in the diesel-electric system. Fuel consumption determines the climate change–related impacts, fossil resource depletion, and, to a lesser degree, particulate matter.

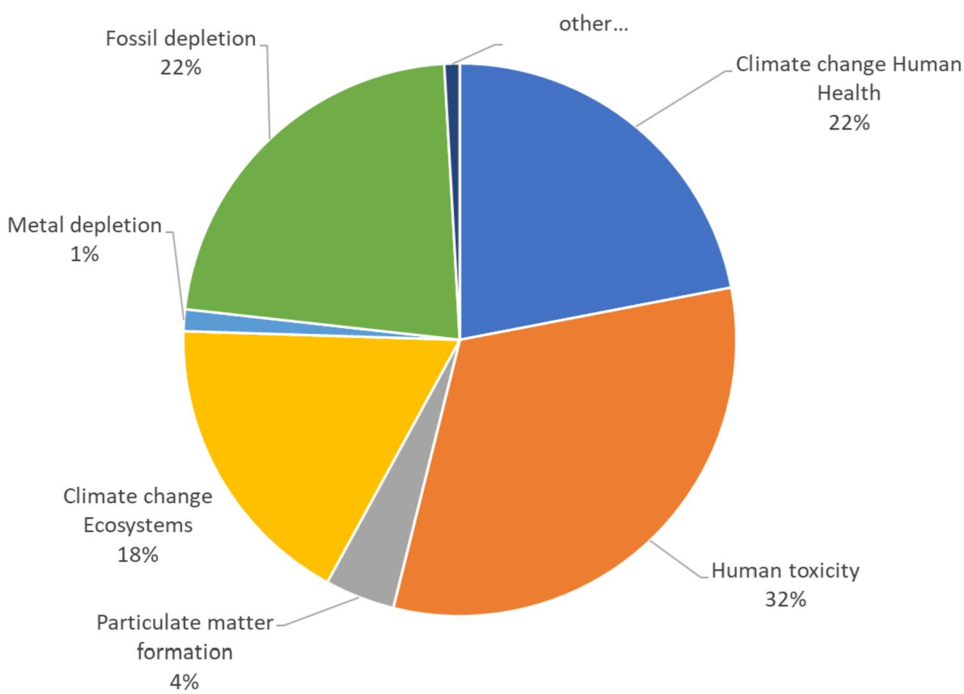


Fig. 3 The relative importance of environmental impacts in the production and use phases of the WeLASER weeder (weighted values, total score indicator, baseline scenario 60 weeds m^{-2})

The production phase is important, although its impact is much lower, accounting for approximately 30% share of the total score calculated for the combined production and use phase (weighted values). The key impacts are attributed to human health and metal depletion. It is mainly related to the production of basic materials (metals: copper, gold). The environmental gains in the disposal phase can further lower it, as the potential negative consequences can be offset by the benefits from the reuse of components and materials in the overall life cycle assessment. The benefits of recycling are related primarily to human toxicity. Proper dismantling and disposal allows for a reduction of negative impacts by 11% (total score). An overview of the key impact categories in the three phases is presented in Fig. 4. The results concerning the mobile platform are in agreement with other studies (Lagnelöv et al. 2021; Martelli et al. 2023). In this study, the impact of the production phase is relatively higher than in the cited studies as the ReCiPe egalitarian perspective was applied, and it is biased toward the human health–related impacts.

The autonomous mobile platform and the high-power laser source are the most impactful subsystems. The contributions of the main WeLASER weeder subsystems to impacts determined for the most important impact categories with respect to the whole life cycle perspective of the robot are presented in Fig. 5. The selected impacts refer to two phases: the production characterized with the impacts related to raw materials manufacturing and the use phase with the impacts related to energy consumption.

3.2 WeLASER production phase

The WeLASER weed control robot, in its basic design, consists of an autonomous mobile platform integrated with a laser weeding implement. In the production phase, the laser implement has a relatively higher impact (expressed as total

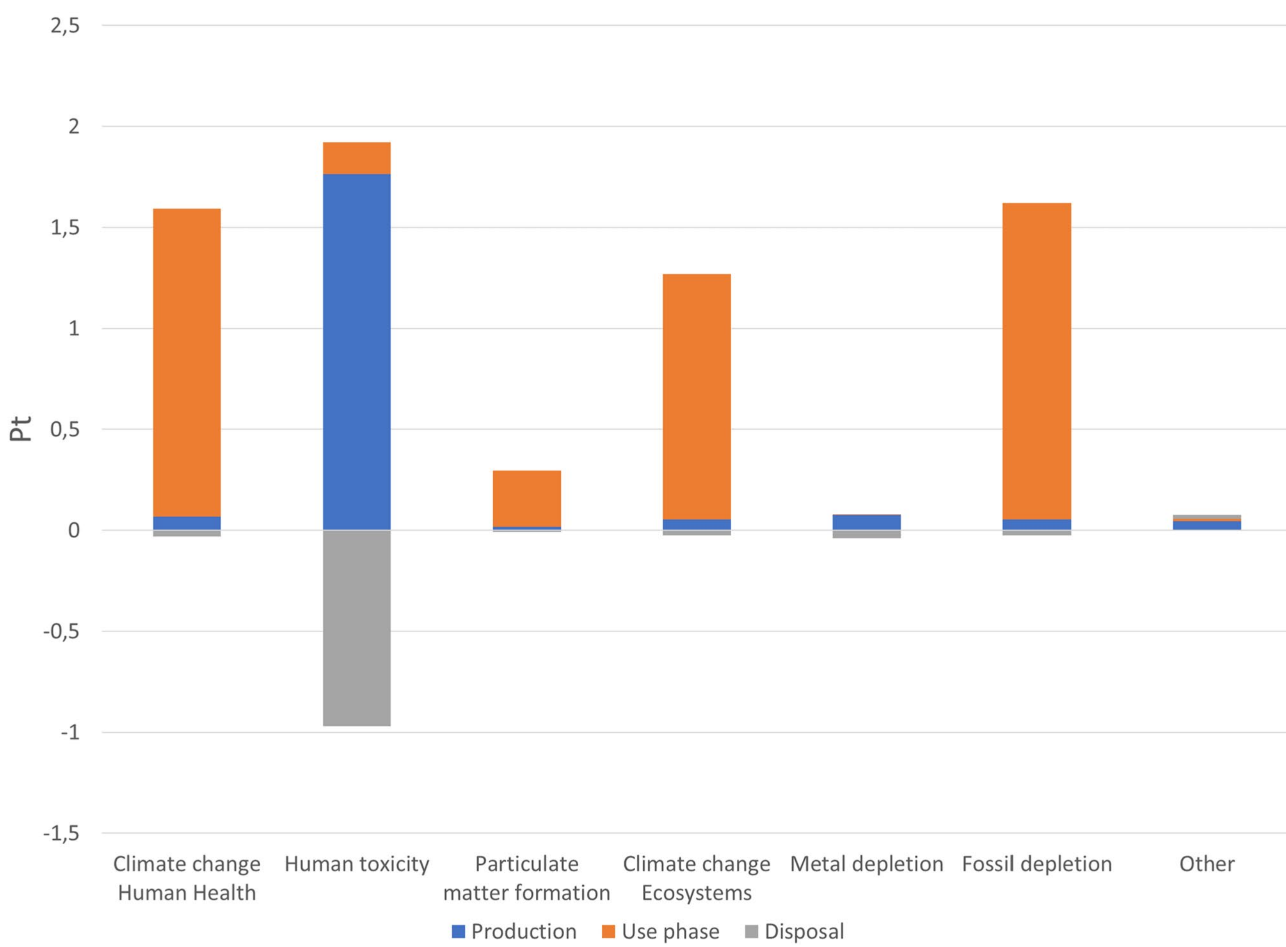


Fig. 4 Breakdown of impacts of the total score of the WeLASER weeder according to Recipe (2016) in the whole life cycle (weighted data, indicator expressed in points ha^{-1})

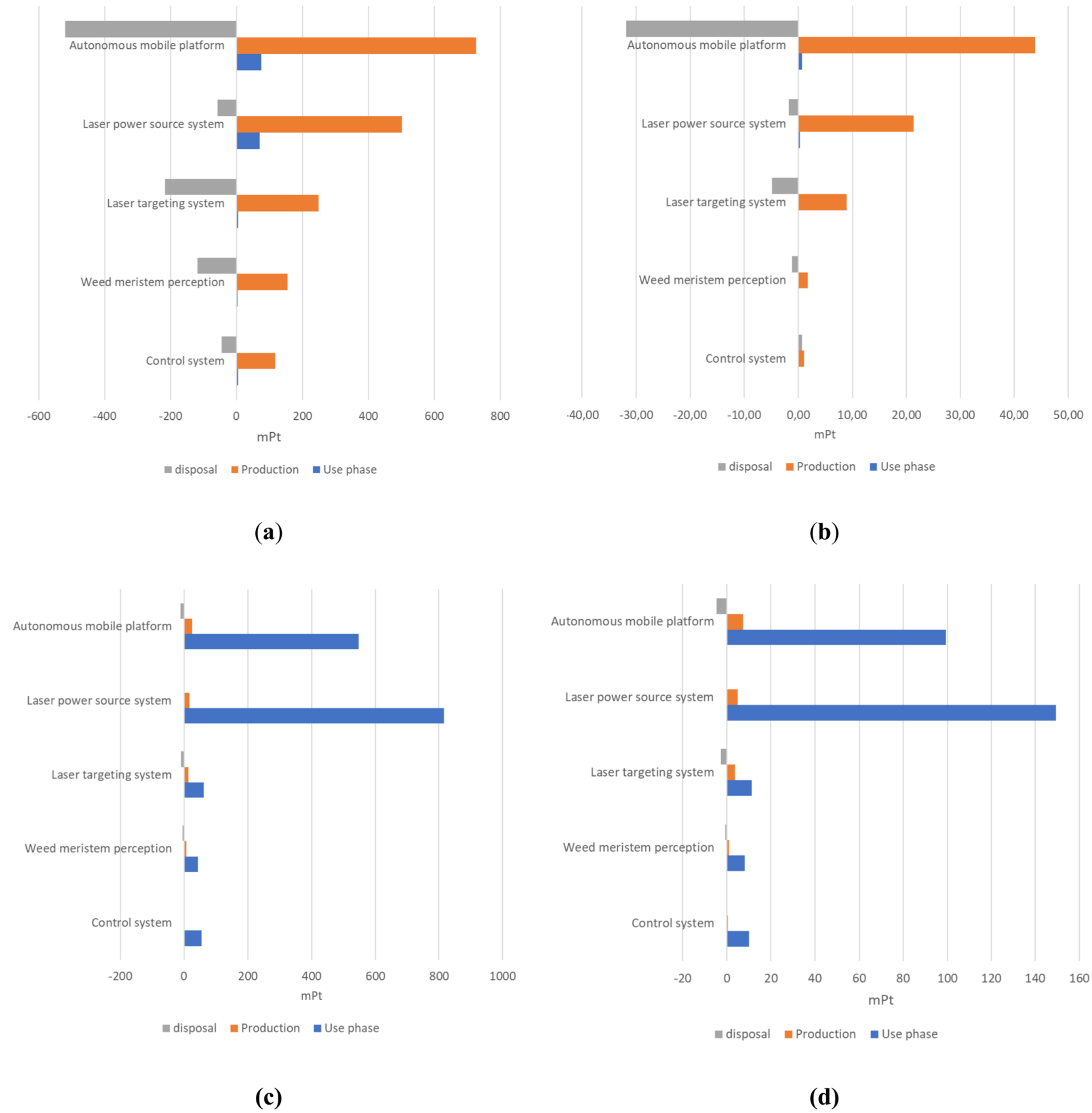


Fig. 5 Life cycle assessment of WeLASER weeder for key impact categories broken down into life cycle phases and main subsystems (impact value expressed in mPt, milipoints ha^{-1} of weeded area). Impact categories: **a** human toxicity; **b** metal depletion; **c** climate change human health; **d** particulate matter formation

score). The laser weeding implement has a share of approximately 58%, and the autonomous mobile platform 42%. Two components greatly impact the laser implement score: the high-power laser source subsystem (29%) and the laser targeting subsystem (15%). The weed meristem perception subsystem has a relatively low impact (8%) as well as the central controller (6%) (Fig. 6).

