Journal of Cleaner Production 380 (2022) 134887

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Environmental benefits of circular food systems: The case of upcycled protein recovered using genome edited potato

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ARTICLE INFO

Keywords:
Life cycle assessment (LCA)
Resource recovery
Circular bioeconomy
Food waste valorization
CRISPR-Cas9

ABSTRACT

Although essential in the human diet, large quantities of available protein are currently lost or under-utilized within the food system, including protein rich side streams from conventional potato starch production. By using the genome editing technique CRISPR-Cas9, conventional starch potato cultivars can be upgraded to facilitate high-value recovery of potato protein fit for human consumption. In turn, this could support the nessecary transition towards more circular food systems. The aim of this study was to assess what environmental benefits could be gained by shifting from conventional protein recovery practice to a novel approach using genome edited potato. Our results, using consequential life cycle assessment, showed that the novel protein recovery scenario provided substantial environmental savings for every ton potato starch produced, with a reduction in global warming impact, terrestrial acidification, land use and ecosystem damage of −720 kgCO$_2$eq, −13 kgSO$_2$eq, −760 m^{2}a crop eq, and -1.1×10^{-5} species.yr respectively. The potential environmental benefits of using genome edited potato were maintained even when simulating reduced tuber yield, increased production inputs, and substitution of various protein sources. Although currently limited by EU legislation and technical maturity, high-value protein recovery from food side streams holds a promising potential to support sustainable production and circularity within the food system.

1. Introduction

Due to limited planetary resources and global population growth, a transition towards circular food systems will be required to meet the future nutritional needs. Our ability to increase food production is limited by an increasing competition for land and natural resources, often resulting in overexploitation, damage to vital ecosystems, and substantial environmental impact (Rockström et al., 2020; Tian et al., 2021). Resource inefficiencies, under-utilized food side streams and unsustainable dietary patterns are major risk factors for global food security, climate change mitigation and maintained biodiversity (Crenna et al., 2019). To ensure sustainability within future food systems, multi-action approaches are urgently required, ranging from circular supply chains, increased production limits and use of genetically engineered crops, to a shift towards plant-based diets (Godfray et al., 2010; Qaim, 2020). Achievement of these goals require in-depth knowledge and assessment of the supply chain (Vidergar et al., 2021).

Protein from animal and plant sources supplies essential macronutrients to the human diet. With a steadily growing global population, the increased demand for protein must be accommodated without exceeding the planetary boundaries or further jeopardizing the sustainable development goals set by the United Nations (Scherer et al., 2020). A transition towards plant-based diets generally infers lower environmental impact, while also bringing additional health benefits compared with animal-based diets (Willett et al., 2019; Röös et al., 2020; Rysselberge and Röös, 2021). Potatoes are considered among the most important food crops globally (FAO. World, 2021), containing both starch, protein, fiber and trace nutrients. Potato starch, derived via industrial processing where the protein, fibre and nutrient fractions are removed, is often used as an additive to improve stability and texture in for instance sauces, bread and soups, as well as gluten-free and plant-based products. Alongside food applications, potato starch is also used within paper and textile industry. The global market for potato starch was around 3.4 million metric tonnes (tons) in 2020, and is expected to continue to increase (Kowalczewski et al., 2022). In Sweden alone, over 878 000 tons of potato were harvested in 2020, of which around 40% was used to produce potato starch (Wahlstedt, 2020). The remaining protein, fiber and trace nutrients arising as side streams are

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https://doi.org/10.1016/j.jclepro.2022.134887
Received 18 March 2022; Received in revised form 18 August 2022; Accepted 24 October 2022
Available online 28 October 2022
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most commonly reused to produce dietary fiber (Sampaio et al., 2020; Singh et al., 2022; Dey et al., 2021), treated in biorefineries, anaerobic digestion, or evaporated and sold as animal feed or fertilizer (Souza Filho et al., 2017; Caldeira et al., 2020; Grommers et al., 2009). However, increased circularity and re-usability of by-products within the food system is identified as an important step towards sustainable food systems.

Potato protein is one of few the plant-based proteins that supplies a complete amino acid profile (Pęksa and Miedzianka, 2021), with a high biological value that implies high quality and absorption when consumed by living organisms (Camire et al., 2009). Isolated potato protein, in particular the main protein structure *patatin*, can be used in food applications to substitute egg or dairy as it exhibits excellent emulsifying, gelatinizing, and foaming properties (Johansson and Samuelson, 2018; Fu et al., 2020a). Unlike soy, dairy, egg, and wheat, potato protein is free from allergens (Hussain et al., 2021). The current protein recovery practice within starch production involves heat coagulation of an acidified potato liquid, which cause irreversible structural changes to the protein molecules. This approach results in a product disadvantageous for food applications (Stark et al., 2020), as neither the amino acid profile nor the functional properties of the protein are maintained. Alternative recovery methods for maintained protein functionality and nutritional value have been extensively researched (Fu et al., 2020b), but due to high development costs and technical limitations no realistic solution for industrial implementation has yet been found. Another limiting factor is high levels of *glycoalkaloids* naturally present in potatoes, including *α-solanine* and *α-chaconine*, which are chemical compounds acting as a defense system against pests and pathogens. To avoid toxic effects when consumed, an upper threshold of 200 mg *total glycoalkaloids* (TGA)/kg fresh potato is set for Swedish food products (Swedish Food Agency, 2021a). Once removed from the starch flow, TGA accumulate in the by-products and thereby reduces its reusability within food application (Schrenk et al., 2020).

