Agricultural Systems 222 (2025) 104185

Contents lists available at ScienceDirect

Agricultural Systems

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

How to use residual biomass streams in circular food systems to minimise land use or GHG emissions

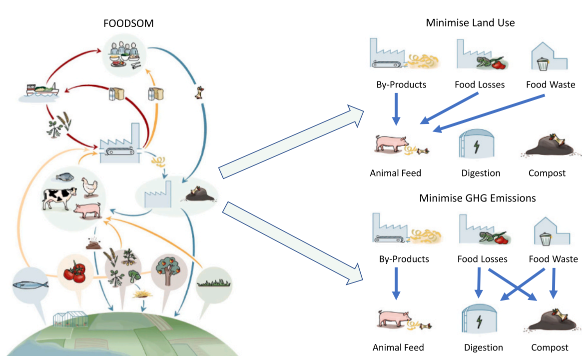
Benjamin van Selm [a,b,*], Renske Hijbeek [b], Corina E. van Middelaar [a], Imke J.M. de Boer [a], Martin K. van Ittersum [b]

[a] Animal Production Systems group, Wageningen University & Research, P.O. Box 338, 6700, AH, Wageningen, the Netherlands
[b] Plant Production Systems group, Wageningen University & Research, P.O. Box 430, 6700, AK, Wageningen, the Netherlands

HIGHLIGHTS

- Using by-products, food loss and waste for animal feed, compost or anaerobic digestion is assessed with a food system model.
- By-products should be used as animal feed to minimise agricultural land use and GHG emissions.
- Food loss and waste should be used as animal feed to minimise agricultural land use, composted or digested to minimise GHG.
- GHG allocation of anaerobic digestion (to food system or energy sector) determines if food waste is composted or digested.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Mark van Wijk

Keywords:
By-products
Food loss & waste
Dietary change
Animal feed
FOODSOM

ABSTRACT

Context: Transitioning to future circular economies and food systems will increase demand for biomass in society. Residual streams, which include food loss, food waste and by-products (e.g., rapeseed meal) from agriculture and food production are a valuable source of biomass in more circular food systems. It is currently unclear if and whether these residual streams should be utilised optimally: as animal feed, composted as organic fertiliser or for anaerobic digestion to produce biogas (methane) and digestate (fertiliser) to minimise environmental impacts from food systems.
Objective: Our aim is to understand which residual streams are to be utilised as animal feed, compost or for anaerobic digestion in circular food systems to achieve minimum agricultural land use and greenhouse gas (GHG) emissions under scenarios with different dietary preferences.
Methods: Taking the Netherlands as a case study, we employed the FOODSOM model, an iterative linear optimisation model of a circular food system in the Netherlands. FOODSOM minimises agricultural land use or GHG emissions while meeting the dietary requirements of the population. Four scenarios based on two different human diets and two food system objectives (i.e., minimise land use or GHG emissions) were developed.
Results & conclusions: Our results show by-products should be fed to livestock when aiming to minimise agricultural land use and GHG emissions, food loss and waste is best fed to livestock when minimising land use, but composted or digested when minimising GHG emissions. The decision to compost or digest food waste depends

* Corresponding author at: Animal Production Systems group, Wageningen University & Research, P.O. Box 338, 6700, AH, Wageningen, the Netherlands.
E-mail address: ben.vanselm@wur.nl (B. van Selm).

https://doi.org/10.1016/j.agsy.2024.104185
Received 26 April 2024; Received in revised form 2 August 2024; Accepted 6 November 2024
Available online 16 November 2024

on whether the GHG emissions from anaerobic digestion are assigned to the food system or the biogas (methane) produced.
Significance: Our results provide guidance on how residual streams, including food loss, food waste and by-products can be optimally utilised in future circular food systems to achieve minimal agricultural land use and GHG emissions when meeting dietary requirements.