3.3 The mobile platform

The highest impact of the autonomous mobile platform is related to the electronic components (34%) of the total score (weighted) calculated for this subsystem. It is mainly related to the use of gold and copper, their extraction, processing, and treatment of production wastes (sulfidic tailings).

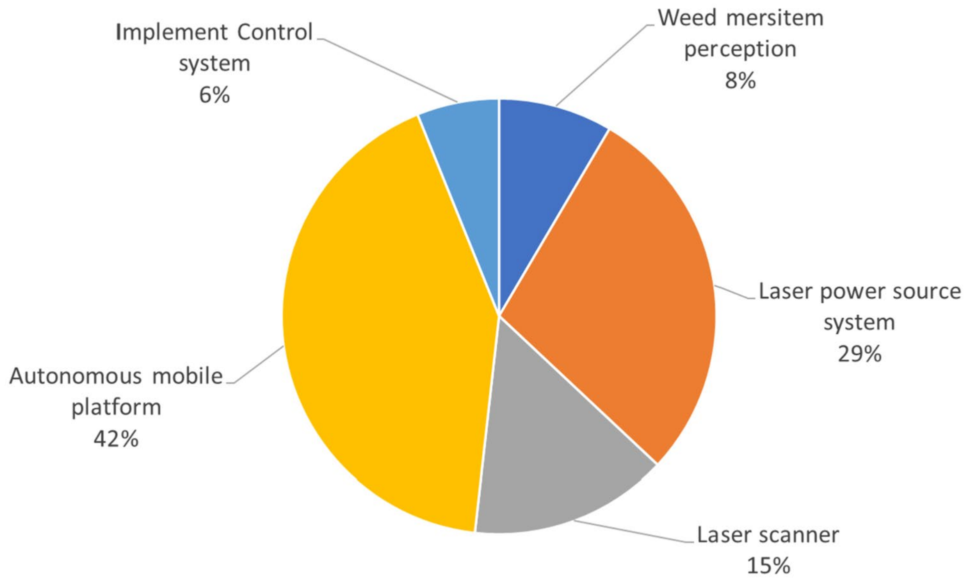


Fig. 6 Relative share (%) of the WeLASER weeder subsystems in the total score calculated for the production phase (Recipe 2016)

The production of other metals (nickel) plays a minor role. Electric relays and cables contribute 24%. Structural elements, chassis, platform suspension, caterpillar, and wheels, predominantly made of steel, have a share at the level of 20% of the total score. The low impact of these components can be also related to high use of recycled materials instead of virgin materials. The power components including the diesel engine, electricity generator, and electric engines have only 14% share. Human health is the most important impact category, with a share of 84% of the total score. The main impacts of the mobile platform broken down into particular components are presented in Fig. 7.

3.4 The WeLASER implement (laser-based weeding tool)

The main component of the autonomous weeder is the laser-based weeding tool, which consists of a high-power laser source, a meristem targeting perception subsystem, and the central controller. In the production phase, the highest impact for all components is related to human toxicity. The high-power laser source and the targeting subsystem are the most impactful. The identified production processes of components and their assembly have a relatively low impact compared to the production of raw materials.

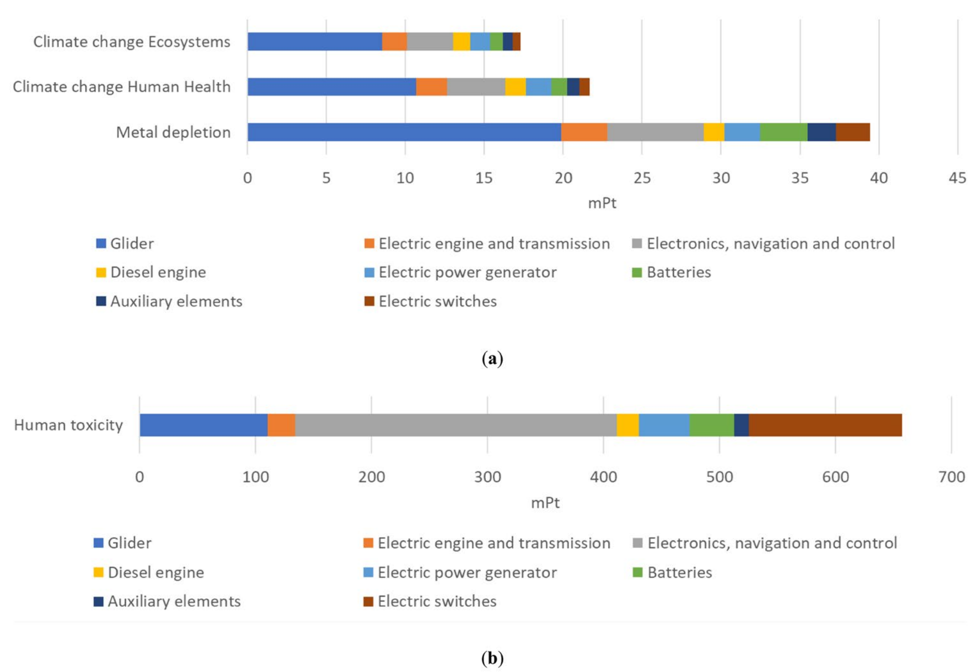


Fig. 7 Contribution of components of the WeLASER autonomous mobile platform to selected main impacts (indicator ha.$^{-1}$ of weeded area) calculated for the production phase and expressed in millipoints—mPT of impact indicators. Key impacts: **a** climate change human health, climate change ecosystems, metal depletion; **b** human toxicity (different scales)

The high-power laser source is the most impactful part of the weeding implement. It is designed to contain four functional units, each consisting of a laser source, chiller, electric cables, and laser fibers, installed in an enclosure. Its share is 49% of the total score of the production phase. The dominant components are the thulium fiber laser diodes and the electronic and electric elements (37% share of the weeding implement). Each unit requires efficient cooling and is supported by a chiller. The total impact allocated to the production of four heat management components (chillers) is around 11%. The key processes determining the impacts are the production of copper and gold. Copper is used as an electric conductor, heat sink, and effective heat transfer medium in functional elements, mainly electronic and electric components. The contribution of the main components to selected impacts is presented in Fig. 8.

Four laser targeting units correspond to four high-power laser source subsystems. Each unit has a laser scanner unit and a linear axis for moving the cabinet with the scanner head. All units are installed in a common enclosure. The scanner units have a share of 18% of the laser implement, including the scanner head (5%), the electronics: visual processing unit and control (7%), and the linear axis (3%). The impacts are also related in this case to the extraction of the raw materials of gold (electronics) and copper (galvanometers, servomotors, electronics, and cables). The functional components are built in an enclosure with safety curtains, which impact is of minor importance (Fig. 9).

The weed meristem perception subsystem consists of cameras and a computer processing the visual data and determining the meristem position for laser targeting (Fig. 10). The weed meristem perception has relatively low impact compared to the other subsystems (14% of the total score of the weeding implement). The cameras and the computer have the highest impact in this subsystem (3% and 10%, respectively). The remaining share is allocated to cables, lighting, and enclosure (1%).

The control unit has a relatively low impact compared with the other subsystems. The relative share of the main impacts for the human health and metal depletion category identified of this subsystem broken down by component is provided in Fig. 11.

The human toxicity category has the highest share of the total score calculated for the components of the above subsystems (86%). This impact is mainly determined by the processing of virgin materials, which contain metals. It must to be underlined that in all subsystems of the WeLASER implement the analyzed impacts, especially in case of human toxicity impact category are related to the production of metals: Copper and Gold. The contribution of these processes is between 60 and 80% of the total score. The production processes include both the production of virgin materials