The environmental aspect of implementing recovery solutions that allow available food resources to be utilized according to the highest value possible has been thoroughly stressed in previous studies (Despoudi et al., 2021; Scherhaufer et al., 2020; Cicculo et al., 2021). With respect to sustainable food systems, the environmental cost of under-utilized side streams could be avoided as these resources are ultimately produced in vain. For potato protein side streams this could be achieved using novel plant breeding methods, such as the mutagenesis *genome editing* (GE) technique *CRISPR-Cas9*. This technique could offer substantial benefits compared with conventional potato breeding, especially considering production yields, macronutrient composition, and specific trait development (Tiwari et al., 2022; Hofvander et al., 2022; Hüdig et al., 2022). Multiple studies show that genome edited food crops can also support fulfilment of the UN's sustainability goals (Rashid et al., 2021; Menz et al., 2020). Traditional *genetic modification* (GM), using *transgenesis*, have been cultivated commercially since the 1990s in some parts of the world, with resistance to pests and diseases, tolerance to herbicides, and increased yields being common traits of GM crops (Brookes and Barfoot, 2020). However, commercial crop development within the EU has so far been hindered by legislation (European Commission, 2021a) and only a few GM crops, including soybeans and rapeseed, are currently approved for use in food production (Swedish Food Agency, 2021b). Polarizing concerns among consumers and policymakers regarding the safety and impact of genome-editing have also limited commercializing, despite that no increased risk compared with conventional plant breeding has been scientifically established (Bauer-Panskus et al., 2020; Turnbull et al., 2021; Pixley et al., 2022). In recent years, the public awareness and acceptance regarding genome edited food crops have advanced notably since the first GE crop entered the open market in 2021 (Waltz, 2021). Many researchers also highlight the long-term consequences of restricted development, and argue that innovations are required to achieve sustainable food production (Herrero et al., 2021; Camerlengo et al., 2022). It is further suggested that the potato crop in particular would benefit greatly from novel plant breeding methods (Halterman et al., 2016), where the CRISPR-Cas9 is considered one of the most versatile tools for crop improvement (Hofvander et al., 2022). Applied within conventional potato starch production, this approach can facilitate improved protein recovery in two main ways: i) by reducing the natural TGA level, and ii) by stabilizing the *patatin* structure and making it less sensitive to heat (Johansson and Samuelson, 2018). In turn, this would enable protein recovery with maintained amino acid functionality and low TGA levels. As considerable quantities of potato protein are produced annually, this could be utilized to support future protein needs.

Assessing the environmental performance compared to current practice is crucial to enable evaluation of the sustainability potential of emerging technologies. The general consensus suggests that novel plant breeding techniques infer lower climate impact and reduced acidification, while also supporting maintained ecosystem functionality (Dastan et al., 2020; Eriksson et al., 2018). At present, the impact categories global warming and acidification are most frequently included in agricultural life cycle assessments (Alhashim et al., 2021), while ecosystem aspects are rarely adequately assessed (Asselin et al., 2020). Multiple studies have emphasized the importance of including land use and ecosystem aspects when assessing food impact (Bartek et al., 2021; Crenna et al., 2020). Despite its scientific and industrial relevance, research is currently lacking with respect to the ecosystem impact of using genome edited crops. Moreover, no previous study has to our knowledge assessed the environmental impact of using CRISPR-Cas9 to facilitate large-scale recovery of high-value potato protein. The aim of this study was therefore to assess and evaluate the environmental performance and potential ecosystem damage of introducing a genome edited cultivar in conventional potato starch production. Our results could thereby provide important support for policy recommendations, further research and development, industry implementation, and increased consumer awareness.

2. Material and method

2.1. Goal and scope

Life cycle assessment (LCA) is a systematic method for quantifying environmental impact during a product's life cycle. Following the ISO-standards, a prospective consequential approach (CLCA) was used to assess the impact shifting to a high-value protein recovery within current potato starch production (Ekvall et al., 2016). A functional unit representing *1 ton potato starch* was selected to reflect the function of the main product, where data from previous research was used to model an industrial-scale recovery process of potato protein. The LCA-software SimaPro 9.3 was used to model the system, using the ReCiPe 2016 (H) method to assess impact at midpoint and endpoint level. Marginal datasets from Ecoinvent 3.8 was used for the background system, while substitution via system expansion was favored over economic or mass allocation in the foreground system (ISO. ISO, 2006). This study assumed a negligible influence of market forces and indirect land transformation to simulate maintained production costs and efficiency during commercial implementation. Potential deviations from current practice are instead addressed in the sensitivity analyses to enable a transparent scenario analyses.

2.2. Description of scenarios

The systems were modeled as two parallel starch scenarios: a conventional *Feed scenario* where the potato protein replaced Brazilian soybean meal, and a conceptual *Food scenario* where potato protein replaced Swedish eggs. Included in the system boundary were production and end-of-life for required inputs, alongside transport and buildings used for processing. Construction and maintenance of additional infrastructure were outside the scope of this study. Sweden was the site location for both scenarios, primarily using site-specific input data. Avoided products due to by-product substitution was assumed to replace equivalent products, based on either nutritional profile or commercial use. Supporting information, including datasets used to model inputs, is available in *Supplementary Material*.

2.2.1. Feed scenario: conventional potato starch process

Potato starch produced in northern Europe often use the Solanum tuberosum L. cv. *Kuras*, with an average macronutrient composition of 75% water, 19% starch, 2% protein, 1.6% fiber, and 2.4% trace nutrients (Godard et al., 2012). The main output is native potato starch, while fiber from potato pulp, protein from potato fruit juice, and agricultural fertilizer refined from potato water are the main by-products (Fig. 1).