1. Introduction

Competition for biomass in society is increasing due to limited supply, and increased demand (Haberl et al., 2014; Krausmann et al., 2013; Muscat et al., 2020). Demand for biomass will continue to increase as society shifts towards a more circular economy and food system (PBL, 2020). In circular food systems, biomass is prioritised for basic human needs (e.g., food production) while non-essential use of biomass and unnecessary losses (e.g., due to overconsumption) are avoided (Muscat et al., 2021). Residual streams including food loss (which occur at the beginning of the supply chain, i.e., post harvest losses and processing and packaging losses), food waste (which occur at the other end of the supply chain, i.e., distribution waste and consumption waste), and by-products (e.g., wheat bran after making wheat flour from wheat grain) are valuable sources of biomass in circular food systems (De Boer and Van Ittersum, 2018). Residual streams not suitable for human consumption can be recycled as animal feed, fertiliser or used to produce energy to close nutrient cycles (Slorach et al., 2019; van Zanten et al., 2023). While recycling residual streams to close nutrient cycles is a core objective of circular food systems, it is currently unclear which residual streams should be used as animal feed, composted to be used as fertiliser, or digested through anaerobic digestion to produce biogas, when reducing environmental impacts such as agricultural land use or greenhouse gas (GHG) emissions. Reducing agricultural land use can lead to more land being available for nature conservation and biodiversity, while reducing GHG emissions can contribute to minimising the effects of climate change.

In a more circular food system, livestock can convert different types of residual streams (e.g., food loss and waste, by-products) into nutrient dense animal-sourced food and manure that can be returned to the soil to fertilise crops (Billen et al., 2021). Feeding residual streams to livestock reduces the demand for animal feed production, which can contribute to reducing feed-food competition and thus reduce agricultural land use and potentially GHG emissions (Röös et al., 2016; van Selm et al., 2022). Based on this rationale, recent research has focused on feeding residual streams to livestock to maximise the production of animal-sourced food and avoid feed-food competition (Frehner et al., 2022; Röös et al., 2016; Van Hal et al., 2019; van Selm et al., 2022). However, in a circular system other utilisation pathways also exist (O'Connor et al., 2021; Slorach et al., 2019). Alternatively, residual streams can be composted, and the compost can be returned to the soil to fertilise agricultural land and to improve soil quality. Utilising composted residual streams can replace artificial fertilisers and thereby, reduce GHG emissions from the production of artificial fertilisers (e.g., for nitrogen) or prevent mining of scarce resources (e.g., in the case of phosphorus) (Cortés et al., 2020; De Boer and Van Ittersum, 2018). Finally, residual streams can be digested through anaerobic digestion to produce biogas and digestate (Vasco-Correa et al., 2018). Biogas can be used as a source of renewable energy and replace fossil energy, while digestate can be returned to the soil to fertilise cropland and grassland (O'Connor et al., 2022). Similar to compost, digestate can therefore replace artificial fertilisers.

The demand for animal-sourced food in human diets inherently influences the utilisation of residual streams. Current diets contain large quantities of animal-sourced food, which implies high demand for animal feed (Springmann et al., 2018a; Willett et al., 2019). Alternatively, circular diets or healthy and sustainable diets would contain considerably less animal-sourced food (Springmann et al., 2018b; van Selm et al., 2023b; van Zanten et al., 2023; Willett et al., 2019), especially in affluent countries, which reduces demand for animal feed. Dietary preferences, therefore, can influence the optimal utilisation of residual streams in food systems.

While circular food systems have been shown to reduce land use and GHG emissions in food systems when using residual streams as animal feed (van Zanten et al., 2023), it is unclear if this is the most optimal utilisation option. In other words, questions remain on how residual streams should be utilised to achieve minimum agricultural land use or GHG emissions, and how the optimal utilisation pathway is affected by the human diet. The aim of this paper, therefore, is to understand how residual streams should be utilised (as animal feed, compost, or for anaerobic digestion) in circular food systems to achieve minimum agricultural land use and GHG emissions with different dietary preferences.

2. Material & methods

Taking the Netherlands as a case study, we employed FOODSOM, a food system optimisation model to quantify the flow of biomass through the food system. For this study, FOODSOM was extended to include anaerobic digestion as a utilisation pathway for residual streams. The options to use residual streams as feed or compost were already included previously (van Selm et al., 2023b). We took four scenarios from van Selm et al. (2023b) and added anaerobic digestion as a processing option to understand how alternative human diets and environmental objectives (minimum agricultural land use or minimum GHG emissions) impact the optimal flow of biomass in future food systems, with an emphasis on utilisation as feed, compost, or bio-energy.

