



Life cycle assessment of different strawberry production methods in Germany with a particular focus on plastic emissions

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Abstract

Purpose Using plastic for strawberry cultivation (so-called plasticulture) is widespread to extend cultivation, reduce weed stress and water and nutrient demand, and protect plants. We assess the environmental impacts of different plasticulture methods, including possible impacts caused by the (accidental) emission of plastics. The goals are to help farmers determine the most environmentally friendly cultivation technique and to test the inclusion of plastic pollution in life cycle assessment (LCA).

Methods An LCA is conducted for a baseline scenario without plasticulture and 11 plasticulture scenarios. The scenarios are modeled using the regionalized ecoinvent 3.8 cut-off database. The functional unit is 1 kg of strawberries of marketable quality at the farm gate produced in the year 2021. The amounts of fertilizer, irrigation, and strawberry output of the scenarios are adapted depending on the plasticulture method based on an extensive literature review. The environmental impacts are assessed using the life cycle impact assessment methods of the Product Environmental Footprint (PEF) recommended by the Joint Research Centre of the European Commission, which is extended to account for plastic-related impacts. The impacts are normalized, weighted, and aggregated, resulting in one single impact score per scenario.

Results and discussion The scenarios using either a combination of conventional mulch film and row cover or biodegradable mulch film have the lowest total impacts; a macro tunnel or greenhouse causes the highest impacts. There seems to be no trade-off between maximizing productivity and lowering environmental impacts: the scenario with the highest yield also has one of the lowest overall impacts. Only direct emissions are considered regarding plastic pollution. Besides, the plastic pollution impact category is currently limited to the persistence of plastic in the environment and is extendable to but is not yet accounting for exposure and effect of plastic emission on humans and ecosystems.

Conclusion Plasticulture can increase the yield and reduce environmental impacts for strawberry cultivation compared to open field cultivation. With the used normalization and weighting factors, plastic pollution makes up a considerable share of the overall environmental impact of strawberry cultivation, supporting the recent efforts of different research groups to include plastic emissions in LCA by developing suitable characterization factors.

Keywords PEF · Environmental footprint · Carbon footprint · Agriculture · Mulching · Tunnel · Greenhouse · Plasticulture · Plastic pollution

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1 Background and aim

Although politicians, the industry, and consumers agree that plastic should not be released into the environment (Nielsen et al. 2020), plastic pieces can be found in nearly all ecosystems worldwide (Li et al. 2020), including remote areas (Li et al. 2016; Bergmann et al. 2019). The call to action “Our Ocean, Our Future” at the conference organized by the United Nations (2017) calls on all stakeholders to conserve and sustainably use the oceans, seas, and marine resources. Alarming, current studies increasingly indicate that plastic in the environment can threaten biodiversity and ecosystem services, such as food production (Steinmetz et al. 2016; Horton et al. 2017; Wong et al. 2020).

Commercial agriculture often relies on plastic usage (so-called plasticulture) to extend cultivation periods and adjust the harvest time within the year to meet market demands with local production, improving the division of labor year-round and increasing earnings (Lieten 2005). Plasticulture is assumed to affect fruit quality and productivity positively (Galati et al. 2020) while reducing the demand for water and nutrients (Kasirajan and Ngouajio 2012), thus making agricultural production possible in areas with otherwise unfavorable conditions (e.g., water stress) (Kader et al. 2017; Gao et al. 2019). Usually, most plastic is recollected from the environment after serving its purpose and disposed of in the local waste management system. Different end-of-life treatment options for agroplastics can be found, e.g., in Galati and Scalenghe (2021). However, the used plastic (e.g., mulch film) may rip during recollection and pieces remain on the soil. Besides, erosion of plastic products during their use may lead to emission of plastic particles into the environment (Bertling et al. 2018; Kalberer et al. 2019). If not adequately removed and recycled, agroplastics are left on the field or burnt outside of proper treatment plants, releasing harmful substances into the air (Briassoulis 2006; Kader et al. 2017).

One commonly used methodology to determine and compare the environmental impacts of processes and products, such as agroplastics, is life cycle assessment (LCA) (ISO 14040:2006 2009; ISO 14044:2006 2006). The LCA research community largely agrees that the method needs further development to consider plastic emission-related environmental impacts (Sonnemann and Valdivia 2017). To characterize these impacts, (at least) four aspects need to be considered (Woods et al. 2021; Maga et al. 2022): (i) emitted plastic masses, (ii) the fate of the plastic emission in the environment, (iii) exposure pathways and probabilities of organisms to the emission, and (iv) the effects of such exposure on the well-being of the organism, population, and ecosystem.

While the environmental impacts of different end-of-life treatment options can be modeled using existing databases (e.g., openLCA, Gabi) and impact assessment methods (e.g., product environmental footprint (PEF), ReCiPe, Impact-World+), the impacts of plastic pieces emitted during the usage in plasticulture have not yet been fully understood and incorporated into impact assessment methods. Several attempts have been made to include plastic emission-related environmental impacts in LCA. For example, Civancik-Uslu et al. (2019) proposed a littering indicator to quantify emitted plastic masses and Siegfried et al. (2017) and Unice et al. (2019) mapped out textile fiber and tire wear pathways into the environment. More comprehensively, the members of the “Plastic Leak Project” generated life cycle inventory (LCI) data for plastic litter emissions into the environmental compartments marine water, freshwater, and terrestrial for a variety of processes such as tire use, textile manufacturing and use, and packaging production (Peano et al. 2020). When considering plastic emissions in LCI data, Maga et al. (2021) highlighted the relevance of correctly assessing the initial release to allow for accurate impact assessment. Regarding the fate of plastic emissions, Maga et al. (2022) suggest using fate factors based on the emissions’ persistence in the environment to develop characterization factors (CFs) linked to existing or new impact categories such as ecotoxicity. Regarding the effect factor, Woods et al. (2019) suggest a method to assess the risk of entanglement of organisms in marine plastic debris and its impact on marine biodiversity. Likewise, Saling et al. (2020) and Lavoie et al. (2021) propose dose-dependent toxicity-based effect factors. However, the link between toxicological consequences on individual organisms and an entire species’ population viability and assemblage remains unclear (Browne et al. 2015). While Corella Puertas et al. (2022) developed CFs based on persistence-based fate factors combined with the effect factors of Lavoie et al. (2021), the applicability of these marine and freshwater-focused approaches to terrestrial impacts must still be verified and other threats posed by plastic emissions, e.g., the transport of pollutants or invasive species, incorporated. A comprehensive LCIA modeling framework for marine plastic litter impacts has been developed by Woods et al. (2021), which may be extended regarding impacts also on terrestrial environments. However, no framework currently exists to assess the terrestrial impacts of plastic emissions in LCA comprehensively.