An average tuber yield of 50 ton per hectare (ha) was used in this study (Stark et al., 2020), requiring an irrigation input of 30 mm three times per season (L ä nsstyrelsen i V ä stra G ö talands l ä n, 2018) and electricity input of 1062 kWh per ha to power the irrigation pump (Lundgren, 2000). Additional input of insecticides, herbicides, and fungicides was used according to previous research (Ahlmén and Ingvarsson, 2002), alongside input of mineral fertilizers (Kalium, 2021). A total of 18 diesel tractor hours per ha was assumed during cultivation and harvest (L ä nsstyrelsen i V ä stra G ö talands l ä n, 2018). Assuming an average 2% (w/w) deducted tuber loss, the harvested potatoes were transported 30 km from farm to starch factory (Axelsson, 2013). Input data used to model the cultivation, harvest and delivery of potatoes, are listed in Table 1.

During the conveying and cleaning process that initiates starch production, about 1% (w/w) of dirt and soil is removed using fresh water and mechanical scrubbing. The amount of water required was based on previous data (Pingmuanglek et al., 2017), of which 15% was re-circulated from fiber processing (Axelsson, 2013). Following cleaning, the tubers are shredded to release starch granules from the cellular fluid, whereupon the potato pulp is separated from the potato fruit juice (PFJ). Around 5–12 m^3 of PFJ, with a protein content of 30–41% (w/w), can be obtained per ton potato (Karboune and Waglay, 2015). A centralizer and suction process was used to separate starch from PFJ (Lyckeby, 2020), and the remaining starch milk is then refined and dewatered using centrifuges before dried to a final water content of 20% (w/w) (Kot et al., 2020). Energy and heat inputs were used according to previous studies (Lundholm, 2020). All inputs used during native starch production are listed in Table 2.

After separation from the starch flow, the potato pulp is further treated to obtain a fiber product for reuse within food and feed application (Stärkelseproducenter, 2019). Once removed, the PFJ is pumped to a protein recovery facility to remove remaining insoluble components before heat treatment. Using a centrifuge and electrical dryer, the coagulated protein fraction is dried to 80% (w/w) protein content (Johansson and Samuelson, 2018) for reuse in animal feed. An evaporation process is used to refine the potato water before re-used as agricultural fertilizer (Lyckeby, 2020). Energy inputs in by-product processing was used according to previous studies (Lundholm, 2020), and the input data required for each process stage are listed in Table 3.

Potato fiber has similar commercial use as wheat bran in food applications and barley grain in feed production, and was assumed to replace equal amounts these products (Lyckeby, 2020). Potato protein is considered a high-quality alternative to non-GM Brazilian soybean meal

Table 1
Process data for the *cultivation* process, expressed per 1 ton potato starch.

		Amount	Unit
Planting and cultivation			
Input	Potato seeding	1.80×10^2	kg
	N fertilizer	1.57×10^1	kg
	K_2O fertilizer	9.59×10^0	kg
	P_2O_3 fertilizer	3.57×10^0	kg
	Herbicide	0.02×10^0	kg
	Insecticide	0.26×10^0	kg
	Fungicide	0.04×10^0	kg
	Electricity	9.26×10^1	kWh
	Water	7.85×10^1	m^3
	Diesel	1.01×10^1	kg
	Machinery	3.00×10^{-3}	unit
	Transport (to farm)	6.10×10^1	km
Harvest and transport			
Input	Machinery	3.00×10^{-3}	unit
	Diesel	6.73×10^0	kg
	Transport (from farm)	3.00×10^1	km
Output	Harvested tubers	4.36×10^0	ton

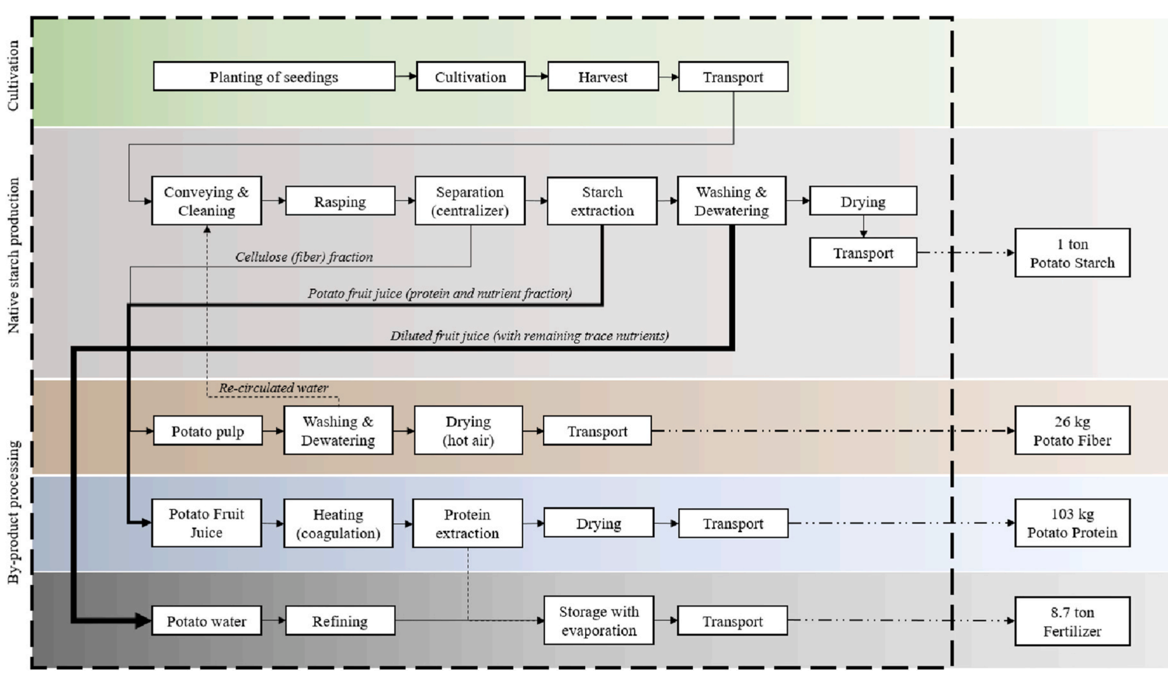

Fig. 1. Illustration of processing required in conventional starch production to produce native potato starch, with potato fiber, protein, and fertilizer as by-products. The dashed line represents the system boundary, and dotted lines show re-circulated flows.