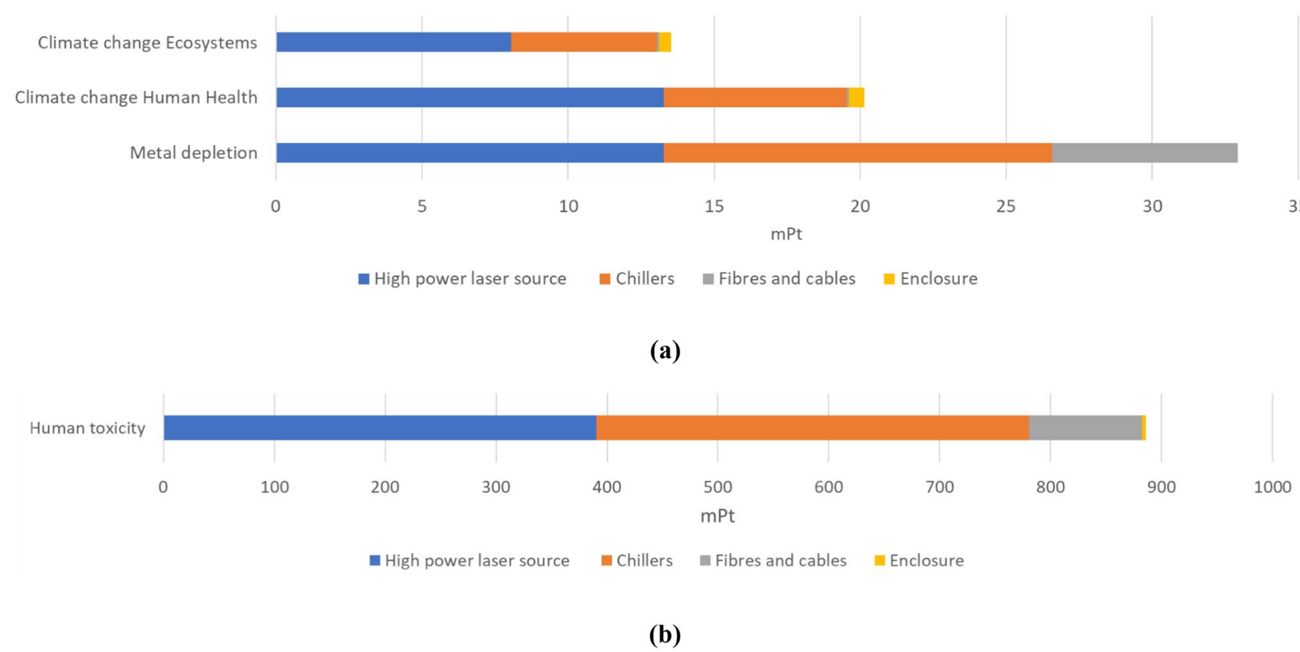
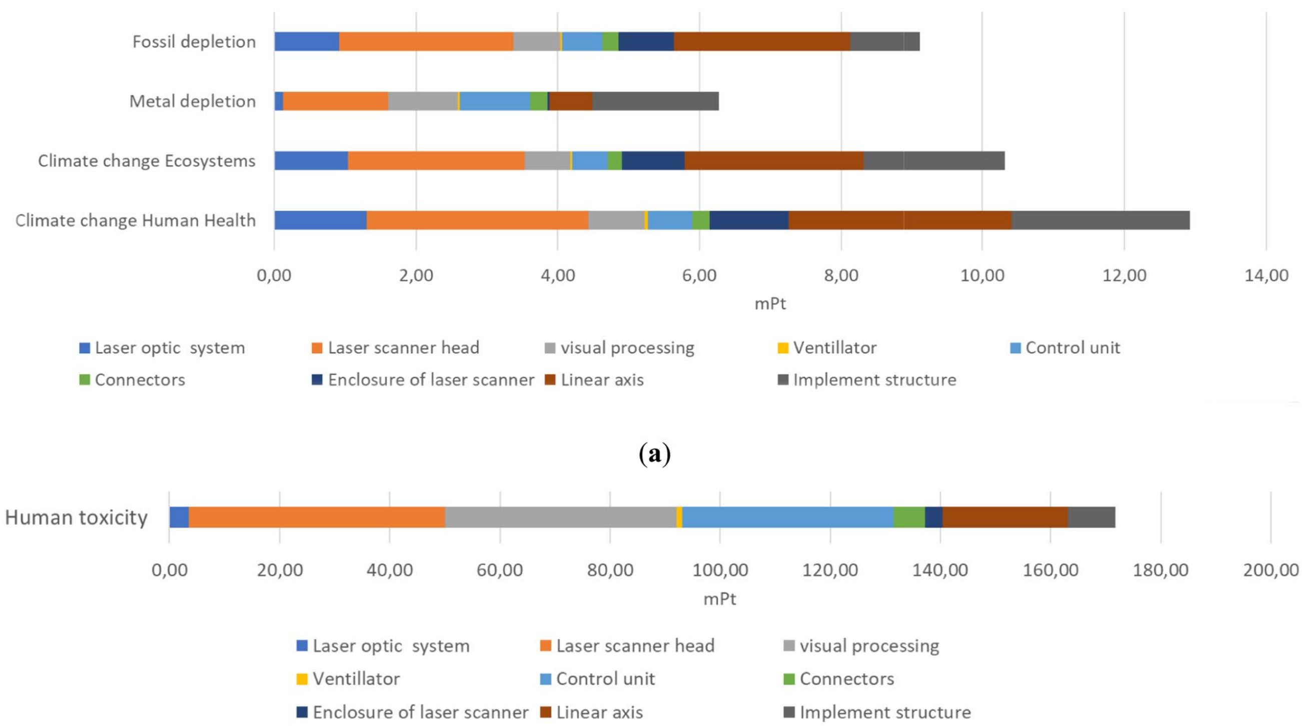


Fig. 8 Contribution of the WeLASER high-power laser source components to selected impacts (indicator ha^{-1} of weeded area) calculated for the production phase and expressed in millipoints—mPT of impact indicators. Key impacts: **a** climate change human health, climate change ecosystems, metal depletion; **b** human toxicity (different scales)



(a)

(b)

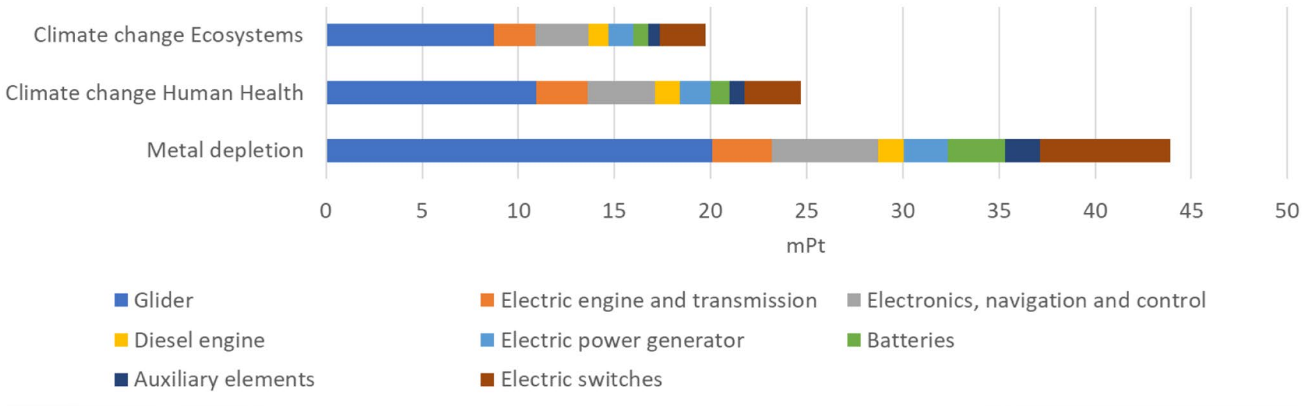
Fig. 9 Contribution of the WeLASER laser targeting subsystem components to selected impacts (indicator ha^{-1} of weeded area) calculated for the production phase and expressed in millipoints—mPT of impact indicators. Key impacts: **a** climate change human health, climate change ecosystems, metal depletion and fossil depletion; **b** human toxicity (different scales)

and by-products from the production of other metals. These indicators correspond to the impacts attributed to the treatment or disposal of sulfidic tailings in the processes of metal production.

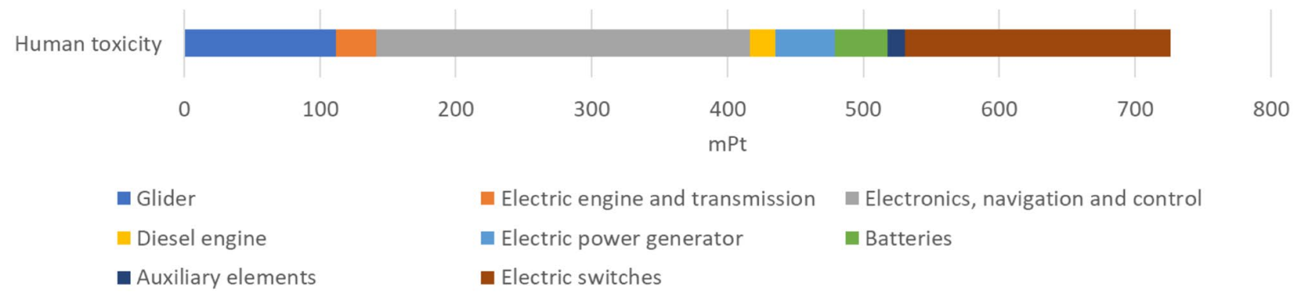
3.5 The WeLASER weeder use phase

The impacts in the phase of the WeLASER weeder use are mainly determined by the energy requirement for the specific weeder's subsystems. In the baseline scenario, the share of the impact for this phase of the total score, for the laser implement is 64%, and the mobile platform is 36%. The most impacted categories in the use phase are climate change and human health (32% of the total score), climate change—ecosystem (26%), fossil fuel depletion (33%), and, to a lower degree, particulate matter (6%) and human toxicity (3%). The high-power laser source is the most impactful subsystem of the weeding implement regarding total score and particular impact categories. It is related to the thermal energy allocated for electricity generation in the diesel–electric engine and, accordingly, the diesel fuel consumption. The share of the total score for this phase is 52%.

The energy consumption of the meristem perception subsystem is relatively low in operation and standby mode (4%), in which energy for computer operation accounting for the highest proportion. The energy demand of the meristem targeting system is also relatively low in operation and standby mode. The associated operation of computer and the cameras has a share of 4% of the total impact. The energy use of the control unit is also relatively low (5%) in operational and standby modes, while the impact of its electronics is the highest (up to 3%). Although the maintenance impacts (excluding spare parts replacement) are of minor importance, there is some uncertainty related to the life cycles of certain components, especially electronics. The short life cycles of electronics determine the potential need for frequent replacements, which can further rise the impacts allocated to their production. Certain impact is also allocated to the transportation of the machine to the field from the storage place. This aspect can be important for optimizing the business models of WeLASER weeder application, for example, machine lending or hiring of services, as it can be sensitive to the distance to be covered between the fields served, and storage places. Figure 12 presents the



(a)



(b)

Fig. 10 Contribution of the WeLASER weed meristem perception components to selected impacts (indicator ha^{-1} of weeded area) calculated for production phase and expressed in millipoints—mPT of impact indicators. Key impacts: **a** climate change human health, climate change ecosystems, metal depletion; **b** human toxicity (different scales)

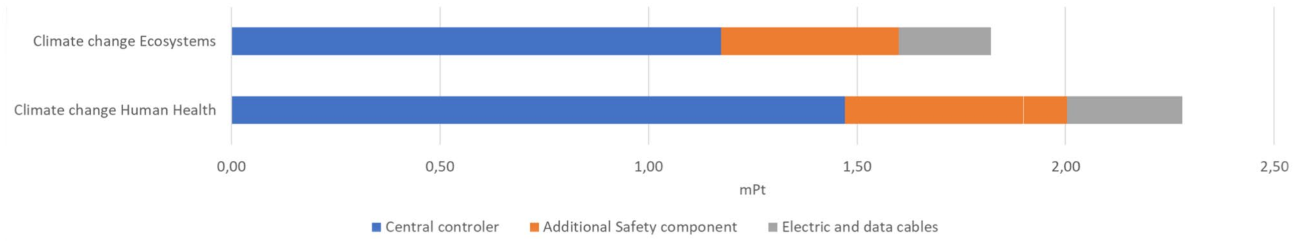
impact for the impact categories most strongly associated with the use phase—constituting more than 98% of the total score.