As the first case study applying the persistence-based fate factor suggested by Maga et al. (2022), this study assesses the impacts of cultivating strawberries with the help of different plasticulture methods based on an extensive literature research. The usage of plastic for strawberry cultivation (so-called plasticulture) is widespread in Germany (Society for plastics in agriculture 2019) for the following purposes:

- i. Extension or advancing of the cultivation period and protection against frosts (non-woven fabrics, flat or perforated film applied on 5965 of a total of 11,500 ha used for strawberry cultivation in Germany (51.9%))
- ii. Weed management (conventional, embossed, and biodegradable mulch film applied on 3627 ha (31.5%))
- iii. Protection systems (tunnels, greenhouses, roofs, nets, and a combination thereof applied on 1314.5 ha (11.4%))

There are areas where strawberry is cultivated without plasticulture (open field production), while a combination of more than one plasticulture method may be used in other areas. Besides the plasticulture methods, there are several further possible entry pathways of plastic into soil during strawberry cultivation, e.g., as impurities in compost (Bläsing and Amelung 2018; Weithmann et al. 2018; Bertling et al. 2021) or via soil enhancements, planting containers, trays, grow bags, swellable plugs, packaging used during nursery (Bertling et al. 2021), or irrigation pipes (Bertling et al. 2018; Bläsing and Amelung 2018). However, these practices do not represent stand-alone cultivation methods.

The primary goal of this study is to determine the differences regarding the environmental impacts of different strawberry cultivation practices in Germany, which can help farmers decide on the most suitable cultivation technique. Secondly, the study contributes to developing the LCA methodology to include possible environmental impacts caused by plastic emissions by testing the approach suggested by Maga et al. (2022) and applying it to a real-life example. The result can serve as a practical basis for scientific discussion regarding incorporating plastic emissions into LCA.

2 Materials and methods

2.1 Goal and scope definition

An LCA is conducted for Germany's most typical strawberry cultivation plasticulture scenarios, employing a cradle-to-farm-gate approach. The impacts of the plasticulture scenarios are compared to each other and to a "no treatment" scenario (NT), which serves as a baseline and represents strawberry cultivation in the open field without plasticulture. The compared scenarios are: base scenario without treatment [NT]; mulching with a film made of conventional polymers (50- μ m-thick polyethylene (PE) film) [T1], embossed film (105- μ m-thick polypropylene (PP) film) [T2], and biodegradable film (20- μ m-thick polyester-complexed starch biopolymer film) [T3]; row covering alone (200- μ m-thick spun-bonded PP film) [T4] and in combination with conventional mulch film [T5]; soil solarization alone (100- μ m-thick PE film) [T6] and with the film left on the ground after

solarization for mulching (50- μ m-thick PE film) [T7]; low tunnel alone (200 μ m thick low-density PE (LDPE) film over steel arches) [T8] and in combination with conventional mulch film [T9]; macro tunnel (film made of ethylene-vinylacetat-copolymer (EVA) over steel arches) [T10]; and greenhouse (double-layer air-inflated EVA sheets over plastic or steel arches) [T11]. Figure 1 presents the scenarios and the cultivation methods they entail.

The analyzed strawberry cultivation system can be divided into a background and a foreground system (see Fig. 2), which are both part of the considered system boundaries.

The background system includes pre-farm processes, such as the extraction of resources (e.g., oil to produce diesel), the production of inputs (e.g., fertilizer) and their transportation to the farm, and nursery (seedling production), as well as post-farm processes, such as the end-of-life of the inputs used, e.g., plastic film. The foreground system includes on-farm strawberry production and harvest processes, namely seedling planting, irrigation, fertilizer and pesticide application, machine operations (e.g., tillage), crop protection (plasticulture), and harvest. Infrastructure only employed for some of the LCA scenarios, such as greenhouses or tunnels, is part of the foreground system.

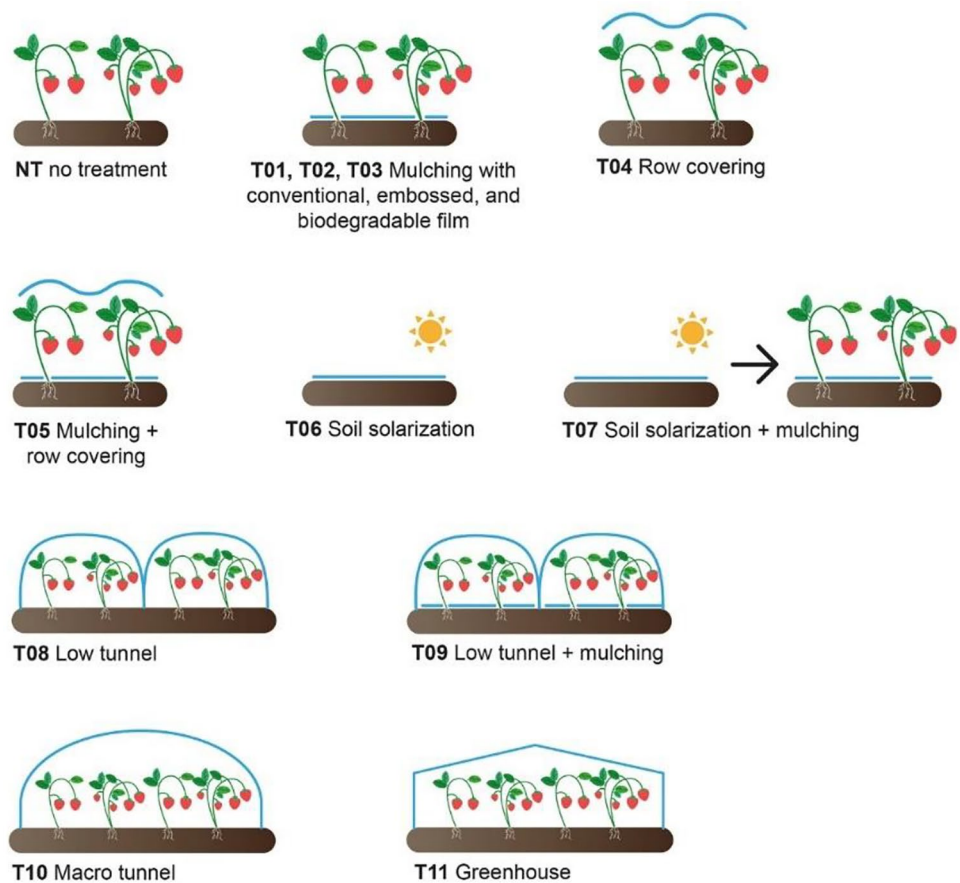
2.2 Compilation of the life cycle inventory

The LCA scenarios are modeled using the software open-LCA (Ciroth et al. 2020) and the regionalized ecoinvent 3.8 cut-off database (Wernet et al. 2016). The functional unit is 1 kg of strawberries of marketable quality at the farm gate produced in the year 2021. The amounts of fertilizer, irrigation inputs, and strawberry outputs for the plasticulture scenarios are adapted depending on the cultivation method based on an extensive literature review. Research papers were identified from peer-reviewed journals accessible via the search engine ScienceDirect based on different combinations of the search terms "strawberry," "plastic," "polymer," "non-woven," "fleece," "mulch," "LCA," and "life cycle" in the abstracts, titles, and keywords. Following a snowball approach, research papers cited in the identified publications were also considered. The extracted datasets regarding input or output parameters are provided in Online Resource 1. The data used for the LCI can be found in Online Resource 2.