Table 2
Process data for *native starch production,* expressed per 1 ton starch.

		Amount	Unit
Conveying and cleaning			
Input	Harvested potatoes	4.36×10^{0}	ton
	Water	8.30×10^{0}	m^3
	Water (re-circulated)	1.34×10^{0}	m^3
	Electricity	3.14×10^{1}	kWh
	Heat	3.52×10^{1}	kWh
	Processing facility	0.10×10^{-6}	unit
Output	Cleaned potatoes	4.31×10^{0}	ton
	Wastewater	8.35×10^{0}	m^3
	Solid residues	5.00×10^{1}	kg
Rasping and separation			
Input	Cleaned potatoes	4.31×10^{0}	ton
	Water	3.99×10^{1}	m^3
	Electricity	3.14×10^{1}	kWh
	Heat	3.52×10^{1}	kWh
	Machinery	0.19×10^{-3}	unit
	Processing facility	0.10×10^{-6}	unit
Output	Bulk starch milk	4.29×10^{1}	ton
	Potato pulp	1.36×10^{0}	ton
Starch extraction			
Input	Bulk starch milk	4.29×10^{1}	ton
	Electricity	8.72×10^{1}	kWh
	Heat	3.48×10^{1}	kWh
	Machinery	0.19×10^{-5}	unit
	Processing facility	0.10×10^{-6}	unit
Output	Starch milk	2.47×10^{0}	ton
	Potato fruit juice	3.66×10^{1}	ton
	Wastewater	0.14×10^{0}	m^3
Starch purification			
Input	Starch milk	2.47×10^{0}	ton
	Water	7.77×10^{0}	m^3
	Electricity	1.10×10^{-1}	MWh
	Heat	1.50×10^{-1}	MWh
	Machinery	0.19×10^{-5}	unit
	Processing facility	0.10×10^{-6}	unit
Output	Native potato starch	1.00×10^{0}	ton
	Potato water	9.24×10^{0}	m^3

Table 3
Process data for *by-product processing,* expressed per 1 ton potato starch.

		Amount	Unit
Fiber processing			
Input	Potato pulp	1.40×10^{0}	ton
	Electricity	1.93×10^{1}	kWh
	Heat	7.33×10^{1}	kWh
	Pulp processing factory	0.10×10^{-6}	unit
	Transport	6.10×10^{0}	km
Output	Potato fiber	2.61×10^{1}	kg
	Water (re-circulated)	1.30×10^{0}	m^3
Protein production			
Input	Potato fruit juice	3.66×10^{1}	ton
	Electricity	1.56×10^{1}	kWh
	Heat (steam)	5.30×10^{1}	kWh
	Heat (gasol)	5.30×10^{1}	kWh
	Protein production facility	0.20×10^{-6}	unit
	Transport	6.00×10^{1}	km
Output	Potato protein	1.03×10^{2}	kg
	Wastewater	1.82×10^{1}	m^3
	Potato water	1.83×10^{1}	m^3
Fertilizer refining			
Input	Potato water	2.76×10^{1}	m^3
	Electricity	3.45×10^{1}	kWh
	Heat	2.70×10^{1}	kWh
	Evaporation facility	0.10×10^{-6}	unit
	Transport	3.00×10^{1}	km
Output	Potato fertilizer	8.72×10^{0}	ton
	Wastewater	1.88×10^{1}	m^3

in Swedish feed production (Hermansson, 2013), and the protein fraction of 50% (w/w) (Ibáñez et al., 2020; Spiller et al., 2020) was assumed 1:1 replaceable with potato protein. The potato water was assumed to replace mineral nitrogen and phosphorus fertilizers (Spiller et al., 2020). Inputs used to model the substituted products via system expansion are listed in Table 4.

2.2.2. Food scenario: conceptual process using genome edited potato

The main difference from current practice is that the *Food scenario* allow reuse of potato protein within food applications, and therefore the only modeling difference is substituted protein. Since potato protein is of high nutritional value comparable to animal-based proteins and has similar functional properties to eggs (Hussain et al., 2021), this study assumed 1:1 replacement of protein from eggs with an average protein content of 12.5% (w/w). A separate model was created to describe Swedish egg production for the substituted protein, see *Supplementary Material*, and inputs used to model the substituted protein via system expansion are listed in Table 5.

2.3. Sensitivity analysis

The first sensitivity analysis sought to evaluate uncertainties related to input data, where different fertilizers potentially influence environmental impact (Hanserud et al., 2018). This was addressed by shifting to organic fertilizers during cultivation. The two subsequent analyses addressed uncertainties related prospective genome editing techniques. One of the two main ways in which CRISPR-Cas9 can facilitate improved protein recovery is by stabilizing the protein structures, which would infer a recovery process requiring less energy and water inputs. This was accounted for by simulating 30% decreased demand for electricity, heat, and water during starch and protein production. The other way in which CRISPR-Cas9 can be used is by reducing the amount of TGA present (Johansson and Samuelson, 2018), and a potential consequence of reduced TGA levels could be higher use of pesticides to offset a lower tuber defense. This uncertainty was addressed by doubling the pesticide input required. Another relevant aspect for the LCA method is sensibility to production yields, which was evaluated by simulating a decreased tuber yield which ultimately inferring a 20% increase of inputs during all production stages. Another limitation is substitution sensitivity, as this methodological approach might influence the environmental performance (Vadenbo et al., 2017). This was addressed by simulating replacement of alternative protein sources in feed and food.

3. Results

3.1. Environmental impact and ecosystem damage

With respect to environmental impact, the result show that the *Food scenario* inferred lower impact for 13 of 18 midpoint indicators compared with the conventional system. Using potato protein to

Table 4
Process data for the *substituted products,* expressed per 1 ton potato starch.