The use of diesel oil as an energy source for robot operation contributes mainly to the climate change indicators. The energy consumption is reflected in midpoint indicator of climate change which is 44.6 kg CO_2 eq. per ha. The impacts related to energy use were also highlighted as important in other studies (Lagnelöv et al. 2021; Martelli et al. 2023; Mousazadeh et al. 2011). In light of this, the use of diesel oil in precision machinery in agriculture should be considered a temporary solution as other energy sources are potentially more sustainable. For example, Lagnelöv et al. (2021) showed that the battery use in an electric tractor can have 35% of the Green House Gases (Cradle to Gate) emissions in comparison to diesel tractors. Opportunities for reduction of energy consumption in agricultural tractors through application of precision agriculture have been also presented by Gonzales-de-Soto et al. (2015).

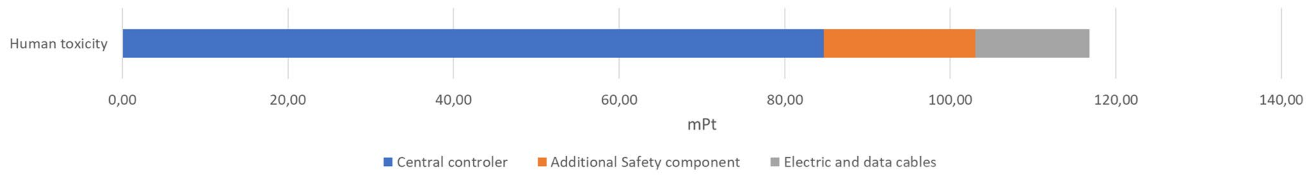
For the prototype WeLASER weeder, the assessment of maintenance was limited to the basic materials related to the autonomous platform (diesel oil, lubricants, and rubber). Pradel et al. (2022) presented data on increase of basic materials demand in robot production and use for various lifetimes assuming 2400 h as a baseline value. In their study, extension of the lifetime up to 10,000 working hours resulted in increase of particular materials demand up to 8.5% for steel, computer, and electric jacks, and 7% for the electric motor but without essential rise in the impacts. Lagnelöv et al. (2021) assumed 20% additional allocation of production activities for repair and maintenance and reported minor change in the impacts associated with these activities.

3.6 The WeLASER weeder dismantling and disposal

The disposal phase is an essential part of the whole life cycle of the machinery. A few potential scenarios of the WeLASER weeder management after end of its life can be considered. Dismantling of the machinery is the first step in this phase. For some parts—especially the laser components—reuse is potentially a viable option. Extending the



(a)



(b)

Fig. 11 Contribution of the WeLASER control unit components to selected impacts (indicator ha^{-1} of weeded area) calculated for production phase and expressed in millipoints—mPT of impact indicators. Key impacts: **a** climate change human health, climate change ecosystems; **b** human toxicity

life of some components in the same function or in other applications will lower the impacts related to their production. Proper dismantling of the machine and reusing of the components and materials can constitute a substantial environmental gain in relation to the production phase (potentially up to 51% of the total score for production phase). It should be noted that the value can be lower due to maintenance issues which were not fully addressed in the study. Considering the need for repairs at the level of 20% of the impact of production phase and adding the impacts attributed to the processes of components reuse, the ratio between impacts of these phases can be expected to be lower by 25 – 30%. There are two categories of materials that have different impacts:

- basic construction components and materials including steel and copper, which have a relatively high potential for reuse and recycling (rates above 85% up to 100%).
- electronic components which currently pose challenges for reuse for which a lower recovery rate was assigned.

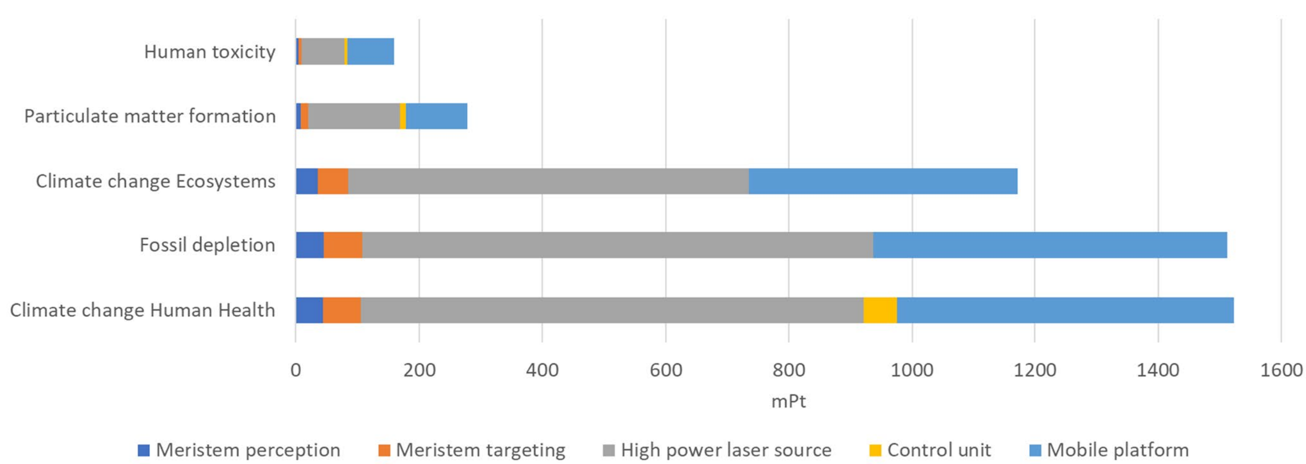
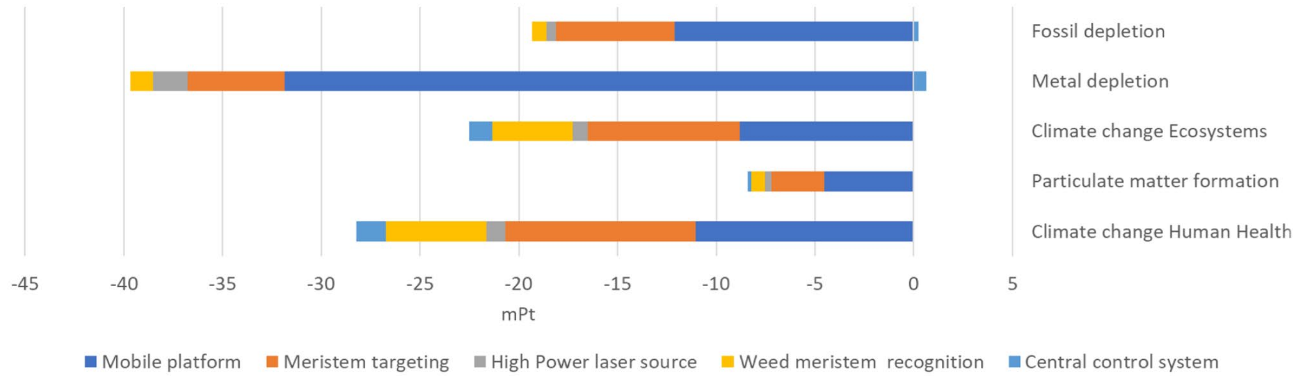
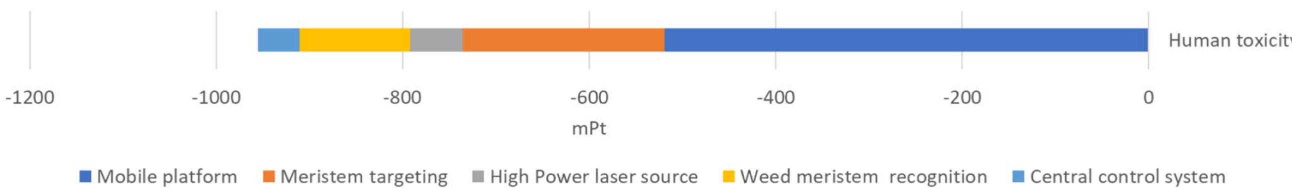


Fig. 12 Contribution of the WeLASER weeder subsystems to selected key impacts (indicator ha^{-1} of weeded area) calculated for use phase and expressed in millipoints—mPT of impact indicators. Key impacts: human toxicity, climate change human health, climate change ecosystems, fossil depletion, particulate matter formation



(a)



(b)

Fig. 13 Impacts broken down for components of the WeLASER weeder subsystems (indicator ha^{-1} of weeded area) calculated for production phase and expressed in millipoints—mPT of impact indicators. Key impacts: **a** fossil depletion, metal depletion, climate change human health, climate change ecosystems; **b** human toxicity (different scales)

It should be noted that for the assessment of production processes, there are important the rates of recycled materials used. An essential issue is the reuse rate of electronic components, which should be considered from the perspective of common waste management system. Dismantling and reuse of subsystems or components are considered as a baseline scenario in the assessment. High rates of reuse result in net environmental gains, especially in the human toxicity category (Fig. 13). The ratio between the gains (impact reduction) for disposal phase and the impacts in production phase calculated for the human toxicity impact category is high for the autonomous mobile platform (71.5%) and the laser targeting system (86.7%). Low values were observed for the control system (38.2%) and the high-power laser system (11.9%). In case of the laser implement subsystems the high share is attributed mainly to recycling of electronics, e.g., DC/DC converters and laptops in case of the laser implement subsystems. For the autonomous mobile platform, the recycling of structural components contributes up to 25% of the total score for this phase. Similar to the production phase, the highest contribution to the impacts in the disposal phase is attributed to the electronic and electric components and the corresponding gold and copper materials. Because they are produced in various processes as main products or byproducts, the burdens and benefits in the APOS system are allocated between the respective processes.