2.3 Estimation of plastic emission

Most agricultural plastic is removed from the soil; the erosion of the materials and the subsequent emission of microplastics into the environment are undesired side effects (Serrano-Ruiz et al. 2021). Bertling et al. (2021) estimate that all plasticulture methods are relatively open environments with a considerable probability of plastic emission to

Fig. 1 Summary of the analyzed scenarios of the treatment options NT to T11; the blue color represents the plastic material



the environment. Based on the expected exposure to weather conditions, mechanical stress, and the separability from the soil of the plastics employed, Bertling et al. (2021) estimate annual mass loss rates of 3.2% for mulch and soil solarization film, 0.32% for row covers and embossed film, and 0.032% for tunnel and greenhouse film. We assume that so-called biodegradable film is tilled into the soil after usage; therefore, a loss rate of 100% is assumed in scenario T03. Like Bertling et al. (2021), we assume plastic losses are directly emitted to the soil.

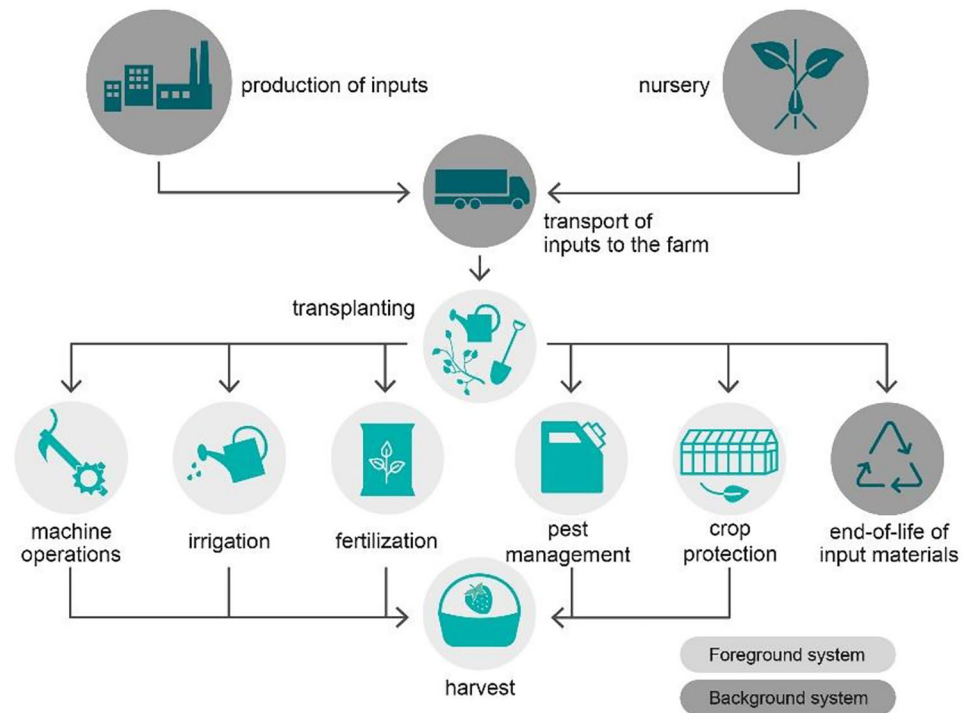
2.4 Life cycle impact assessment

The environmental impacts are assessed using the life cycle impact assessment (LCIA) method of the Product Environmental Footprint (PEF) 3.0 recommended by the Joint Research Centre of the European Commission (EC-JRC) (Publications Office of the European Union 2012), which is extended by a method accounting for plastic-related impacts. The PEF-characterized midpoint indicator results are normalized using global normalization factors (Joint Research Centre of the European Commission 2018) for the reference year 2010. Two different sets of weighting factors (WFs) for the PEF LCIA method provided by the EC-JRC are applied;

one is referred to as “33:33:33”-approach because it combines the weighting results of three sources equally, and the other is referred to as the “50:50”-approach because it combines the weighting results of two approaches equally. The two approaches are (i) panel based and (ii) a combination of evidence-based (building upon the research described in Soares et al. 2006) and expert judgment. For the panel-based approach, two different groups were asked: (a) individuals of the general public and (b) LCA experts (Joint Research Centre of the European Commission 2018). As recommended by the EC-JRC, toxicity impacts (human toxicity cancer, human toxicity non-cancer, and freshwater ecotoxicity) are excluded from the normalization and weighting because those impact categories are not seen as sufficiently robust (Joint Research Centre of the European Commission 2018).

Since plastic impacts on the environment are currently not considered by the PEF LCIA method, the analysis is extended by assessing the persistence of the scenarios' plastic emissions measured in plastic pollution equivalents (PPE). The persistence of plastics is defined as the time a plastic emission remains in the environment (Maga et al. 2022). PPE depend on the degradation time of a plastic in the environment (expressed by the specific surface degradation rate, SDR), the diameter of the emitted plastic

Fig. 2 System boundaries of the presented LCA of strawberry cultivation



item, the initial environmental compartment, and redistribution patterns. Results in the “plastic pollution” category are expressed as kg PPe. The CFs provided by Maga et al. (2022) encompass redistribution mechanisms within the environment. However, the impacts of the redistribution of adjacent pollutants or leached additives to other compartments (van Cauwenberghe et al. 2013, Jambeck et al. 2015, Chae and An 2018, de Souza Machado et al. 2018, Wong et al. 2020) are not considered. The biodegradability of the starch-blend film is factored into the impact assessment by applying the corresponding fate factor of Maga et al. (2022). Nevertheless, it must be noted that this fate factor is based on starch blends whose compositions differ from the one used in this study, possibly impacting the quality of the results. While Maga et al. (2022) do not provide factors for EVA, they suggest using an SDR of 0.001 μm per year for polymer types with no degradation data available. Based on this SDR and the redistribution patterns, CFs are calculated. A time horizon τ_H of 100 years is applied as for global warming potentials in the PEF LCIA method. By choosing a time horizon τ_H of 100, short-term effects of plastic pollution are addressed, and long-term consequences are not overestimated.