2.1. FOODSOM

FOODSOM is food system optimisation model of the Dutch food system created in GAMS 42 (van Selm et al., 2023a; van Selm et al., 2023b). FOODSOM minimises agricultural land use or GHG emissions at the food system level while meeting the dietary requirements of the Dutch population.

Agricultural land forms the basis of FOODSOM. On arable land and grassland, or in greenhouses, orchards, and mushroom sheds, 49 representative crops can be grown (one productivity level, based on current management due to limited data). Conversion of arable land to grassland was not permitted. Crop yields are based on national statistics or survey data (CBS, 2019; De Ruijter et al., 2020). Crops are fertilised with crop residues, animal manure, compost, digestate and artificial fertiliser to meet nitrogen (N), phosphorus (P), and potassium (K) requirements. Nitrogen fertilisation is calculated based on crop requirements by accounting for harvested N, N losses from volatilisation (N_2O, NH_3, NO_x, N_2), N losses from leaching and N inputs including atmospheric deposition, net mineralisation in peat soils and biological N fixation by legume crops. We assume all remaining N is available to the crop on the long term. Phosphorus and K requirements are based on a balanced fertilisation approach including an unavoidable loss fraction (Lun et al., 2018). GHG emissions from the production of artificial fertilisers are also included in FOODSOM.

Five livestock systems (dairy, beef, broiler chickens, laying hens, pigs; three productivity levels; high, medium low; high represents current livestock productivity in the Netherlands) are included in the model. Livestock can consume feed-food crops (i.e., crops also suitable for human consumption), by-products (e.g., wheat bran), food losses and waste, grassland resources and synthetic amino acids to meet their nutrient requirements (protein and energy). Feed intake capacity constraints are also included. Manure is stored in a manure management system to be later applied to the soil or anaerobically digested with the digestate being applied to the soil. GHG emissions from crop and livestock systems are calculated using national GHG inventory methodologies (Lagerwerf et al., 2019; van Bruggen et al., 2021). In addition to livestock, marine fish can be caught and utilised in the food system.

Crop, livestock and fisheries products are processed into food (e.g., wheat into flour) for human consumption which also produces by-products (e.g., wheat bran, blood and bone meal). The ratios of food to by-products are based on technical conversion factors (FAO, 1996; Vellinga et al., 2013). Food is also lost (e.g., during storage or during processing) and food is wasted (e.g., during consumption or in the supermarket) as it moves along the supply chain. The quantity of food lost and wasted is based on food loss and waste fractions (Caldeira et al., 2019).

Eventually, food is consumed by humans to satisfy nutritional requirements (27 nutrients). Nutritional requirements are defined by national nutrient consumption recommendations (Brink et al., 2019). Further constrains are applied at a food group level to ensure the human diet remains feasible (see Section Scenarios).

Residual streams, which include by-products from processing raw materials (e.g., wheat) into food products (excluding crop/field residues; e.g., straw), food losses (i.e., post-harvest losses and processing and packaging losses) and food waste (i.e., distribution and household waste) can be processed into animal feed, composted, or anaerobically digested. The quantities of residual streams available is a function of the model and the scenario specification, which determine the area of crop produced and the human diet. There is no limitation on the share of residual streams that can be utilised as animal feed, compost or anaerobic digestion. For animal feed, food loss is treated as individual feed product (e.g., wheat or wheat flour), while food waste is grouped with similar products of the same food group (distribution waste, e.g., grain waste) or into a single product (consumption or household waste, e.g., consumption waste) for logistical reasons. Processing by-products and food loss and waste into animal feed, compost, or anaerobic digestion results in additional GHG emissions (Boldrin et al., 2009; Mayer et al., 2021; Vellinga et al., 2013).

Finally, food items can also be imported and exported. In this study we assumed up to 25 % of the nutrients consumed in the human diet could be imported from outside the Netherlands. Importing food items enables the consumption of products that cannot be produced in the Netherlands. However, in our model the N, P and K in imports must equal N, P and K in exports to prevent an accumulation or a depletion of nutrients at a national scale (van Selm et al., 2023a). We note that these assumptions about import and export are very different from the current situation in the Netherlands, as the focus of our analysis is on optimum use of residual biomass streams when minimising environmental impacts of the food system.