3.7 The weeding techniques comparison

WeLASER weeder is a technique that can potentially replace both herbicides and mechanical weeding. It can also be considered as a complementary technique in agricultural production systems. It can be a viable alternative to manual weeding. Its application in practice would depend on many conditions: crop types, cultivating systems, types of farms, weed species, and weed coverage. To better understand the potential opportunities, WeLASER weeder was compared with other techniques that perform the function of weed control, assuming average conditions for operating in 1 ha of field in one passage. The comparison is therefore only indicative as complex and tailored weeding strategies must be taken into consideration. The comparison was performed using Ecoinvent v3.8 data for the respective agricultural techniques. An example of sugar beet crop weeding was

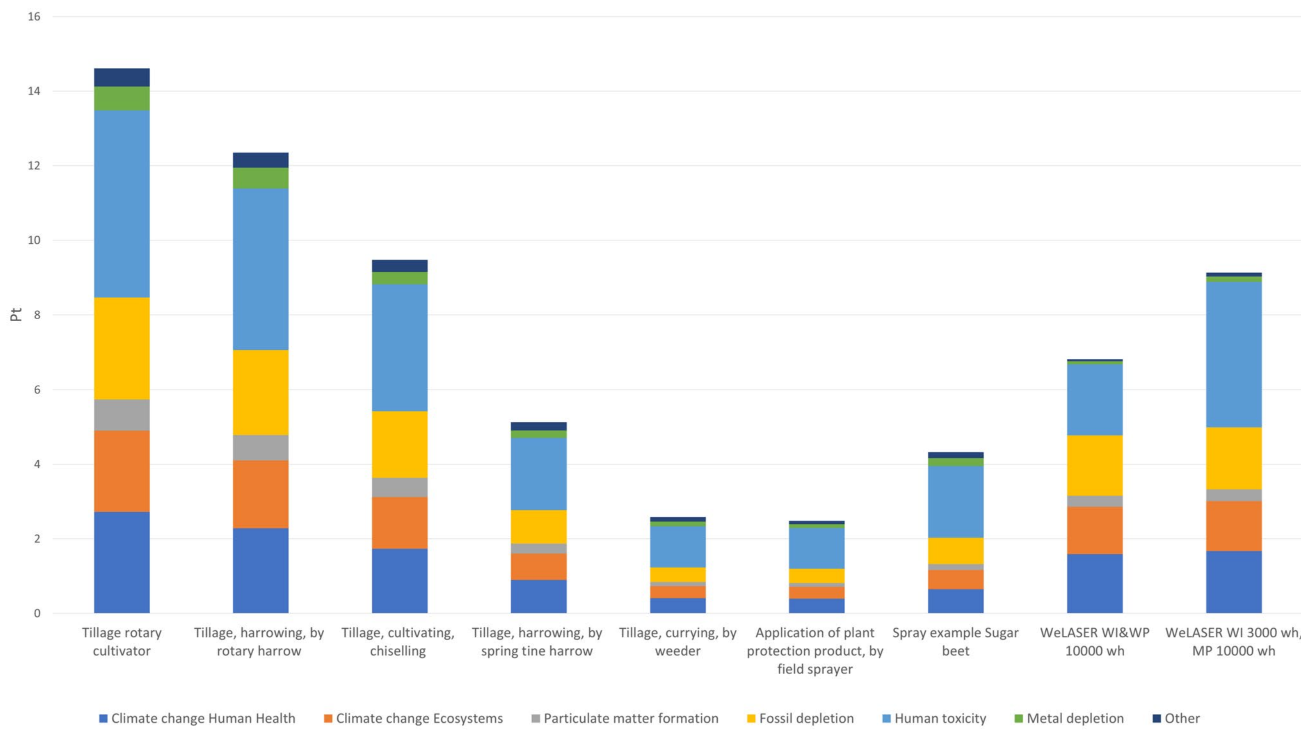


Fig. 14 Indicative comparison of various processes related to weeding in crop production systems based on Ecoinvent 3.8 and WeLASER weeder variants in cradle to gate analysis (production and use phases), functional unit 1 ha of weeded area, expressed in point (Pt) impact indicator. WI, weeding implement; MP, mobile platform; wh, working hours

used to compare the technique of herbicides spraying with WeLASER weeder for the same parameters (1 ha and one passage). In the recalculations of the indicator per ha (Ecoinvent v3.8 spraying process), herbicides were selected in the modified process, 88% allocation for herbicides was used for the sprayer operations, and the number of 4 passages was assumed.

These cultivation methods include a variety of weeders and multipurpose techniques such as harrowing. The comparison (Fig. 14) gives an insight into the key factors that determine weeding strategies in the crop production cycles. In all cases, the dominant environmental performance factor is fuel consumption in the use phase. The results indicate that the commonly used weed control methods differ in the total score value and the key identified impacts.

The production of the machinery has relatively low impact. In all compared cases of weed control techniques, the high impact in the human toxicity category is the most important in this phase. It is related predominantly, as in case of WeLASER weeder, to production of metals from raw materials, especially copper (tailing ponds). Steel and brass productions are also identified as important factors of the impacts for mechanical weeding. Manual work was not included in the comparison as it must be assessed in a wider socio-economic context.

Pradel et al. (2022) underlined that the tractor production process from Ecoinvent v3.8 is based on old data from 2002 and has not been updated since then. According to their study, modern tractors are characterized by higher metal depletion (ReCiPe method), higher human toxicity indicators, and lower global warming potential indicators (CML method) in the production phase. This can be attributed to the lack of electronic components or associated electric cables in the Ecoinvent v3.8 process, which is not representative of actual tractor technologies. From this perspective, it can be expected that to some extent the impacts related to the WeLASER autonomous mobile platform can be aligned to a certain extent with that of new agricultural machinery.

Energy consumption related to machine operations plays a significant role. When direct energy of weeding operation for various weeding methods were compared, in case of moldboard plowing (depth 25 cm), the energy values on sandy loam and loamy clay ranged from 160 to 169 MJ ha^{-1} and 230 to 237 MJ ha^{-1}, respectively. For chisel plowing, energy consumption ranged between 100 and 800 MJ ha^{-1} in various climatic and soil conditions. For secondary tillage treatment techniques, such as flex-tine, spring tooth, roller, tandem

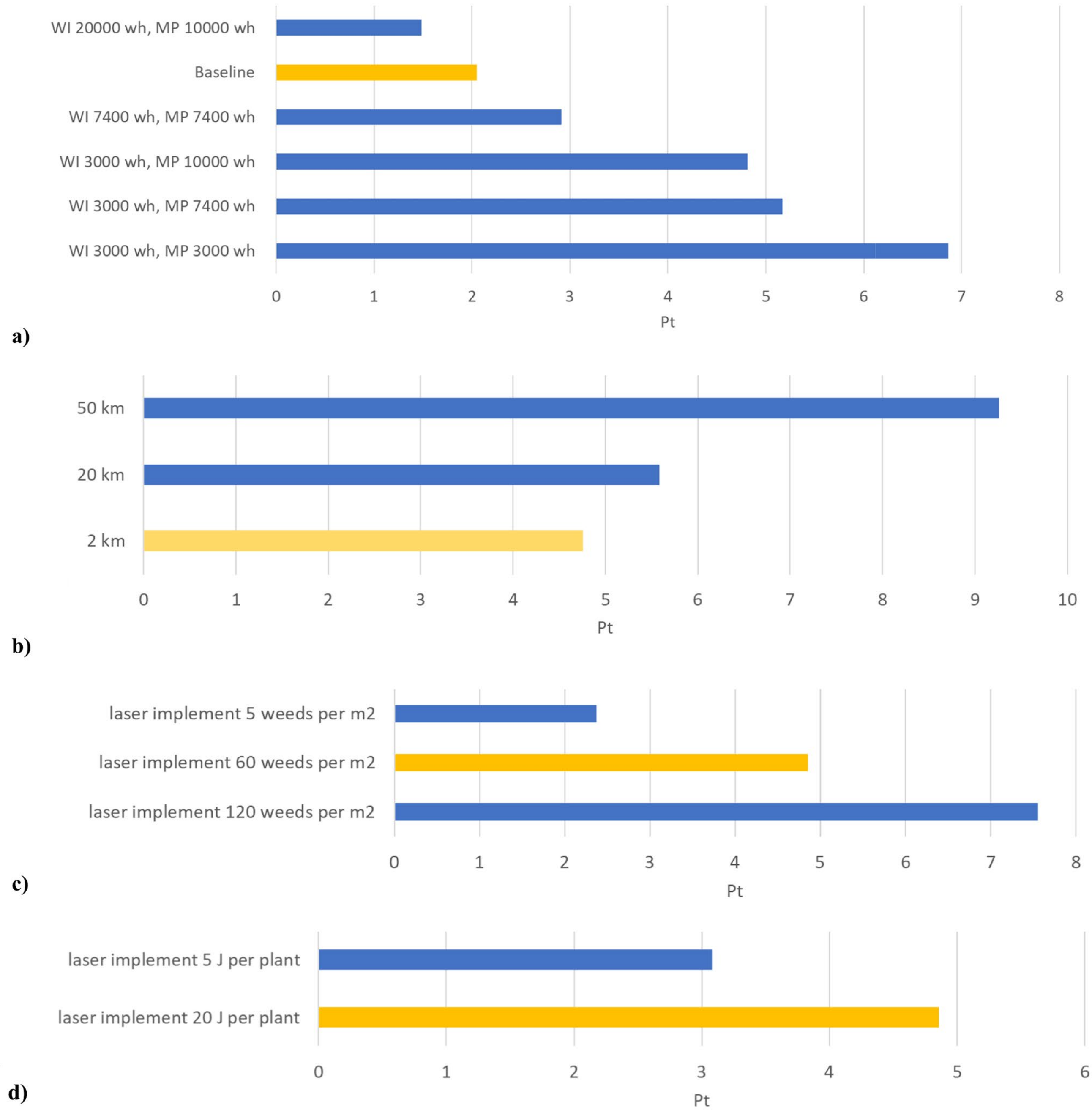


Fig. 15 Sensitivity analysis for the WeLASER weeder (total score indicator ha^{-1}). Baseline scenario presented in yellow. Parameters analyzed: **a** production phase: working hour parameter (WI, weeding implement; MP, mobile platform; wh, working hours); **b** use phase: parameter of operational transportation distance to the field; **c** use phase: parameter of weeds density; **d** use phase: parameter of energy required per plant meristem

harrows, sweep cultivators, basket weeders, rotary hoes, and rod weeders, the energy consumption for weeding (draft force) was reported to be between 4.2 and 50 MJ ha^{-1} (Coleman et al. 2019). For chemical weeding, the reported diesel consumption for boom-type trailed and self-propelled sprayers at various crop stages was at the level between 1.0 and 3.9 l diesel ha^{-1}, suggesting an energy consumption for herbicides application between 37 and 145 MJ ha^{-1} (Coleman et al. 2019). In these cases, energy consumption (including tractor) also depends on local conditions and is at the level of the weed density of 5 weeds m^{-2} calculated for the WeLASER case (Table 6). Therefore, WeLASER weeder potentially can be a competitive method, but it would depend on specific conditions related to the crop production system and the way of its usage.

When comparing the damage assessment, the WeLASER weeder (baseline scenario) 20% higher impact for human toxicity (DALY) than for chemical spraying in a sugar beet crop, and 147% higher in Climate Change Human Health indicator. When analyzing the contribution of individual processes, the spraying method in the human toxicity category is up to 60.7% by the impacts related to the machinery, including especially the tractor (21.1%), the sprayer (16.9%), and the diesel energy (9.39%), and only up to 39.3% by herbicides use. Only four Ecoinvent v3.8 processes for herbicides use contributed to the results: triazine-compound unspecified compound (23.1%), benzimidazole-compound (8.41%) [thio] carbamate-compound (5.5%), and pesticide, unspecified (1.4%).