For plastic pollution, no normalization factor exists to date. Some authors have quantified plastic emissions, e.g., Jambeck et al. (2015) (only mismanaged plastic waste), Bertling et al. (2018) (including emissions that might be recovered, e.g., by street cleaning), Amadei et al. (2022)

(only marine and beach litter), and the OECD (2022). However, these values only quantify plastic emission, which still needs to be characterized to calculate plastic pollution. A first attempt to develop a normalization factor for plastic pollution was made by Bertling (2022) for Germany but has not yet been subjected to peer review. Based on an emission of 4.0 kg/(cap a) and an assumed share of easily degradable polymers such as polyhydroxyalkanoates or polycaprolactone of 1% (1 kg PPe/kg), medium degradable polymers such as rubber or polylactic acid of 34% (10 kg PPe/kg), little degradable polymers such as polysulfones or polyamides of 20% (50 kg PPe/kg), and hardly degradable polymers such as polyolefins, polystyrene, or polyvinylchloride of 45% (90 kg PPe/kg), they estimate the annual PPe to be ~ 215 kg PPe/(cap a). Applying the same assumptions to a global annual emission of 2.8 kg/(cap a) based on the plastic emission estimate of the OECD (2022) and population data provided by the United Nations (2022) leads to a normalization factor of ~ 150 kg PPe/(cap a) for plastic persistence. Because their assumptions have not yet been scientifically verified, this normalization factor can only be used as a proxy to give a rough indication of the scope of the plastic problem. Because no WF exists for plastic pollution, this category’s results will be weighted with the highest and lowest WF of each approach. The WFs of the PEF impact categories are scaled down accordingly to reach a total of 100%. The WFs used can be found in Online Resource 4.

3 Results

The results of the literature review can be found in Online Resource 1. Online Resource 2 includes a summary of the parameters used for the compilation of the LCI of the scenarios regarding water and nutrient demand, yield, and plastic emissions based on the literature review. The nutrient demand was adapted based on the molecular mass of the nutrient (N, P, K) in the fertilizer inputs of the original datasets. Details regarding the environmental impacts of the plasticulture scenarios can be found in Online Resource 4. NT has one of the three highest impact scores in 9 of the 17 impact categories and one of the lowest three scores regarding plastic pollution. T10 (macro tunnel) and T11 (greenhouse) also reveal comparably high impacts in the PEF impact categories compared to the other scenarios. T05 (row covering combined with conventional mulch film) has one of the three lowest impact scores in all PEF impact categories. However, the impact score of plastic pollution of T05 only ranks eighth. T01 (conventional mulch film) and T07 (soil solarization in combination with conventional mulch film) also have one of the lowest three impact scores in 12 and 8 out of the 17 impact categories, respectively. However, regarding plastic pollution, NT, T04 (row covering), and T08 (low tunnel) have the lowest impact scores. All scores per impact category can be found in Online Resource 4.

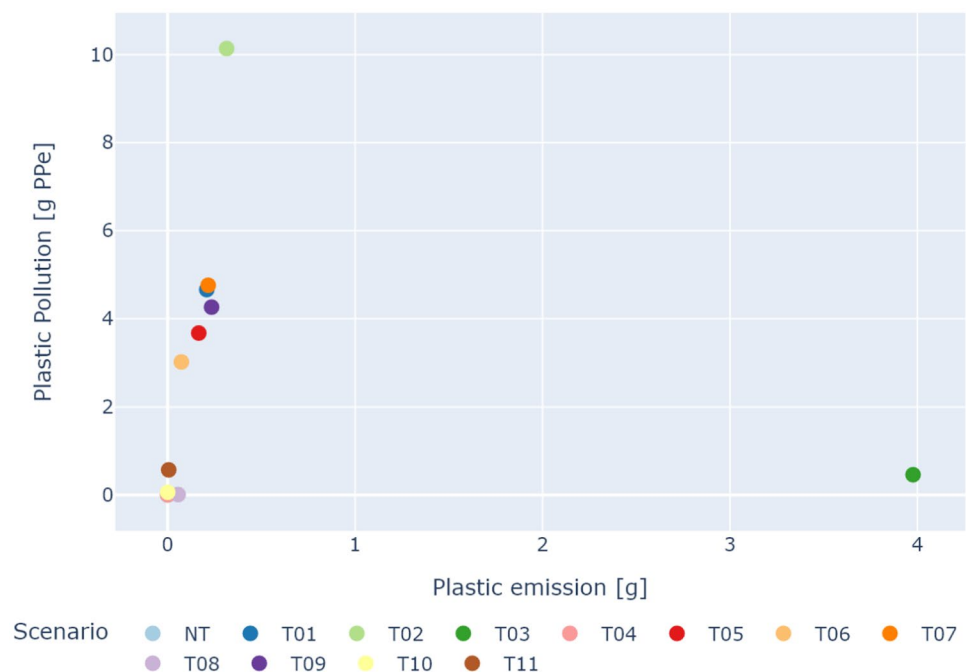
Figure 3 displays the amount of emitted plastic masses on the *x*-axis and plastic pollution on the *y*-axis. T03 emits the highest amount of plastic: 3.98 g per kg strawberries because the biodegradable mulch film used for T03

is entirely tilled into the soil after the cultivation period. NT and T04 emit the least plastic (0.0 and 0.00006 g per kg strawberries, respectively). Figure 3 shows that plastic pollution is not linearly correlated to the amount of plastic emitted. Due to the biodegradability of the starch-based mulch film in T03, the plastic pollution score of T03 is only one-tenth of the one of conventional mulch film (T01). Plastic pollution is the highest in T02 with 0.01014 kg PPe because the yield is comparatively low in this scenario (1.17 kg compared to 1.0 kg in NT) and the polymer used for the embossed mulch film (PP) hardly degrades.

The normalized and weighted impact scores can be found in Online Resource 4. When applying the 50:50-weighting approach, T03 and T05 have the lowest total impacts (8.65E-04 and 8.33E-04 with $WF_{\text{plastic pollution}} = 3.47$, and 8.06E-04 and 1.00E-03 with $WF_{\text{plastic pollution}} = 13.61$). The highest environmental impacts are caused by T10 (2.46E-03 or 2.21E-03, depending on $WF_{\text{plastic pollution}}$) and T11 (3.29E-03 or 2.99E-03). NT ranks eighth with $WF_{\text{plastic pollution}} = 3.47$ and sixth with $WF_{\text{plastic pollution}} = 13.61$, starting with the lowest overall impact score.

When applying the 50:50-weighting approach, 8.2–19.2% of the overall environmental impacts are contributed by the impact category “climate change” depending on the scenario and $WF_{\text{plastic pollution}}$. Further top three contributing categories to the total environmental impacts are “plastic pollution” (0.0–54.4%), “water use” (5.0–18.4%), and “marine eutrophication” (5.3–12.1%). Plastic pollution is among the top three contributors to the overall environmental impacts in three scenarios (T01, T02, and T07) with $WF_{\text{plastic pollution}} = 3.47$

Fig. 3 Emitted plastic mass per scenario and plastic persistence in the environment



and six scenarios (T01, T02, T05, T06, T07, and T09) with $WF_{\text{plastic pollution}} = 13.61$. In T03, “acidification” is the second largest contributor, accounting for 11.9–12.4% of the impacts due to direct emissions (54.7%) and diesel burned in agricultural machinery (40.2%). In T09, “resource use (fossil)” contributes 9.9–12.8% to the overall impacts caused mainly by the low tunnel production (45.8%), diesel burned in agricultural machinery (33.7%), and mulch film production (17.4%). In T10 and T11, “resource use (minerals and metals)” is the third largest contributor to the environmental impacts due to the production of the infrastructure. If the 33:33:33-weighting-approach is applied, the same categories contribute most to the overall impacts; only the categories’ shares of the total impact change slightly. No matter which weighting approach is used, the ranking of the scenarios according to their overall impact score is the same. In contrast to the weighting approach, $WF_{\text{plastic pollution}}$ influences the ranking of the scenarios: while the two scenarios with the lowest and highest environmental impacts are the same, the ranks of four scenarios change by more than one rank with the higher $WF_{\text{plastic pollution}}$ compared to the lower one: the ranking of scenarios with a comparatively low plastic pollution score NT and T04 improve by two ranks, each. Contrarily, the ranking of T02 worsens by four ranks and the ranking of T09 by two ranks due to the comparatively high impact score for plastic pollution.