2.2. Animal feed

Feeding residual streams to livestock was already implemented in FOODSOM (van Selm et al., 2023a). The nutrient content of residual streams, and other animal feed is based on feed tables (Spek and Van Wesemael, 2021). We assumed all available residual streams could be fed to livestock in this study. However, ruminants cannot consume food loss, food waste, and by-products containing meat, and cannibalism was prevented (i.e., pigs could not consume meat and bone meal from pigs). GHG emissions from feeding livestock were based on national GHG inventory methodologies (Lagerwerf et al., 2019; van Bruggen et al., 2021).

2.3. Compost

Composting was also an existing pathway in FOODSOM. All residual streams can be composted. GHG emissions (N_2O and CH_4) resulting from composting are based on the initial N and carbon (C) content of the residual stream (i.e., the original compost feedstock) and the final N and C content (C:N ratio of 15) (Boldrin et al., 2009). It was assumed that 38.5 % of the initial N input was lost during the composting process through volatilisation and leaching (Boldrin et al., 2009).

2.4. Anaerobic digestion

In this study, anaerobic digestion was added to FOODSOM as a utilisation pathway for food loss and waste, by-products, and manure. It was assumed that during the anaerobic digestion process of food loss and waste, and by-products, 9.2 % of N and 6 % of P and K was lost (Schievano et al., 2011). Remaining N, P, and K could be applied as a digestate fertiliser with a C:N ratio of 5.5 (Schievano et al., 2011). Anaerobic digestion also results in GHG emissions, and these were estimated per kg of waste (Mayer et al., 2021).

Manure from ruminants and pigs can also be anaerobically digested. Biogas production from manure is based on livestock diets and the associated volatile solid excretion and methane production potential of manure. Nitrogen losses and GHG emissions also occurred during the digestion process (Melse and Groenestein, 2016).

In addition to producing digestate, anaerobic digestion produces biogas (methane). Therefore, the GHG emissions associated with anaerobic digestion can be assigned to the digestate (i.e., the food system, as digestate is used to fertilise crops) or to the biogas (i.e., the energy sector, as biogas is assumed to be used as an energy source outside the food system). The decision to assign GHG emissions associated with anaerobic digestion to the food system or the energy sector can influence the optimal utilisation pathway of residual streams and manure when minimising GHG emissions. Therefore, both allocation options were explored in this study. However, detailed findings on livestock diets, fertilisers, and N flows are only shown with GHG emissions from anaerobic digestion assigned to the energy sector. The primary product of anaerobic digestion is biogas to be used outside the food system; therefore it is most appropriate to assign emissions from anaerobic digestion to the energy sector. Additional figures with GHG emissions from anaerobic digestion assigned to the food system can be found in the supplementary material.

A sensitivity analysis was performed on GHG emissions and nutrient losses of composting and anaerobic digestion for all scenarios. GHG emission factors and nutrient loss coefficients were increased and decreased by 12.5 % and 25 % respectively to assess the sensitivity of the utilisation of residual streams to these technical coefficients.

2.5. Scenarios

Four scenarios were developed to understand how residual streams are utilised optimally, i.e. as animal feed, fertiliser or as a source of biogas in circular food systems (Table 1). Scenarios were based on two factors: two human diets and two environmental objectives. The quantity of residual streams and optimal utilisation pathway is dependent on the human diet and the environmental objective being minimised.

The environmental objective was to either minimise agricultural

Table 1
Overview of scenarios included in this study.

#	Scenario	Diet	Objective
1	Current-Land	Current	Min. agricultural land
2	Current-GHG	Current	Min. GHG
3	Circular-Land	Circular	Min. agricultural Land
4	Circular-GHG	Circular	Min. GHG

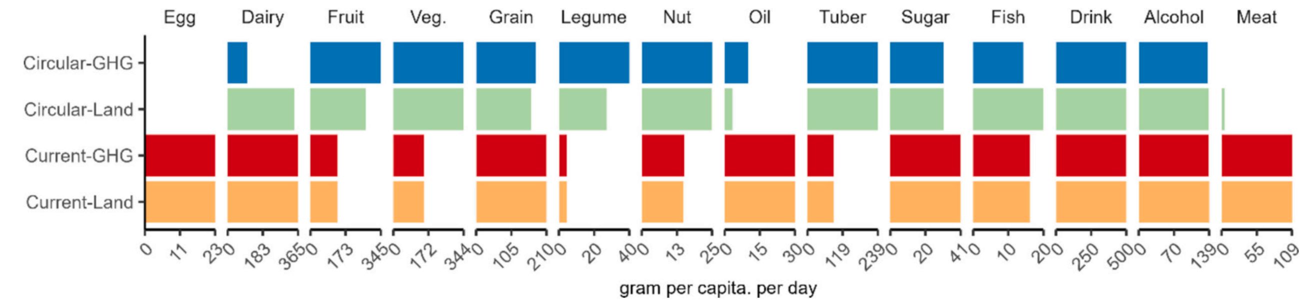


Fig. 1. Human diet in grams per capita per day.