3.8 Sensitivity analysis

In the chosen approach, the parameters determining the lifetime of the WeLASER weeder components depend on the operational time which is related to the weed density and speed of the robot. Therefore, the assessment results depend to a large extent on the robots' life cycle duration (working time). In the case of WeLASER weeder, 10,000 working hours are assumed in the baseline scenario for both the autonomous mobile platform and the high-power laser implement. This mobile platform life span aligns with the life span for tractors in the Ecoinvent v3.8-related process. Martelli et al. (2023) also assumed this factor at the same level in a LCA study for an orchard tractor. Lagnelöv et al. (2021) assumed 15,000 working hours for an electric tractor and Vahdanjoo et al (2023) estimated the same figure for an agricultural robot. In the case of Ecoinvent v3.8, agricultural processes such as tillage and harrowing, the weeding implements are characterized by a shorter life cycle (3000 working hours). In the study by Pradel et al. (2022) of robots in vineyards, the lifetime of the weeding robot was assumed to be between 2400 and 5000 h with maximum set at 7400 operational hours. Sensitivity analysis on the robot's lifetime showed that environmental impacts related to human toxicity can be greatly reduced by its extension. The current study represents an optimistic situation in which the potential reduction for the impact of the production phase is not so important due to its relatively long lifetime. We also assumed that the autonomous mobile platform and the high-power laser weeding implement can be analyzed separately in terms of their respective lifetimes. The lifetime span was set for the mobile platform between 3300 and 10,000 working hours and for the weeding laser between 3300 and 20,000 working hours. There were also considered situations of replacing both subsystems independently, e.g., replacing the implement on the same mobile platform as a part of the maintenance/refurbishment of the machine. The sensitivity in the lifetime span of the robot is substantial and is in the range between – 27% (– 0.6 Pt) and 234% (4.8 Pt) for the production phase (Fig. 15a). It should be noted that the impact indicators of the production recalculated per hectare in the intended lifetime depend on the density of the weeds. The possible changes to the design and production schemes of the WeLASER weeder in terms of materials used and industrial processes are rather limited, and this aspect was not considered sensitive. Nevertheless, in the final design, the implement can be utilized as a functional component integrated into an autonomous mobile platform or, possibly, as a separate weeding implement for conventional tractors. In the use phase, there are many factors that influence environmental performance:

- The operational settings, speed, weeds density, variance of terrain and environmental conditions.
- The final performance of the design, energy consumption and weeding efficiency of the WeLASER weeder (expected efficiency of 60–90%).
- The transportation requirements for the WeLASER weeder as it requires supporting transport.

Fuel consumption and energy efficiency during operation determine the environmental performance for the entire life cycle. Because the laser treats with precision the meristems, the energy demand in operation is determined by the weed/meristem density in the treated area. In this study, a variation between 5 and 120 weeds m^{-2} was assumed to be feasible for the analyzed model of prototype design (Fig. 15c). The relative change of the impacts (total score) between the baseline scenario and the minimum and maximum weed densities are – 51.2% (– 2.5 Pt) and + 55.5% (2.7 Pt). Another important parameter is the energy required for killing a plant meristem. This depends on the growth stage of the weeds and the weed species. In the laboratory studies conducted as part of the WeLASER project, the range of potentially efficient operation that ensures the desired weeding efficiency is between 5 and 20 J of optic energy per plant. The results are presented in Fig. 15d. The difference between the baseline scenario and the low energy variant (5 J per meristem) is – 36.6% (– 1.8 Pt). Coleman et al. (2019) reported a wide range of energy required for CO_2 laser pyrolysis of weeds depending on laser type and weed species. The range of this laser is between 21 and 350 J per weed, for diode laser pyrolysis it is 47 – 750 J per weed, and for thulium laser pyrolysis 230 J per weed and neodymium:yttrium aluminum garnet (ND:YAG) 70 – 1400 J per weed (Coleman et al. 2019). The efficacy of WeLASER weeder is expected to be much higher because it only targets the meristem reducing the need for optic energy. Nevertheless, for some types of weeds, higher values than 20 J per weed meristem can be expected. This also underlines the need for extensive testing of the machine and provision of appropriate tools for assessing its suitability for particular conditions on the farms. The use of renewable electricity is one solution to improve the environmental performance, but provision of appropriate guidance for energy-efficient operations is also wise.

The WeLASER weed controling robot is not intended to be an autonomous vehicle in public spaces. Therefore, additional transportation is required. It is sensitive to long transport - more than 10 km ha^{-1} and small plots below 10 ha - as these parameters are interrelated (linear function). Since the indicator is calculated per 1 ha of weeded area, the burden of transportation depends on the field area and the distance. The larger the area and shorter the distance, the smaller the burden. In the opposite case the burden becomes higher. In the baseline scenario, a distance of 1 km (2 km there and back) is assumed for 1 ha of field. Distances of 10 and 25 km were tested in the analysis and led to increase in the total score of 17.4% (0.8 Pt) and 94.8% (4.5 Pt), respectively (Fig. 15b). This is important when considering possible business models, for example, external services for small farms. In the case of the machinery ownership, the transportation issue is of less importance. Pradel et al. (2022) showed that the distance between the plots and the place where the robots are stored can only be relevant for longer distances. According to the study, the breaking point at which the transport of the robot outweighs the environmental gains in terms of carbon footprint is around 12 km. The number of passages needed during the crop production cycle and the geometry of the fields were also highlighted. One of the discussed opportunities for reducing the impact related to transportation of the robot is by designing modular robot, or by equipping the robot with multiple tools (Grimstad and From 2017; Xue et al. 2017). From this point of view, the business model of the WeLASER weeder application must consider this aspect, e.g., small-scale farming services. The sensitivity of the assessment is presented in Fig. 15.

It was found that in the study, the egalitarian perspective of the ReCiPe method, the results were very sensitive to electronic components, their type, quantity, and the approach to their characterization. This is also important because the potential for the recovery of key materials in recycling processes of electronic waste is still limited. The choice of the interpretation perspective in the ReCiPe 2016 method is related to the health concerns giving higher priority to the human toxicity impact category in the overall assessment. In this approach there arises uncertainty in the interpretation of impact assessment of the production phase. Moreover, it is crucial with respect to maintenance of the weeder in the use phase as the impacts can be raised by 8 – 20% in a prolonged lifetime. A better understanding of these issues is crucial in assessment of precision agriculture which relies heavily on electronic devices. The assessment of the end-of-life phase using the APOS model has shown that the electronic waste management is an important factor in the life cycle perspective due to the treatment of hazardous wastes associated with metal production.

3.9 Data uncertainty

There is substantial data uncertainty regarding the final commercial WeLASER product as the study is based on a model of the final products. The data uncertainty in the assessment of the production phase is moderate. It is mainly related to expert estimates of material composition based on literature, project characterization of particular components, and use of proxy data for particular components. Proxy data derived from literature was used to characterize parameters such as the lifetime of the device, both for the implement and for the mobile platform. Because the assessment is sensitive to short life spans, this aspect needs to be further scrutinized. In the study this issue was considered in a manner comparable to other techniques.

In the assessment of the use phase, there are data uncertainties with regard to energy consumption as the assessment is based only on preliminary testing of the robot under field conditions, data on agricultural operations, and engineering assumptions of the energy distribution between the traction and the laser equipment. Pradel et al. (2022) stated that there is a need to obtain data about the energy consumption of robots in their use phase to be able to carry out more precise and comparative LCAs with conventional solutions.

In comparison of WeLASER weeder with other techniques, there is no certainty about the potential strategies for its using (weed control efficiency, number of passages, limitations related to weather, ground, and crop cultivation conditions). Moreover, the key benefits of the weeder are not considered in the study (e.g., chemical free weeding, no soil disturbance, low soil compaction, less negative impact on living organisms (Andreasen et al. 2022, 2023)). The assessment of the disposal phase depends on the current efficiency of post-service management of the machinery and the actual situation in Europe of implementing of the related requirements, especially regarding the electronic wastes. In this study, the best-case scenario was assumed of high reuse rates for the machinery components. It must be underlined that the agricultural machinery's post-service life should be disposed in a controlled manner to ensure high environmental performance in this phase.

4 Conclusion

The conducted LCA study shows that the WeLASER technique is potentially a viable and environmentally sound weed control solution. Despite its complexity, it does not entail pose a significant burden on the environment. The main impacts are attributed to the phase of WeLASER weeder usage and are mostly related to thermal energy generation by the machine in a diesel engine. In terms of the electrical energy required for weeding operation, the laser-based technology is an efficient solution. It is also confirmed by other studies (Coleman et al. 2019). The robot's energy management is designed to be flexible, and to distribute the electric energy between traction and laser operation. Climate change and particulate matter impact categories are the most relevant, as they represent a typical profile for non-renewable energy generation. In light of this, more sustainable energy solutions should be considered. There are potentially huge opportunities to utilize renewable energy, such as renewable electricity (Gorijan 2021), bioethanol (Hoseinzadeh-Bandbafha et al. 2021), or hydrogen (Zulfikar 2021).

The production of the weeding implement and the mobile platform has a relatively low impact in relation to the entire life cycle. The overall impact assessed for the laser weeding implement is slightly higher than this of the mobile platform. The main impact categories in the production phase, in particular human health, are related to resource use and raw material production. It primarily concerns non-ferrous metal production, copper and gold, which are used in the manufacture of electric and electronic components. It must be emphasised that this aspect is not specific to WeLASER technique as automation and electronics are widely used in the society, and their environmental performance depends on the efficiency of the socio-economic system for recovery of metals from the waste streams of advanced technologies. At the same time the production processes of the individual components are of minor importance.

The results also show that the WeLASER weeder has a relatively moderate environmental impact compared to other techniques, especially mechanical and chemical weed control methods, but it must be smartly used to achieve the best performance. Moreover, it must be noted that the uncertainties in the assessment and the qualitative aspects of the solution are in favor for WeLASER technique. These are related to the key benefits—positive impacts such as improved environmental conditions, higher food quality, potential for enhancing biodiversity in agricultural land, and lower soil compaction. These aspects are not reflected in this study.

On the basis of the study results, there were formulated key policy implications and key design recommendations.

Key design recommendations:

Optimise and reduce the energy demand for the robot activity (high-power laser) and use alternative, renewable electricity for powering the weeder.

Provide an opportunity for reusing particular components by ensuring their durability, safety, and resistance to harsh conditions (e.g., electronics) and for final disposal through a recycling-orientated waste processing scenario.

Reduce and optimize the use of components characterized with high environmental impact, (e.g., copper produced from raw materials).