Regarding “climate change,” the biggest contributor in most scenarios is diesel burned in agricultural machinery (e.g., 52.2% in NT, 44.5% in T05, 49.6% in T07). In T08,

T09, T10, and T11, it is the production of the respective infrastructure (33.5% in T08, 47.6% in T09, 48.9% in T10, and 72.4% in T11). In NT, direct emissions of strawberry cultivation contribute 21.3% to the global warming impacts and irrigation 20.6% due to the operation of the water pump. The contribution of plastic production to climate change is less than 1% in T04 and ranges between 3.4 and 7.7% in the other scenarios involving a mulch film or row cover. In mulch film scenarios, plastic waste management contributes up to 13.7% to the global warming impacts if a PE film is used and 9.6% in T02 where a PP film is used.

Most of the impacts on “water use” are generated via irrigation (54.4–99.6% depending on the scenario). The production of mulch films, row covers, tunnels, and greenhouses contributes up to 45.4% to the water use impacts. During strawberry cultivation, small amounts of water are released back to surface water and groundwater, resulting in a negative contribution to water use accounting for 2.4–4.5% of the impacts.

In NT, 79.0% of the marine eutrophication impacts are generated by direct emissions, mainly via fertilizer application, and 18.8% by diesel combustion in agricultural machinery. Although the shares vary among the scenarios, the main contributors do not change.

Figure 4 visualizes the contribution of different processes to the environmental impacts of strawberry cultivation in each impact category. Scores are given for T01 as an illustrative example. Data on the other scenarios can be found in Online Resource 4. Plasticulture (indicated in dark blue) refers to

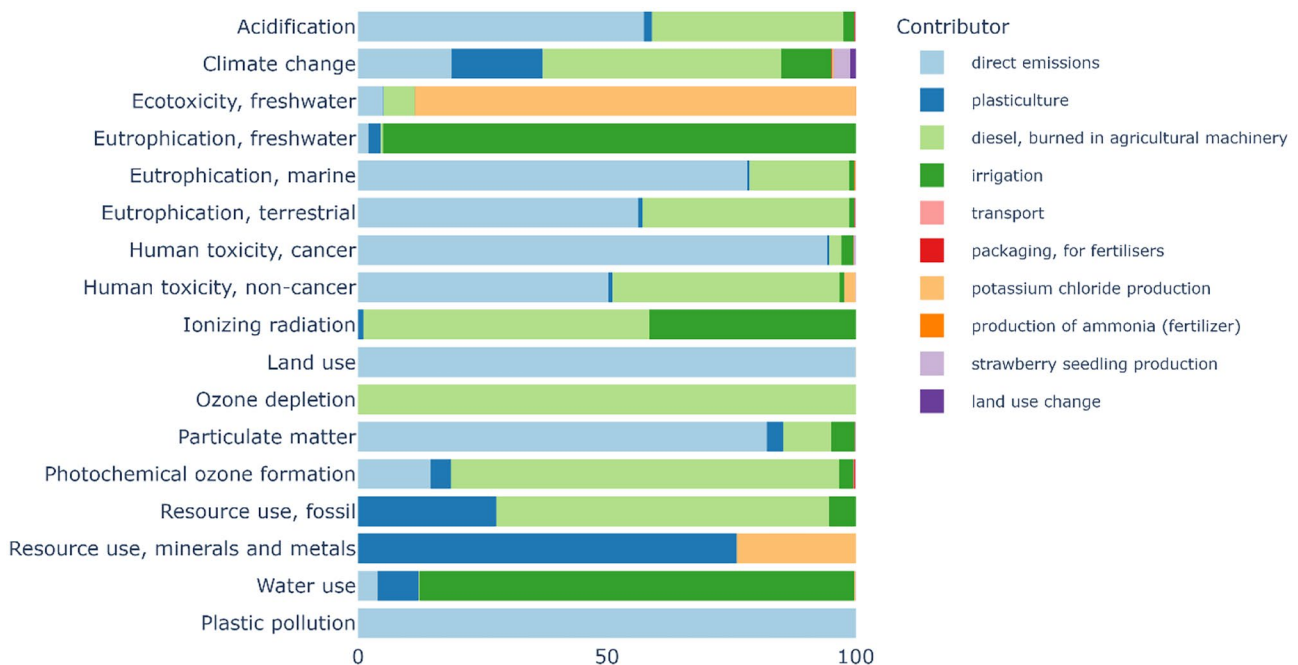


Fig. 4 Contribution analysis of an example scenario: mulching with conventional film (T01)

material production, installation, and end-of-life of the materials needed for the plasticulture method. Indicated in light blue, direct emissions (e.g., leaching of fertilizer to soil) cause more than 50% of the impacts in six to eight of the considered impact categories for the scenarios NT and T01–T09. For these scenarios, plasticulture contributes less than 50% to all impact categories, except for “resource use, minerals and metals” for scenarios T01 and T05–T09 and “resource use, fossil” for T09. In T10 and T11, direct emissions only contribute 50% or more to two impact categories: “marine eutrophication” and “land use.” For these scenarios, the contribution of plasticulture to the impacts is greater: it contributes more than 50% to four categories in T10 and nine categories in T11.

Figure 5 displays the total normalized and weighted impact scores for all scenarios and four variations: the 50:50-approach with $WF_{\text{plastic pollution}} = 3.47$ (a) and 13.61 (b) and the 33:33:33-approach with $WF_{\text{plastic pollution}} = 3.74$ (c) and 14.65 (d).

In scenarios with low plastic pollution (NT, T03, T04, T08, T10, T11), the overall impact score is 7–12% lower when the higher WF is chosen for plastic pollution, regardless of the weighting approach. Independent of $WF_{\text{plastic pollution}}$, the 50:50-approach leads to 1–5% lower impacts for all scenarios than the 33:33:33-approach.

Figure 6 displays the contribution of the impact categories to the total impact scores for all scenarios and two variations: the 50:50-approach with $WF_{\text{plastic pollution}} = 3.47$ (a) and 13.61 (b).