		Amount	Unit
Substituted fiber			
Input	Potato fiber	2.61×10^{1}	kg
Avoided product	Wheat bran	-1.31×10^{1}	kg
	Barley grain	-1.30×10^{1}	kg
	Transport (to industry)	-6.00×10^{1}	km
Substituted protein			
Input	Potato protein	1.03×10^{2}	kg
Avoided product	Soybean meal (Brazil)	-1.74×10^{2}	kg
	Transport (Brazil)	-1.19×10^{3}	km
	Transport (Norway)	-1.07×10^{4}	km
	Transport (Sweden)	-5.92×10^{2}	km
Substituted fertilizer			
Input	Potato fertilizer	8.70×10^{0}	ton
Avoided product	N fertilizer	-2.60×10^{0}	kg
	P fertilizer	-0.50×10^{0}	kg
	Transport (to farm)	-6.00×10^{1}	km

Table 5
Process data for *substituted protein,* expressed per 1 ton potato starch.

		Amount	Unit
Substituted protein			
Input	Potato protein	1.03×10^2	kg
Avoided product	Egg (Sweden)	-6.62×10^2	kg
	Transport	-6.00×10^1	km

substitute eggs over soybean meal changed the global warming result from a negative impact to global warming savings, while also close to halving the land use impact and reducing terrestrial acidification by over five-fold (Table 6). The *Food scenario* was also found to infer lower marine eutrophication and fine particulate matter formation, while the Feed scenario resulted in lower mineral resource scarcity and toxicity. A negative value indicates reduced environmental impact and origin from substitution.

The *Food scenario* also inferred lower damage to 8 of 12 endpoint categories compared with the conventional *Feed scenario*. For every ton starch produced, the *Feed scenario* resulted in -6.8×10^{-6} species.yr and the *Food scenario* -1.8×10^{-5} species.yr. This translates to over two-fold more favorable conditions with respect to biodiversity, since a negative value for ecosystem damage indicate mitigated loss of species. With respect to ecosystem damage, the results showed that the main contributing factors for both scenarios were global warming and land use, while in the *Food scenario* there was also a considerable contribution from reduced terrestrial acidification (Fig. 2).

3.2. Sensitivity analysis

Shifting to the *Food* scenario resulted in higher environmental savings with respect to global warming, land use, and terrestrial acidification even when simulating increased pesticide use, organic fertilizers, reduced processing inputs, and decreased tuber yield. Only a slight change was observed when assessing the sensitivity of data parameters, indicating that these were not a major source of uncertainty in this study. On the other hand, the protein product substituted was shown to give higher uncertainty. Overall, the results indicated that the highest biodiversity and environmental savings, with respect to climate impact, acidification, and land use, were obtained when the recovered potato protein replaced animal-based protein sources, such as eggs and dairy (Fig. 3).

Table 6
Environmental impact per 1 ton potato starch produced.

		Feed scenario	Food scenario	Difference (absolute value)
Global warming	kg CO_2 eq	1.8×10^2	-5.4×10^2	-7.2×10^2
Stratospheric ozone depletion	kg CFC_{11} eq	-1.1×10^{-3}	-4.1×10^{-3}	-3.0×10^{-3}
Ionizing radiation	kBq Co-60eq	1.1×10^1	2.8×10^0	-8.3×10^0
Ozone formation. Human health	kg NOx eq	1.0×10^0	4.8×10^{-1}	-5.3×10^{-1}
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.1×10^{-1}	-9.0×10^{-1}	-1.1×10^0
Ozone formation. Terrestrial ecosystems	kg NOx eq	9.7×10^{-1}	5.2×10^{-1}	-4.5×10^{-1}
Terrestrial acidification	kg SO_2 eq	1.9×10^0	-1.1×10^1	-1.3×10^1
Freshwater eutrophication	kg P eq	-3.5×10^{-1}	2.1×10^{-1}	5.6×10^{-1}
Marine eutrophication	kg N eq	-2.4×10^{-1}	-1.1×10^0	-8.5×10^{-1}
Terrestrial ecotoxicity	kg 1.4-DCB	1.0×10^4	1.2×10^4	1.4×10^3
Freshwater ecotoxicity	kg 1.4-DCB	5.5×10^1	5.6×10^1	3.7×10^{-1}
Marine ecotoxicity	kg 1.4-DCB	7.5×10^1	8.2×10^1	7.6×10^0
Human carcinogenic toxicity	kg 1.4-DCB	4.4×10^1	3.8×10^1	-6.4×10^0
Human non-carcinogenic toxicity	kg 1.4-DCB	1.2×10^3	9.4×10^2	-2.7×10^2
Land use	m^2a crop eq	-8.7×10^2	-1.6×10^3	-7.6×10^2
Mineral resource scarcity	kg Cu eq	2.9×10^0	4.2×10^0	1.2×10^0
Fossil resource scarcity	kg oil eq	2.0×10^2	1.6×10^2	-4.1×10^1
Water consumption	m^3	1.1×10^2	9.5×10^1	-1.6×10^1

4. Discussion

One of the key findings in the present study was that using genome edited crops to facilitate high-value protein recovery from potato starch side streams could infer considerable environmental savings compared with the conventional recovery practice. The conceptual *Food scenario* was shown to reduce the environmental impact for every ton starch produced, especially considering global warming, terrestrial acidification, and land use. These midpoint indicators also had the highest contribution to ecosystem damage, likely since the ReCiPe method applies a constant characterization factor from midpoint to endpoint level (Huijbregts et al., 2017). The environmental cost of cultivating and production showed a negligible contribution to the overall impact compared with the environmental savings enabled by replacing protein products. Compared with current practice, the *Food scenario* also resulted in over two-fold the ecosystem savings, illustrating considerable benefits of genome edited potato protein recovery with respect to biodiversity. These results can be considered valid provided that no adverse trait or quality consequences emerge from editing the potato genome. When assessing impact of emerging technologies, it is especially important to consider uncertainties related to technological maturity and limited representation in available datasets. The benefits of recovering available resources and re-circulating them back to the food system was evaluated in sensitivity analyses, where substituting food over feed unequivocally inferred higher ecosystem and environmental savings. This is in line with previous findings (Scherhaufer et al., 2020; Moreno-González and Ottens, 2021; Scuderi et al., 2021), which suggest that circular recovery of high-value protein could reduce the environmental impact related to food and thereby support production within planetary boundaries.