Enhance opportunities for implementation of intelligent weeding approaches based on combinations of weeding techniques, integrated (dual technique) machinery, and planning of the weeding operations based on prior field investigations (e.g., weeding implement to be used in common tractor, autonomous platform allowing for the whole range of activities, applicability in row weeding).

Key policy implications:

The use of WeLASER weeder requires that conditions for proper disposal, dismantling and maintenance are in place, and that appropriate services are well developed and commonly available in the farming sector.

There are important opportunities for application of renewable energy, electricity, bioethanol or hydrogen in agriculture, and dedicated value chains for fuels should be developed in this sector.

The availability of electronics with low environmental footprint should be enhanced in the socio-economic system.

The value chain of production and business models can provide essential room for optimisation of the machinery construction focused on lowering the environmental impacts.

For intelligent use of WeLASER weeder, there is a need for well-designed, efficient and optimised weeding strategies applied in practice by farmers, taking into account the type of crops, scale of production, and combination with other techniques. Here, farm advisers play an important role.

Improvements in the environmental performance of electric and electronic equipment should be pursued further.

Business models such as leasing, hiring, sharing, and purchase, must take into account the aspect of long-distance transportation and maintenance efficiency.

Author contribution Conceptualization, JK and DDMT; methodology, JK and DDMT; validation, JK, MW, HS, PHdS, LE, and KS; formal analysis, JK and DDMT; investigation, JK and DDMT; resources, PHdS, LE, and KS; data curation, JK; writing—original draft preparation, JK; writing—review and editing, JK, DDMT, and CA; visualization, JK and LE; supervision, JJC and CA; project administration, JK; funding acquisition, PGdS, CA, JK, JJC, and MW. All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by Copenhagen University We are thankful for the funding of the project WeLASER (Sustainable Weed Management in Agriculture with Laser-based Autonomous Tools, Grant Agreement ID 101000256) by European Commission under H2020-EU.3.2.1.1. Further, all sources of this paper have been cited and adequately referenced.

Data availability The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Declarations

Conflict of interest The authors declare no competing interests.

References

Adeux G, Munier-Jolain N, Meunier D, Farcy P, Carlesi S, Barberi P, Cordeau S (2019) Diversified grain-based cropping systems provide long-term weed control while limiting herbicide use and yield losses. Agron Sustain Develop 39:42. https://doi.org/10.1007/s13593-019-0587-x

Andreasen C, Scholle K, Saberi M (2022) Laser weeding with small autonomous vehicles: friends or foes? Front Agron 4:841086. https://doi.org/10.3389/fagro.2022.841086

Andreasen C, Vlassi E, Johannsen KS, Jensen SM (2023) Side-effects of laser weeding: Quantifying off-target risks to earthworms (*Enchytraeids*) and insects (Tenebrio molitor and Adalia bipunctata). FrontAgron. 5:1198840. https://doi.org/10.3389/fagro.2023.1198840

Andreasen C, Vlassi E, Salehan N (2024) Laser weeding of common weeds. Front Plant Sci (submitted)

Balafoutis A, Beck B, Fountas S, Vangeyte J, Wal TVD, Soto I, Gómez-Barbero M, Barnes A, Eory V (2017) Precision agriculture technologies positively contributing to GHG emissions mitigation, farm productivity and economics. Sustain 9:1339. https://doi.org/10.3390/su9081339

Benhammou A, Tedjini H, Hartani MA, Ghoniem RM, Alahmer A (2023) Accurate and efficient energy management system of fuel cell/battery/supercapacitor/AC and DC generators hybrid electric vehicles. Sustain 15:10102. https://doi.org/10.3390/su151310102

Bonanno A, Materia VC, Venus T, Wesseler J (2017) The plant protection products (PPP) sector in the European Union: a special view on herbicides. Eur J Develop Res 29(3):575–595. https://doi.org/10.1057/s41287-017-0088-1

Borgy B, Gaba S, Petit S, Reboud X (2012) Non-random distribution of weed species abundance in arable fields. Weed Res 52:383–389. https://doi.org/10.1111/j.1365-3180.2012.00920.x

Bortolini M, Mora C, Cascini A, Gamberi M (2014) Environmental assessment of an innovative agricultural machinery Int. J Operat Quant Managem 20(3):243–258

Casamayor JL, Su D, Ren Z (2018) Comparative Life Cycle Assessment of LED Lighting Products Lighting Res Technol 50(6):801–826. https://doi.org/10.1177/1477153517708597

Coleman GRY, Stead A, Rigter MP, Xu Z, Johnson D, Brooker GH, Sukkarieh S, Walsh MJ (2019) Using energy requirements to compare the suitability of alternative methods for broadcast and site-specific weed control. Weed Technol 33:633–650. https://doi.org/10.1017/wet.2019.32

Coleman G, Betters C, Squires C, Leon-Saval S, Walsh M (2021) Low energy laser treatments control annual ryegrass (*Lolium rigidum*). FrontAgron 2:601542. https://doi.org/10.3389/fagro.2020.601542

Cummins (2023) Application guidance notes: technical information from cummins generator technologies, Cummins Generator Technologies AGN 182 – Operating Efficiency of an Alternator AGN 182 ISSUE B/6/6. https://www.stamford-avk.com/sites/stamfordavk/files/AGN182_B.pdf. Accessec 17 Jul 2023

Daheim C, Poppe K, Schrijver R (2019) European Parliament, Directorate-General for Parliamentary Research Services, Precision agriculture and the future of farming in Europe – Scientific foresight study. European Parliament. https://doi.org/10.2861/020809

Degieter M, Steur H, DE Tran D, Gellynck X, Schouteten JJ (2023) Farmers' acceptance of robotics and unmanned aerial vehicles: A systematic review. Agron J 115(5):2159–2173. https://doi.org/10.1002/agj2.21427

Downs HW, Hansen RW (1998) Estimating farm fuel requirements, Fact Sheet No. 5.006., 9/1998 Colorado State University. Available at https://www.hort360.com.au/wordpress/wp-content/uploads/2015/03/Estimatiing-Farm-Fuel-Requirements.pdf. Accessed 31 Oct 2023

EC (2019) European Commission Regulation (EU) 2019/1781 of 1 October 2019 laying down eco-design requirements for electric motors and variable speed drives pursuant to Directive 2009/125/EC of the European Parliament and of the Council, amending Regulation (EC) No 641/2009 with regard to ecodesign requirements for glandless standalone circulators and glandless circulators integrated in products and repealing Commission Regulation (EC) No 640/2009, Official J. Eur Union, L 272/74, 25.10.2019

Emmi L, Fernández R, Gonzalez-de-Santos P, Francia M, Golfarelli M, Vitali G, Sandmann H, Hustedt M, Wollweber M (2023) Exploiting the internet resources for autonomous robots in agriculture. Agricult 13:1005. https://doi.org/10.3390/agriculture13051005

Eriksson M, Ahlgren S (2013) LCAs of petrol and diesel a literature review. SLU, Swedish University of Agricultural Science Department of Energy and Technology Report, 2013:058, Uppsala, ISSN 1654–9406. Available at https://pub.epsilon.slu.se/10424/17/ahlgren_s_and_eriksson_m_130529.pdf. Accessed 31 Oct 2023

Fuhrberg P, Ahrens A, Schkutow A, Frick T (2020) Welding of transparent and opaque polymers with single-mode Tm-doped fiber lasers. Photon Views 17(2):64–68. https://doi.org/10.1002/phvs.202000013

Gerhards R, Bezhin K, Santel H-J (2017) Sugar beet yield loss predicted by relative weed cover, weed biomass and weed density. Plant Prot Sci 53(2):118–125. https://doi.org/10.17221/57/2016-PPS

Gonzalez-de-Soto M, Emmi L, Garcia I, Gonzalez-de-Santos P (2015) Reducing fuel consumption in weed and pest control using robotic tractors. Comput Electron Agric 114:96–113

Gorijan S, Ebadi H, Trommsdorff M, Sharon H, Demant M, Schindele S (2021) The advent of modern solar-powered electric agricultural machinery: a solution for sustainable farm operations. J Cleaner Product 292:26030

Grimstad L (2014) Powertrain, steering and control components for the NMBU agricultural mobile robotic platform Norwegian University of Life Sciences Faculty of Environmental Science and Technology Department of Mathematical Sciences and Technology.

Grimstad L, From PJ (2017) The Thorvald II agricultural robotic system, robotics. Robotics 6(24):17. https://doi.org/10.3390/robotics6040024

Grisso RD (2004) University of Nebraska – Lincoln DigitalCommons@University of Nebraska – Lincoln Biological Systems Engineering: Papers and Publications Biological Systems Engineering Predicting Tractor Fuel Consumption Virginia Tech.

Hannemann LL (2016) Design and testing of an autonomous ground robot for agricultural applications, BioResource and Agricultural Engineering BioResource and Agricultural Engineering Department California Polytechnic State University, San Luis Obispo.

Heisel T, Schou J, Christensen S, Andreasen C (2001) Cutting weeds with a CO2 laser. Weed Res 41:19–29. https://doi.org/10.1046/j.1365-3180.2001.00212.x

Hillerström H, Troborg U (2010) Customized LCA for network cameras, Master of Science Thesis, Stockholm, Sweden KTH