The scenarios can be grouped according to the contribution pattern of the impact categories to the overall results. In group A (NT, T04, T08), plastic pollution contributes less than 0.1% to the overall impacts because no plasticulture is employed (NT), very little plastic is emitted during plasticulture (T04), or the plastic emission degrades comparably rapidly (T08). Group A scenarios have no impact on the water and nutrient demand during cultivation. Group B consists of all scenarios employing conventional or embossed mulch film (T01, T02, T05, T07, T09), leading to a contribution of plastic pollution to the impacts of 8.7–54.4% and reducing the water and nutrient demand during cultivation. T06 also employs plastic film for soil solarization, leading to plastic pollution impacts of 4.4–17.7%, but does not affect water and nutrient demand. Because of this difference to the scenarios in group B, T06 forms group C. The scenario with the biodegradable film (T03) does lead to a lower water and nutrient demand, but plastic pollution impacts are low compared to the scenarios in group B (1.2–5.5%). Therefore, group D consists of T03 only. The last group, E, contains T10 and T11, the only scenarios where resource use for infrastructure installation is among the top three contributing categories to the overall impact score (contribution of 9.8–12.0%). Plastic pollution occurs, but its contribution to the overall impact score is small (0.1–1.9%). Water and nutrient demand are not affected by the scenarios in this group.

Fig. 5 Total impact scores of the plasticulture scenarios: (a) 50:50-approach; $WF_{\text{plastic pollution}} = 3.47$; (b) 50:50-approach; $WF_{\text{plastic pollution}} = 13.61$; (c) 33:33:33-approach; $WF_{\text{plastic pollution}} = 3.74$; (d) 33:33:33-approach; $WF_{\text{plastic pollution}} = 14.65$

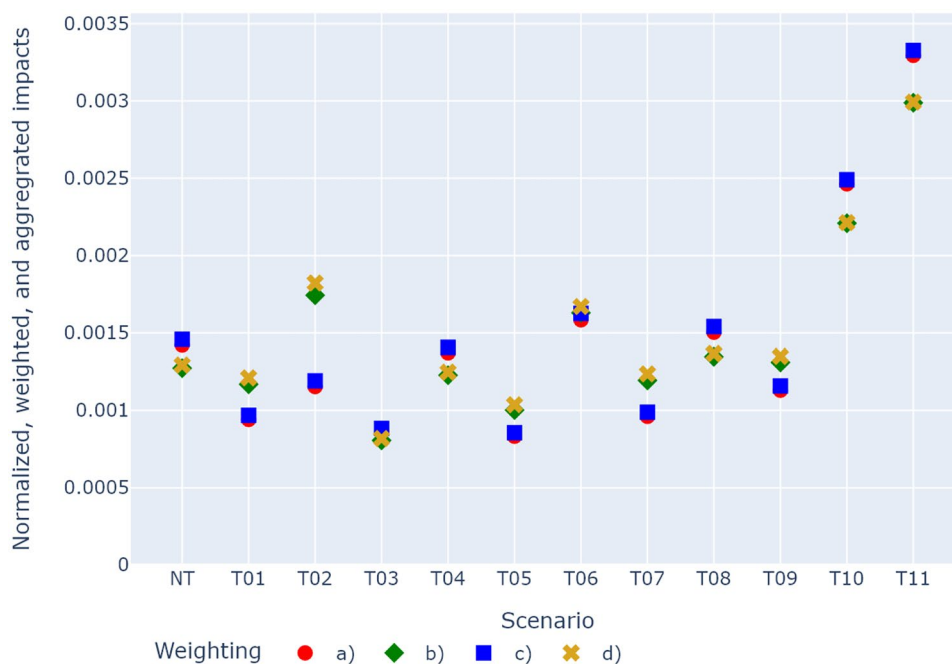




Fig. 6 Contribution of the impact categories to the total impacts of the plasticulture scenarios (50:50-approach): (a) $WF_{\text{plastic pollution}} = 3.47$; (b) $WF_{\text{plastic pollution}} = 13.61$

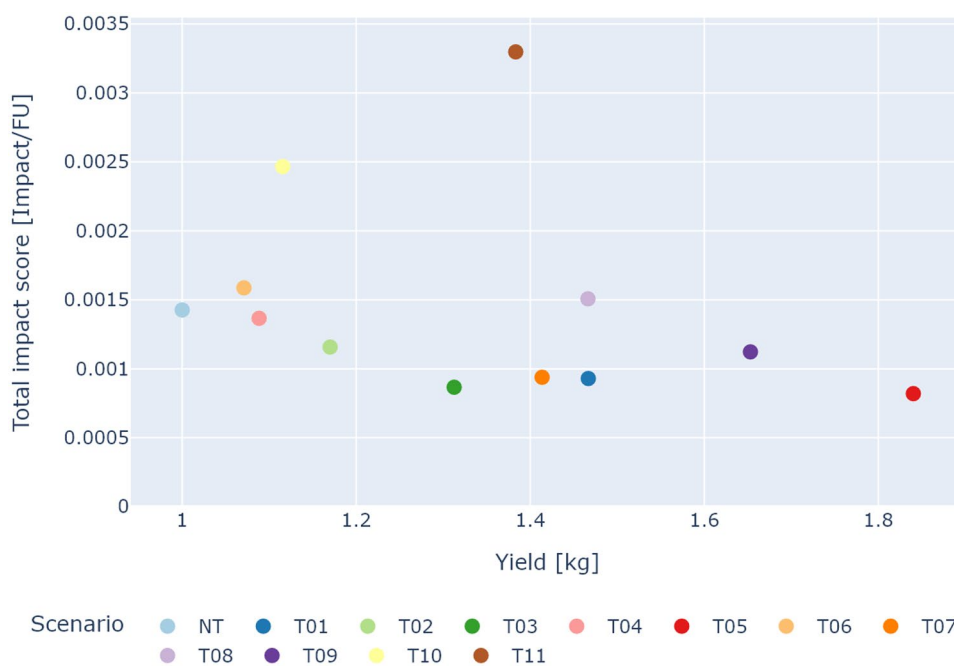
4 Discussion

4.1 Overall environmental impacts of strawberry cultivation

Surprisingly, there seems to be no trade-off between maximizing productivity and lowering environmental impacts. Instead, the scenario with the highest yield (T05) also has the best or second-best overall impact score, depending on $WF_{\text{plastic pollution}}$. This finding is supported by other authors, e.g., Tabatabaie and Murthy (2016). Substituting conventional with biodegradable mulch film (T01 vs. T03) reduces the overall impacts by 8.2–32.1% depending on the weighting approach and $WF_{\text{plastic pollution}}$. With a high $WF_{\text{plastic pollution}}$, using biodegradable mulch film results in the lowest overall impacts. Figure 7 displays the yield according to the literature review on the *x*-axis and the total impact score

on the *y*-axis using the 50:50-weighting approach with $WF_{\text{plastic pollution}} = 3.47$. Located in the top left corner, the scenarios using a macro tunnel (T10) or greenhouse (T11) for strawberry cultivation result in the highest environmental impacts and only seem attractive if out-of-season yields generate a much higher profit for farmers or out-of-season labor is considerably cheaper. Regarding the plastic pollution impacts, as outlined in Sect. 2.4, no CFs were available for the material used in the macro tunnel and greenhouse (EVA); therefore, the highest possible CF was used. This does not necessarily represent reality. Assuming a degradation speed of EVA equal to one of the fastest materials in this study would improve the ranking of T10 and T11 regarding plastic pollution to ranks second (T10) and third (T11) of all scenarios. Nevertheless, the overall impacts of these two scenarios would still be the worst. Moreover, the yields obtained are mediocre (rank 9 for T10 and rank 6 for T11).