land use (arable crops, greenhouse, crops, tree crops, permanent grassland) or minimise GHG emissions. We hypothesise that optimising the food system for different environmental objectives would result in different utilisation pathways for residual streams and provides insight into the potential trade-offs between the various objectives.

The human diet was either the current diet or a circular diet. The current diet was based on current consumption patterns at a food group level in the Netherlands and includes nutrient consumption constraints (van Rossum et al., 2020). The current diet consists of 110 g of meat, 360 g of dairy products and 16 g of fish, with associated animals and production of animal manure. The circular diet was a result of model optimisation with restrictions to meet the nutrient requirements (27 in total, including macronutrients, vitamins, minerals, fatty acids) of the population and food group constraints to keep the diet feasible for consumption and ensure the diet contains a mixture of food groups. The upper limit of consumption for food groups (e.g., vegetables 344 g per person per day) which does not increase the risk of non-communicable diseases was based on the 95th percentile of current consumption in the Netherlands (van Rossum et al., 2020). The upper limit for consumption of food groups which do increase the risk of non-communicable diseases was based on the EAT-Lancet diet (Willett et al., 2019). In addition, a lower limit is placed on each food group if minimum consumption recommendations were available (Kromhout et al., 2016). A more detailed overview of the food group constraints can be found in van Selm et al. (2023b).

As the precise outcomes of the two human diets are important context to interpret the results of our study, we present these in Fig. 1.

The circular diet resulted in an increase in consumption of the fruit, vegetable, legume and tuber food groups and a decrease in consumption of the egg, oil, and meat food groups compared to the current diet (Fig. 1). The circular diet altered consumption patterns to meet the nutrient requirements of the population without over consumption. In the circular diet, dairy consumption decreased when minimising GHG emissions due to methane emissions from dairy cattle. However, when minimising land-use oil and legume consumption decreased due to relatively low crop yields in the Netherlands. Fish was sourced from marine fisheries, which did not contribute to land use, increasing consumption when minimising land use.

3. Results

3.1. Utilising residual streams

Our analysis shows that the optimal utilisation of by-products and food loss and waste is dependent on human diets and environmental objectives (to either minimise agricultural land use or GHG emissions; Fig. 2). Across all scenarios, by-products were primarily fed to animals. However, in the Circular-GHG scenario, a notable portion of by-products