4.1. Environmental impact of protein recovery in potato starch production

At midpoint level, the *Food scenario* resulted in lower impact for the majority of all impact categories. Cultivation, native starch processing and substituted protein were the main environmental hotspots with respect to global warming, acidification, land use, and ecosystem damage for both scenarios (Fig. 3). The cultivation process relies on large material inputs such as fertilizers, pesticides, water and fossil fuels to ensure high returns. Production of these inputs and combustion-related emissions are probably the main cause for global warming impact and land use, while terrestrial acidification could also origin from ammonia volatilization after fertilizer application (Alhashim et al., 2021). Addressing the data uncertainty related to specific products, the sensitivity analyses of using organic fertilizers showed comparable impact to mineral fertilizers in this study. A similar conclusion can be drawn for reduced need for energy and water inputs, as the result showed that neither fertilizer nor input quantities were a major source of uncertainty. On the contrary, the results instead confirmed that tuber yield was the most sensitive data parameter in this study. This result was somewhat expected since the LCA method originally was developed for industrial processes aiming to reduce impact per production unit, thus the results implicitly tend to favor systems with high production yields. Important to note is that these results should primarily be considered valid for

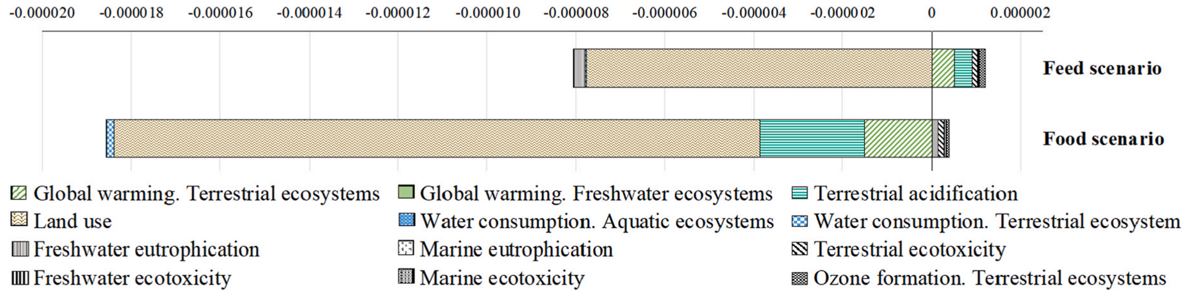

Fig. 2. *Illustration of the contribution for each endpoint indicator to the total ecosystem damage (species.yr) assessed for the* Feed *and* Food *scenarios. A negative value indicates contribution to mitigated damage to ecosystems, primarily due to substitution.*