Industrial Engineering and Management Machine Design, accessed 11.052023, https://www.diva-portal.org/smash/get/diva2:444443/FULLTEXT01.pdf
Hoseinzadeh-Bandbafha H, Rafiee S, Mohammadi P, Ghobadian B, Lam SS, Tabatabaei M, Aghbashlo M (2021) Exergetic, economic, and environmental life cycle assessment analyses of a heavy-duty tractor diesel engine fueled with diesel–biodiesel-bioethanol blends. Energ Convers Managem 241:114300
ISO 14040:2009 (2021) EN ISO 14040:2009/A1:2021–03 Environmental management - life cycle assessment - Principles and structure
ISU (2001) Machinery Management, Fuel Required for Field Operations. IOWA State University, University Extention PM 709, April 2001. https://www.extension.iastate.edu/agdm/crops/html/a3-27.html. Accessed 18 Sept 2023
Jamal A, Chamim ANN, Putra KT, Masfiyah NN, Jusman Y (2018) Analysis of losses of propulsion systems on electric diesel rail trains. J. Electr. Technol. UMY, 2(3):89−101. ISSN 2550–1186, e-ISSN 2580–6823
König A, Nicoletti L, Schröder D, Wolff S, Waclaw A, Lienkamp M (2021) An overview of parameter and cost for battery electric vehicles. World Electr Vehicle J 12:21. https://doi.org/10.3390/wevj12010021
Kowalczyk Z (2011) Zużycie Wybranych Typów Ciągników Rolniczych (Wear of Selected Types of Agricultural Tractors), *Inżynieria Rolnicza*, Instytut Inżynierii Rolniczej i Informatyki, Uniwersytet Rolniczy w Krakowie. *4*(129)/ 143
Kudsk P, Mathiassen SK (2020) Pesticide regulation in the European Union and the glyphosate controversy. Weed Sci 68(3):214–222. https://doi.org/10.1017/wsc.2019.59
Kulan EG, Kaya MD (2023) Effects of weed-control treatments and plant density on root yield and sugar content of sugar beet. Sugar Technol 25(4):805–819. https://doi.org/10.1007/s12355-023-01249-0
Lacour S, Burgun C, Perilhon C, Descombes G, Doyen VA (2014) Model to assess tractor operational efficiency from bench test data. J Terramechanics 54:1–18. https://doi.org/10.1016/j.jterra.2014.04.001
Lagnelöv O, Larsson G, Larsolle A, Hansson P-A (2021) Life cycle assessment of autonomous electric field tractors in Swedish agriculture. Sustain 13:11285. https://doi.org/10.3390/su132011285
Lajunen A, Kivekäs K, Freyermuth V, Vijayagopal R, Kim N (2023) Simulation of alternative powertrains in agricultural tractors. 36th International Electric Vehicle Symposium and Exhibition (EVS36) Sacramento, California, USA, June 11–14, 2023.
Lee H, Jeon J, Park J, Kim G, Yoon S (2012) Developing a combination model of agricultural machine for optimization GHG's based on LCA. American Society of Agricultural and Biological Engineers, Annual International Meeting, p 4368
Lovarelli D, Bacenetti J, Fiala M (2016) A new tool for life cycle inventories of agricultural operations. *J*. Agricult. Engineer. 47(1):40–53. https://doi.org/10.4081/jae.2016.480
Marinescu DG, Tabacu I, Serban F, Tabacu S, Nicolae V, Vieru I (2012) A plug-in hybrid diesel-electric vehicle. World Electric Vehicle J 5(1):210–216. https://doi.org/10.3390/wevj5010210
Martelli S, Mocera F, Somà A (2023) Carbon Footprint of an Orchard Tractor through a Life-Cycle Assessment Approach. Agricult 13:1210. https://doi.org/10.3390/agriculture13061210
Moitzi G, Haas M, Wagentristl H, Boxberger J, Gronauer A (2013) Energy consumption in cultivating and ploughing with traction improvement system and consideration of the rear furrow wheel-load in ploughing. SoilTillage Res 134:56–60. https://doi.org/10.1016/j.still.2013.07.006
Moschitz H, Muller A, Kretzschmar U, Haller L, Porras M, Pfeifer C, Oehen B, Willer H, Stolz H (2021) How can the EU Farm to Fork strategy deliver on its organic promises? Some critical reflections, Agricultural Economics Society and European Association of Agricultural Economists. Eur Choices 20(1):30–36. https://doi.org/10.1111/1746-692X.12294open_ISSN1478-0917eISSN1746-692X
Mousazadeh H, Keyhani A, Javadi A, Mobli H, Abrinia K, Sharifi A (2011) Life-cycle assessment of a Solar Assist Plug-in Hybrid Electric Tractor (SAPHT) in comparison with a conventional tractor. Energy Convers Managem 52:1700–1710. https://doi.org/10.1016/j.enconman.2010.10.033
Muñoz R, Llanos J (2012) Estimation of the lifespan of agricultural tractor using a diffusion model at the aggregate level. Cienc Investig Agrar 39(3):557–562. https://doi.org/10.4067/S0718-16202012000300014
Nagel L (2023) What is the average efficiency of an electric motor, January 20, 2023. Available at https://www.tytorobotics.com/blogs/articles/what-is-the-average-efficiency-of-an-electric-motor
Nemecek T, Kägi T (2007) Life cycle inventories of agricultural production systems data v2.0, (2007). Ecoinvent report No. 15, Zürich and Dübendorf, December 2007
Nordelöf A, Messagie M, Söderman T-M, Mierlo ML, Van J (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 19:1866–1890. https://doi.org/10.1007/s11367-014-0788-0
Nordelöf A, Grunditz E, Tillman A-M, Thiringer T, Alatalo M (2018) A scalable life cycle inventory of an electrical automotive traction machine—part I: design and composition. Int J Life Cycle Assess 23:55–69. https://doi.org/10.1007/s11367-017-1308-9
Nordelöf A, Grunditz E, Tillman A-M, Thiringer T, Alatalo M (2016) A scalable life cycle inventory of an electrical automotive traction machine technical and methodological description, version 1.0 Department of Energy and Environment, Divisions of Environmental Systems Analysis & Electric Power Engineering, Chalmers University of Technology, Gothenburg, Sweden, Report No. 2016:4
Notarnicola B, Sala S, Anton A, McLaren SJ, Saouter E, Sonesson U (2017) The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J Cleaner Prod 40(2):399–409. https://doi.org/10.1016/j.jclepro.2016.06.071
Parsons SD (1980) Estimating fuel requirements for field operations AE-110 Purdue University Cooperative Extension Service West Lafayette, IN 47907. 8/80. https://www.extension.purdue.edu/extmedia/AE/AE-110.html. Accessed 18 Sept 2023
Plizga K (2021) Analysis of energy consumption by electric agricultural tractor model under operating conditions. Agricult Engineer 25:1–12. https://doi.org/10.2478/agriceng-2021-0001
Pradel M, de Fays M, Seguineau C (2022) Comparative life cycle assessment of intra-row and inter-row weeding practices using autonomous robot systems in French vineyards. Sci Total Environ 838(3):156441. https://doi.org/10.1016/j.scitotenv.2022.156441
Rani L, Thapa K, Kanojia N, Sharma N, Singh S, Grewal AS, Kaushal J (2021) An extensive review on the consequences of chemical pesticides on human health and environment. J Cleaner Prod 283:124657. https://doi.org/10.1016/j.jclepro.2020.124657
Rossi M, Favi C, Germani M (2021) Comparative life cycle assessment of refrigeration systems for food cooling: eco-design actions towards machines with natural refrigerants. Int J Sustain Engineer 14(6):1623–1646. https://doi.org/10.1080/19397038.2021.1970274
Schaschke C, Fletcher I, Glen N (2013) Density and Viscosity Measurement of Diesel Fuels at Combined High Pressure and Elevated Temperature. Processes 1:30–48. https://doi.org/10.3390/pr1020030
Schau EM, Traverso M, Lehmann A, Finkbeiner M (2011) Life cycle costing in sustainability assessment—a case study of remanufactured alternators. Sustain 3:2268–2288. https://doi.org/10.3390/su3112268
Silva V, Mol HGJ, Zomer P, Tienstra M, Ritsema CJ, Geissen V (2019) Pesticide residues in European agricultural soils – a hidden reality

unfolded. Sci Total Environ 653:1532–1545. https://doi.org/10.1016/J.SCITOTENV.2018.10.441

Silva V, Yang X, Fleskens L, Ritsema CJ, Geissen V (2022) Environmental and human health at risk – scenarios to achieve the Farm to Fork 50% pesticide reduction goals. Environ Internat 165:107296. https://doi.org/10.1016/j.envint.2022.107296

Su D, Ren Z, Wu Y (2020) Guidelines for selection of life cycle impact assessment software tools. In: Su, D. (eds) Sustain. Product Develop. Springer, Cham. https://doi.org/10.1007/978-3-030-39149-2_4

Thallapalli VKT, Onur AO, Kocakulak T (2021) Modeling of an electric tractor and determining energy consumption values for different duties. Engineer. Perspective 1(2):79–85. https://doi.org/10.29228/eng.pers.51651

Thonemann N, Schulte A, Maga D (2020) How to conduct prospective life cycle assessment for emerging technologies? A systematic review and methodological guidance. Sustain 12:1192. https://doi.org/10.3390/su12031192

Tran D, Schouteten JJ, Degieter M, Krupanek J, Jarosz W, Areta A, Emmi L, De Steur H, Gellynck X (2023) European stakeholders' perspectives on implementation potential of precision weed control: the case of autonomous vehicles with laser treatment. Prec Agricult 24:2200–2222. https://doi.org/10.1007/s11119-023-10037-5

Ueka Y, Yamashita J, Sato K, Doi Y (2013) Study on the development of the electric tractor - specifications and traveling and tilling performance of a prototype electric tractor. Engineer Agricult Environ Food 6(4):160–164

Vahdanjoo M, Gislum R, Sørensen CAG (2023) Operational, economic, and environmental assessment of an agricultural robot in seeding and weeding operations. Agri Engineer 5:299–324. https://doi.org/10.3390/agriengineering5010020

van der Giesen C, Cucurachi S, Guinee J, Kramer GJ, Tukker A (2020) A critical view on the current application of LCA for new technologies and recommendations for improved practice. J Cleaner Product 259:120904. https://doi.org/10.1016/j.jclepro.2020.120904

Van Eygen E, De Meester S, Tran HP, Dewulf J (2016) Resource savings by urban mining: the case of desktop and laptop computers in Belgium. Res ConservRecycl 107:53–64. https://doi.org/10.1016/j.resconrec.2015.10.032

Wernet G, Bauer C, Steubing B, Reinhard J, Weidema B (2016) The ecoinvent database version 3 (Part I): Overview and methodology. Int J Life Cycle Assess 21(9):1–13. https://doi.org/10.1007/s11367-016-1087-8

Wilfong GJ (2019) Modeling and analysis of ground-based autonomous agricultural vehicles. A dissertation submitted to the Faculty of Purdue University, Purdue University West Lafayette, Indiana

Wolff S, Seidenfus M, Gordon K, Álvarez S, Kalt S, Lienkamp M (2020) Scalable life-cycle inventory for heavy-duty vehicle production. Sustain 12:5396. https://doi.org/10.3390/su12135396

Woong LJ, Chul KS, Jooseon O, Woo-Jin C, Hyun-Woo H, Ji-Tae K, Young-Jun P (2019) Engine speed control system for improving the fuel efficiency of agricultural tractors for plowing operations. Appl. Sci. 9:3898. https://doi.org/10.3390/app9183898

Xue J, Fan B-w, Zhang X-x, Feng Y (2017) An agricultural robot for multipurpose operations in a greenhouse. DEStech Trans Eng Technol Res. https://api.semanticscholar.org/CorpusID:55852811

Zhao Y, Chen X, Song Y, Wang G, Zhai Z (2023) Energy and fuel consumption of a new concept of hydro-mechanical tractor transmission. Sustain 15:10809. https://doi.org/10.3390/su151410809

Zhu Z, Yang Y, Wang D, Cai Y, Lai L (2022) Energy saving, performance of agricultural tractor equipped with mechanic-electronic -hydraulic powertrain system. Agricult 12:436. https://doi.org/10.3390/agriculture12030436

Zulfiqar F, Russell G, Hancock JT (2021) Molecular hydrogen in agriculture. Planta 254:56. https://doi.org/10.1007/s00425-021-03706-0