Fig. 7 Total environmental impact score per functional unit (1 kg strawberries of marketable quality at the farm gate produced in the year 2021) (50:50 approach, $WF_{\text{plastic pollution}} = 3.47$) and yield per scenario



Likewise, while NT renders the lowest yield, the environmental impacts are intermediate (ranks 6–8). That explains why most of the area used to grow strawberries in Germany is cultivated using one or more methods of plasticulture (Society for plastics in agriculture 2019). Similarly, as depicted in Fig. 7, embossed mulch film (T02), row covers (T04), and soil solarization (T06) alone score low regarding the yield and intermediate regarding environmental impacts (located at the lower left side of Fig. 7). The yield of T08 is a bit higher, but the environmental impacts are only intermediate. Instead, combining mulch film with row covers (T05) seems the best option (located at the lower right side of Fig. 7). Although it might be expected that increased plastic usage by combining two plasticulture methods would worsen the environmental performance, the increased yield obtained by combining the techniques in T05 offsets the increased plastic pollution impacts. T01, T03, and T07 also result in comparably low environmental impacts, but the yield is only intermediate. The yield is higher in T09, but so are the environmental impacts.

Concerning plastic pollution, all impact scores are relatively low (0.0–0.001 kg PPe). In the worst scenario regarding plastic pollution (T02), producing 1 kg of strawberries causes the emission of ~ 10 g of plastic, which remains in the environment for around one year. Nevertheless, after normalization and weighting, plastic pollution makes up a considerable share of the overall environmental impact of strawberry cultivation (up to 54.5%, depending on the scenario and the weighting method applied). These results exemplify the influence of the normalization and weighting step on the total score in general and, more specifically,

for the plastic pollution impact category. Hence, while we are using a preliminary normalization and a best/worse-case estimate for the weighting factor, this calls for further investigation of global plastic emission inventories and inclusion of future considerations in weighting approaches to estimate the, although subjective, relevance of the plastic pollution matter compared to other environmental impacts.

4.2 Applicability of the plastic pollution methodology

This study is the first to include potential impacts caused by plastic emissions in an LCA by implementing the preliminary impact assessment method developed by Maga et al. (2022). First, the method can point out polymer-specific pollution impacts, which is relevant to compare innovative, biodegradable materials to conventional ones and provide improvement potentials to technology developers. As displayed in Fig. 3, there is a clear difference in the gravity of the impacts of different polymer types, such as biodegradable and conventional ones, but also of different conventional polymer types (e.g., PE vs. PP). This differentiation can support product design and make the environmental impacts of different materials tangible. Nevertheless, for some materials, the fate factors are rather generic. For example, the fate factor for the biodegradable material in this study is based on starch blends whose compositions differ from the one used in this study. Besides, because no fate factor was available for EVA, a generic SSSDR was used. This may impact the quality of the results and increase the uncertainty regarding the derivation of (technical or political) measures.

Second, the method utilizes environmental compartment-specific degradation rates and thus allows for an analysis of impacts focusing on a particular compartment. Nevertheless, a compartment-specific analysis is of little interest in our case study because all plastic is emitted to soil and 97% remains there. A compartment-specific analysis might be helpful, especially for applications where plastic is emitted to a different environmental compartment with greater redistribution or for developing mitigation measures for a particular compartment. Third, the characterization factors provided by Maga et al. (2022) are specific to Germany, which is also the focus of this case study. Based on the literature research and the formulas provided, it is possible to calculate characterization factors for different locations. Besides the location, characterization factors might also change if additional knowledge regarding degradation rates becomes available. The factors are, therefore, adaptable, and a comparison of future plastic pollution studies needs to consider the geographic location and date of publication of the characterization factors used.

Overall, the question remains how to integrate plastic pollution into existing impact assessment methods. The LCIA methods considered by the PEF currently do not address the impacts of plastic emissions on the environment and should, therefore, be extended. However, this is challenging considering that the method has been developed by the European Commission jointly with stakeholders. A first attempt was made in this study, but it relies on normalization and WFs that have not yet been scientifically developed. The value used for normalization in this study is the first estimate and needs to be further validated. Instead of choosing and recommending a particular WF, we employed both the lower and upper bound of the WFs suggested by the EC-JRC for the original impact categories of the PEF LCIA method (Joint Research Centre of the European Commission 2018). The most accurate WF may, however, lie somewhere in between. The WF does not make a difference when ranking the scenarios according to their overall score, but it does when determining the contributing impact categories to the overall score.

4.3 Comparison to the results of other authors

When comparing the results of the present study to those of other authors, several limitations must be considered. First, system boundaries and modeling assumptions are often different. Second, most other authors focused on individual impact categories, such as climate change or water use, and did not calculate impacts regarding all PEF categories for strawberry cultivation. Third, different indicators and assessment methods may be used for specific impact categories. Fourth, some authors do not disclose all the necessary information for a proper comparison or only display certain results in a graph (e.g., Soode-Schimonsky et al. 2017).

Nevertheless, Online Resource 5 displays data found in the literature regarding a complete PEF (including all impact categories suggested by the EC-JRC and a corresponding normalization and weighting) and the most contributing individual impact categories in this research: global warming and marine eutrophication. Although water use is also a relevant contributor to the environmental impacts in this study, the results cannot be compared to other authors (e.g., Yoshikawa et al. 2008; González et al. 2011; Sorgüven and Özilgen 2012; Khoshnevisan et al. 2013; Webb et al. 2013; Valiante et al. 2019; Hosseini-Fashami et al. 2019) who assessed the total water use instead of the deprivation-weighted water consumption according to the available water remaining model as recommended by UNEP (2016). Scenarios that have been examined regarding their environmental impacts by other authors are NT, T01, T05, T10, and T11, as well as further combinations not covered in our research, such as macro tunnel in combination with conventional mulch film, row cover, or both, and greenhouse in combination with conventional or biodegradable mulch film or row cover. When comparing the PEF-compliant results found to our results, please keep in mind that our study is not PEF-compliant due to deviations from the PEF methodology, mostly in the LCI phase and regarding the system boundaries.