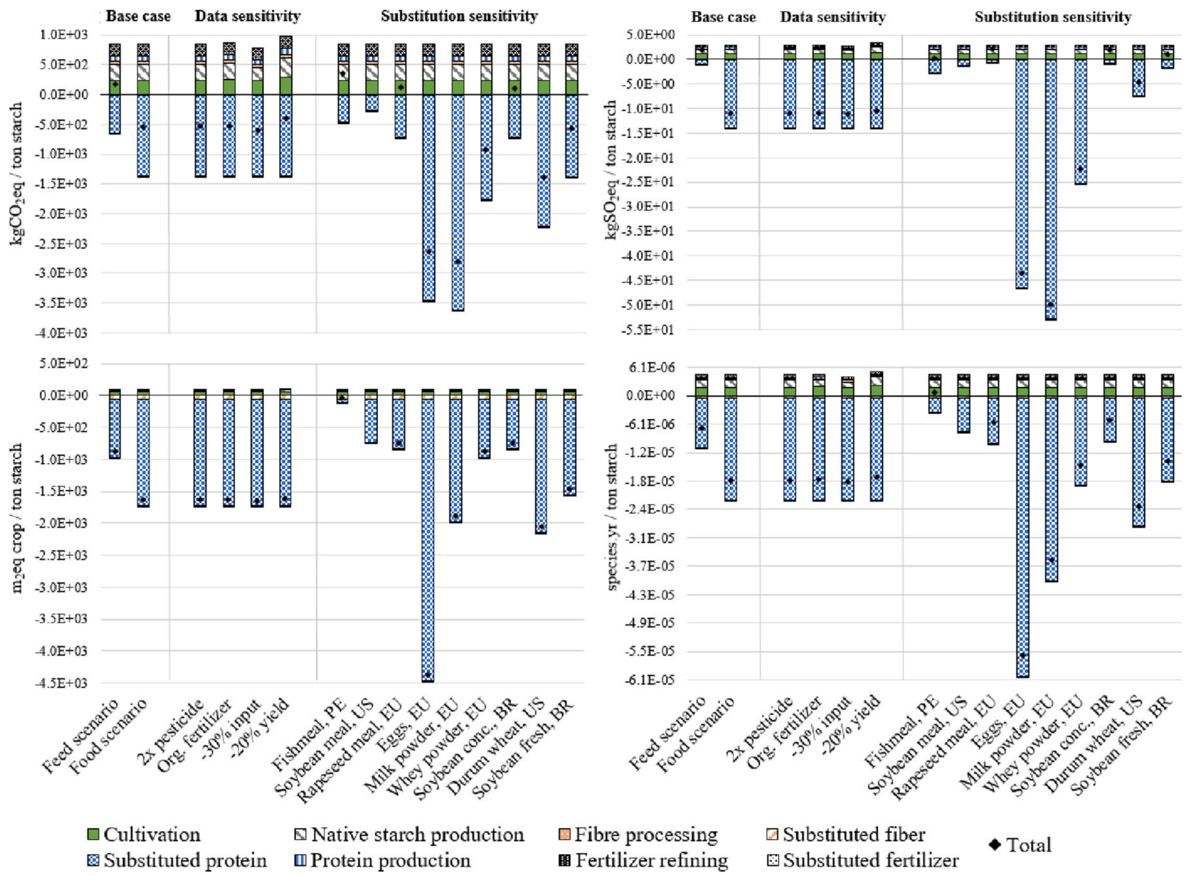

Fig. 3. Sensitivity analysis results with respect to global warming potential, terrestrial acidification, and land use at midpoint level, and ecosystem damage at endpoint level. The contribution of each process to total impact is indicated.

scenarios implemented within current potato starch industry, as major deviations in infrastructure or management was outside the scope of this study. Our results indicate that production yields, climate impact, and land use tend to govern environmental impacts obtained using the LCA method, which is also consistent with previous research (van der Werf et al., 2020). During starch production and by-product processing, the main factors contributing to global warming and terrestrial acidification were electricity inputs and combustion-related emissions from petroleum heating. Since this study assumed input of Swedish electricity mix produced from less than 45% fossil fuels, a low contribution to these impact categories was expected. Compared with the relatively low impact from electricity and water, the impact of buildings was larger than expected, especially since this aspect is often omitted in LCA studies. With respect to land use, the largest contribution originated from inclusion of processing facilities. Although, as the same buildings were used in both scenarios this process related uncertainty is avoided when comparing the systems.

The main sensitivity for the *Feed* and *Food scenario* was substitution of protein products. Higher savings of substituting animal-based was expected (Röös et al., 2020), but particular care was taken to validate the impact related to substitution of eggs and soybean meal as substitution was the main source of sensitivity. Previous studies (Rysselberge and Röös, 2021; Moberg et al., 2019) suggest that Swedish eggs infer a climate impact of 2 kgCO_2eq per kg, which corresponds to about −1300 kgCO_2eq per ton starch when using a 12.5% protein content. This is in line with the results in this study (Fig. 3). The environmental impacts of non-GM and GM soybean meal imported to Sweden has been shown to infer climate impact of 845 kgCO_2eq per ton and 609 kgCO_2eq per ton respectively (Eriksson et al., 2018). With 50% protein content, this translates to climate savings of −282 kgCO_2eq for non-GM varieties and −203 kgCO_2eq for GM per ton starch. These results are in the same order of magnitude as the climate impact of Brazilian non-GM soybean meal and GM soybean meal from US (Fig. 3), although the numerical value for non-GM soybean meal is almost double to that previously found. Plausible reasons for this difference are newer datasets used to describe production and transport, and different assumptions regarding soybean yields. Moreover, the assumed protein content for soybean meal in this study slightly higher than suggested in other studies (Eriksson et al., 2018; Ibáñez et al., 2020), which likely influenced the results as lower protein content per mass unit requires larger product volumes. Moreover, to our knowledge no previous LCA study has accounted for the biological value (BV) of protein products. In the present study, when accounting for the BV, the climate savings of substituted soybean meal (BV 84) would be just over −700 kgCO_2eq per ton starch and the climate savings for substituted Swedish eggs (BV 100) would be around −1400 kgCO_2eq per ton starch (see *Supplementary Material*). Ultimately, accounting for biological value or protein quality could infer higher environmental and ecosystem savings than previously assessed, which is in line with previous research findings (Sonesson et al., 2017). Overall, the result for climate impact of eggs and soybean meal can be considered supportive of previous findings for Swedish conditions.

Another important finding was the importance of including acidification and land use impact when evaluating the environmental performance and ecosystem damage of a food product. The results revealed some potential trade-offs, especially considering climate impact and ecosystem damage. The assumption that potato protein fully replace non-GM Brazilian soybean meal could be considered as an optimal scenario for feed substitution, since the other protein sources in feed inferred considerably lower environmental and ecosystem savings per ton starch. On the contrary, replacing Swedish eggs was found less favorable compared with e.g. replacing European eggs, and thus does not pose as an optimal scenario from an environmental point of view. Moreover, substituting milk powder was the most favorable alternative with respect to climate impact and acidification, while substituting EU eggs was the most favorable with respect to land use and ecosystem damage. Trade-offs like these might cause competition and conflicts between which UN sustainable development goals should be prioritized, demonstrating the importance of addressing potential trade-offs when evaluating different production processes. Similarly, our results indicated that the benefit of avoided mineral fertilizer production did not exceed the environmental cost of refining potato water via evaporation, highlighting a potential need to evaluate the best recovery practices for potato water from the current starch industry.

4.2. Limitations and future outlook

The present results imply that climate impact, acidification, and land use could be suitable indicators for ecosystem damage. However, no LCIA method can fully account for ecosystem damage caused by e.g. direct pesticide application (Huijbregts et al., 2017). This method uncertainty was evident as global warming impact inferred higher damage to ecosystems than additional use of toxic chemicals (Fig. 3), and emphasize the importance of further method development. Another limitation of prospective CLCA studies is the aspect of market effects and land transformation. Even though potato protein is considered a high-value alternative to soybean meal, total replacement of soybean meal is not yet realistic due to competitive prices, limited availability, and current legislation (Hermansson, 2013). Non-GM soybean meal is generally more expensive than GM alternatives (Eriksson et al., 2018), which ultimately infer higher production costs for farmers operating in countries with zero GM tolerance. Thus, a potential outcome of commercialized GE potato could be increased competition with GM crops rather than non-GM varieties. Moreover, if the potato protein were to be upcycled to food production, alternative protein sources for feed would be required to fill the gap. This secondary effect was not covered in the present study, but should be considered in future research as it might reveal important sustainability dimension of upcycled food side streams. Another consideration is that the price of Swedish eggs, which is highly influenced by the production practice (e.g., eco-friendly feed or free-range hens), while the nutritional value is fairly constant. The market value of eggs is therefore difficult to compare from a strict price perspective, since social and environmental aspects also affect demand for this product.

Increased macronutrient recovery, circular food systems, and reduced environmental and ecosystem impacts are fundamental global objectives. Innovations to enable industrial implementation and commercialization would initially be dependent on economic support via research investments, together with legislation to facilitate development. From a sustainability point of view, the social acceptance and economic values related to GE food crops also need to be considered (Peschel and Aschemann-Witzel, 2020). On the international market, genome edited crops have avoided much of the negative controversy related to GM organisms, ultimately since the two techniques are fundamentally different. Although a negative consumer attitude has previously hindered further commercialization, research has observed an increasingly positive consumer attitude towards novel GE food crops (Ramadas et al., 2021). In 2021, European Commission concluded that current legislation for GE food crops is not fit for its purpose, and a modernized policy is currently under discussion (Pixley et al., 2022; European Commission, 2021b).

At present, potato protein can be recovered without genome edited crops, but it is not fit for human nutrition. Since the market value of protein is strongly affected by its purity and nutritional composition, the long-term payoff with respect to profitability and circularity within food systems could be greater with GE potato. It is reasonable to assume that a certain amount of competition with existing products may initially occur when new products are introduced to the commercial market, and for potato protein this might influence production of eggs and imported soybean protein, but could also replace dairy or gluten in sauces, bread, and plant-based products. However, a commercialized potato protein recovered using genome edited crops should initially be considered as a complementary protein source, rather than a competing protein product. Using this available resource at a higher value could also provide an economic advantage for producers and the industry (Scuderi et al., 2021), especially since recovered plant-based protein is predicted to play an important role in future protein production. Similarly, recovered potato protein would further support resilient agriculture and increased food security, as reduced ecosystem damage and maintained biodiversity are cornerstones of resilience to external stressors such as pests, climate change and extreme weather (Colgrave et al., 2021). Further research, development work, industry implementation, and legislation supporting innovations will play a vital role in enhancing future protein production.

4.3. Key recommendations

Maintaining a stable and sustainable food supply, while balancing population growth and limited natural resources, is one of our most urgent global challenges. Since the feed and food sector is highly dependent on imported plant protein, recovering potato protein from local starch side streams could bring meaningful benefits with respect to national self-sufficiency, local entrepreneurship, and fulfilment of environmental objectives. Arguably, adequate policy recommendations and legislation should accommodate these aspects. Moreover, ensuring Nature's ability to provide the resources needed for global food security requires urgent and substantial actions that comply with Agenda 2030 and UN sustainable development goals. As of yet, researchers have failed to identify a stand-alone solution for how to sustainably feed 9 billion people. On the contrary, the main way forward is a broad range of simultaneously adapted solutions aimed to ensure long-term sustainability within the food system. Maintained production yield and enabling protein upcycling to the food system were identified as two of the main factors that should be prioritized in further development of genome edited potato. To fully utilize the benefits identified, there is an urgent need for sufficient research initiatives and substantial policy interventions. The future success will also depend on legal boundaries set by the EU and consumer acceptance. Positive consumer response to genome edited foods can be promoted by government and policy recommendations, while reduced prices, transparent and visible research results, alongside targeted market communication can positively influence consumer acceptance. Such actions could be justified based on the environmental savings, future demand for plant-based protein, and known health benefits. Arguably, all means available actions should be considered to reduce climate impacts, maintain biodiversity, and increase circularity within food production. If not enough is done in time, our conditions for sustainable production and consumption will be further jeopardized and inevitably impact all life on Earth. The ultimate question is therefore whether the benefits of recovering available resources from food side streams exceed the current limitations. This study showed that the environmental benefits of using genome edited crops to facilitate high-value potato protein recovery clearly exceed the environmental costs.

5. Conclusions

This assessment showed that a genome edited potato cultivar created using CRISPR-Cas9 could facilitate high-value protein recovery with considerable environmental savings and avoided damage to ecosystems. Compared with current practice, the new technology resulted in lower environmental impact for 13 of 18 midpoint impact categories per ton starch produced, including over three-fold reduced global warming impact, more than five times lower terrestrial acidification, and about half the land use impact. Shifting to high-value recovery of potato protein also halved the damage to ecosystems, ultimately supporting maintained biodiversity and sustainability within agriculture production. Although the sensitivity analysis showed a model sensitivity towards parameters related to substituted protein products, re-circulating potato protein to the food system still comprised the most favorable scenario from an environmental perspective despite identified sensitivities. If current barriers can be overcome with the prospect of environmental savings, this available plant-based food resource can facilitate increased protein production per cultivated hectare, and thus drive the transformation towards higher circularity and sustainability within the food system.

CRediT authorship contribution statement

L. Bartek: Conceptualization, Methodology, Software, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project administration. **N. Sundin:** Methodology, Resources, Validation, Writing – original draft. **I. Strid:** Conceptualization, Validation, Supervision, Writing – review & editing. **M. Andersson:** Conceptualization, Resources, Writing – review & editing. **P-A. Hansson:** Writing – review & editing, Supervision, Validation. **M. Eriksson:** Conceptualization, Validation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

This study was funded by the Swedish Research Council for Sustainable Development (FORMAS).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.134887.

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