Few comparable studies are available regarding plastic pollution caused by strawberry cultivation. According to Galati et al. (2020), 86 g of plastic polymers are used when producing 1 kg of marketable strawberries, including compost, soil enhancements, and planting containers. However, the authors do not quantify the share of plastic emitted into the environment. Bertling et al. (2021) estimate the amount of plastic emission into agricultural soil in Germany caused by agricultural and non-agricultural processes, including littering. They present emission data for fields cultivated with different types of mulching, row cover, low tunnel, macro tunnel, and greenhouse cultivation; however, the data are not specific to strawberries but to plant cultivation in general. Because the presented data are expressed on a per-hectare basis without a correlation to the yield, a comparison to the results of the present study is difficult.

4.4 Limitations

When interpreting the results of the present study, some limiting factors need to be considered. First, specific data quality inadequacies and uncertainties need to be embraced. For example, the different parameter values used during the compilation of the LCI of this study are derived from a literature review of several authors who conducted experiments that differed in setups, e.g., regarding within-row plant spacing and between-row spacing. Paranjpe et al. (2008) showed that these factors influence the marketable yield per plant. Besides, different cultivars chosen according to climatic

conditions or consumer tastes also result in different yields (Sønsteby et al. 2013). Due to the various factors considered in the presented cultivation models, the impacts of the plant density and the cultivar were neglected.

Second, the models of the plasticulture scenarios are based on a generic dataset initially developed for strawberry cultivation in the USA. The provided data were adapted to German conditions and a pesticide forbidden in the EU (trichloromethane) was deleted. The adoptions, however, were made without verifying them in conversations with strawberry farmers in Germany. While a comprehensive and detailed census of cultivation inputs for all plasticulture scenarios in Germany exceeded the scope of the present study, it needs to be kept in mind that differences in legal and practical prerequisites may lead to the usage of different inputs in different countries. Nevertheless, we assume that the used models reflect strawberry cultivation in Germany with acceptable certainty.

Third, the plastic material inputs are modeled focusing on their primary polymer. Any mixtures of polymer types or additives are considered neither during the LCI phase nor adequately by the characterization factors provided by Maga et al. (2022). On the one hand, such additives might accelerate the degradation, leading to an overestimation of plastic persistence in the environment. On the other hand, additives may cause toxic environmental reactions (Serrano-Ruiz et al. 2020), whose impacts are not addressed.

Fourth, when interpreting the results of plastic pollution, it needs to be kept in mind that so far, only direct plastic emissions are considered. Any plastic emissions during upstream or downstream processes, e.g., mulch film blow molding or recycling, are not yet included in the models. Assuming that plastic is emitted during those processes, the total plastic pollution is likely (much) greater. Besides, the fact that the plastic pollution impact category is currently limited to the mere persistence of plastic in the environment and is extendable to but does not yet include integration with exposure and effect factors needs to be considered.

Finally, it lies in the nature of the PEF LCIA method that impacts on a macro level and at an endpoint level are not considered. For example, on a macro level, plasticulture (especially macro tunnels and greenhouses) significantly prolongs the cultivation period of strawberries in Germany, making cultivation possible both earlier and later in the year. Besides the direct economic benefits for farmers who are thus able to achieve a higher selling price outside the most common harvest period, this also increases the share of locally produced products, possibly influencing the environmental impact of strawberry consumption on a national scale. Since LCI data and characterization factors for plastic pollution are specific to Germany, it is not possible to extrapolate the results of this study to other geographic settings. Furthermore, the indicators of the PEF LCIA method

package are on a midpoint level and do not quantify impacts on an endpoint level, e.g., regarding areas of protection.

5 Conclusion and outlook

Plastic is widely used during strawberry cultivation to adjust specific parameters for farmers' convenience, e.g., soil temperature or moisture. While several other studies estimate or quantify the abrasion or erosion of these plastics during the cultivation and their release into the environment, the present study is the first to relate such emissions to different cultivation methods and put them into the broader context of other environmental impacts. The study presents the effects of eight plasticulture methods and three combinations thereof on the yield, water and nutrient savings, and plastic masses that are to be employed and are assumed to be partly released into the environment. The main highlight is that all cultivation methods using conventional or biodegradable mulch film or a row cover outperform the open field scenario, whether plastic pollution is considered or not. Based on the present results, farmers should opt for the combination of row covers with conventional mulch film. Cultivation management should not focus solely on economic gains, e.g., by adjusting the timing of the harvest with the help of greenhouses, but also consider the environmental impacts of these plasticulture methods and reduce these impacts of the material input by reuse and proper recycling.

This study has several implications for the scientific community. First, the CFs provided by Maga et al. (2022) rely mainly on SSDRs obtained from literature. However, the setups of the experiments vary, making a consolidation into CFs difficult. Besides, the CFs do not consider additives or encompass all polymer types, such as EVA. There is, therefore, a need for further research and standardization. Additionally, the methodology for including plastic-related impacts in LCA needs further development. Although the persistence of plastic in the different environmental compartments enables and facilitates the exposure of organisms and ecosystems to plastic emissions, more research is needed to link it to effects, e.g., on ecotoxicity or soil productivity. The exposure and effect pathways outlined by Woods et al. (2021), the effect factors provided by Saling et al. (2020) and Lavoie et al. (2021), and the CFs developed by Corella Puertas et al. (2022) can serve as a starting point for marine and freshwater. Nevertheless, due to the limited redistribution of plastic initially emitted from soil to other compartments, corresponding frameworks must also be developed for soil and river sediment. Additionally, suitable impact categories need to be defined by incorporating plastic-related impacts into existing or new ones. To assess environmental impacts also on an endpoint level, the effects of plastic pollution on areas of protection need to be further studied and

the methodology presented by Maga et al. (2022) further developed. To integrate plastic impacts into existing impact assessment systems, such as the PEF LCIA method, a suitable weighting method needs to be developed for plastic pollution compared to the other impact categories. The normalization and WFs used in the present study are a first attempt and need to be scientifically discussed and evaluated. With the factors used, plastic pollution makes up a considerable share of the overall environmental impact of strawberry cultivation, supporting the recent efforts of different research groups to include plastic emissions in LCA by developing suitable characterization factors. Besides, the background processes in existing LCA databases need to be adapted by an estimation of plastic emissions to consider the impacts of upstream and downstream processes.

To reduce the environmental impacts of the plasticulture methods, materials scientists should improve conventional materials, e.g., regarding their rip resistance, to limit emission rates. To make biodegradable agroplastics competitive, their effects on the cultivation parameters, such as water and nutrient demand and yield, as well as their degradability under real-life conditions on the field, need to be enhanced.

Concerning the political dimension, the results of this study lead to the suggestion to regulate certain parameters of plastics that are in direct contact with soil, such as rip resistance and permitted polymer types and additives. Besides, the legal framework should incentivize the complete recovery and proper end-of-life treatment of agroplastics. Possible legal restrictions should encourage the use of plasticulture methods that reduce environmental impacts compared to open field cultivation.

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Data Availability All data generated or analyzed during this study are included in this published article and its supplementary information files.

Declarations

Conflict of interest The authors declare no competing interests.

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