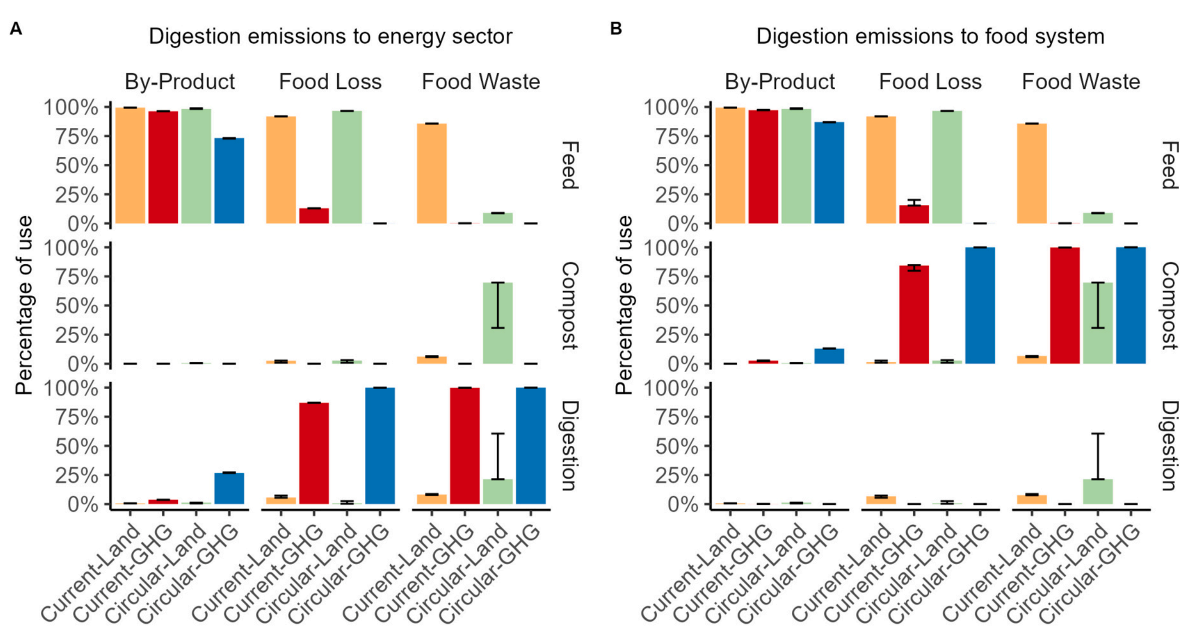


Fig. 2. Flows of by-products (from the processing of raw materials into food products), food loss and food waste utilised as animal feed, compost or anaerobic digestion per scenario. Results are shown as a percentage of available product stream per utilisation pathway. Error bars indicate minimum and maximum values of the sensitivity analysis. A: GHG emissions from anaerobic digestion are assigned to the energy sector; B: GHG emissions from anaerobic digestion are assigned to the food system. Along the x-axis the four scenarios are listed (Table 1).

was also used for anaerobic digestion (Fig. 2A) or compost (Fig. 2B) due to low animal-sourced food demands in the circular diet. Food loss and waste was primarily fed to animals when minimising agricultural land use, except food waste in the Circular-Land scenario, again due to low animal-sourced food demands. When minimising GHG emissions, food loss and waste was primarily used for anaerobic digestion (Fig. 2A) or compost (Fig. 2B), while a small portion of food losses was fed to animals in the Current-GHG scenarios due to the high animal-sourced food demands of the current diet. GHG emissions from composting are lower than GHG emissions from anaerobic digestion, but anaerobic digestion also produces biogas while compost does not.

Processing food loss and waste into animal feed (heating and sterilisation) is emission intensive, which limited the opportunity to use food loss and waste as animal feed when minimising GHG emissions. Utilising food waste as animal feed, however, reduces demand for feed-food crops and therefore reduces agricultural land use. Therefore, with the current diet, food waste was prioritised for feed due to high animal-sourced food requirements. In the circular diet animal-sourced food consumption was relatively low (Fig. 1), which resulted in food waste being distributed amongst all three utilisation pathways when minimising agricultural land use. The decision to either digest or compost food waste was only influenced by favourable N:P:K ratios matching crop fertilisation requirements and, the effect of composting or digestion on land use was therefore limited (as shown by the large error bars in Fig. 2).

3.2. Utilising manure

All pig and dairy cow manure was anaerobically digested when minimising GHG emissions due to lower N and methane emissions during the digestion process compared to traditional manure management systems (results not shown, as a figure would show 100 % of pig and dairy manure to anaerobic digestion in all scenarios minimising GHG emissions). The human diet and the assigning of GHG emissions to the energy sector or food system had no impact on the utilisation of manure.

3.3. Land use and GHG emissions

Figure 3 shows a clear trade-off between environmental objectives. Minimising agricultural land use resulted in higher GHG emissions while minimising GHG emissions resulted in higher agricultural land use. The circular diet resulted in the lowest agricultural land use and GHG emissions.

The choice to assign anaerobic digestion emissions to the digestate (food system) or to the biogas (energy sector) produced had consequences for GHG emissions. Assigning GHG emissions from anaerobic digestion to the energy sector increased the amount of residual streams being digested (Fig. 2 A) and hence the associated GHG emissions from anaerobic digestion (Fig. 3A, solid fraction). However, assigning GHG emissions from anaerobic digestion to the food system resulted in no residual streams being digested when minimising GHG emissions and only a small portion of residual streams being digested when minimising agricultural land use (Fig. 2B). Therefore, the associated GHG emissions from anaerobic digestion were minor (and hence not visible in Fig. 3B) when assigning GHG emissions from anaerobic digestion to the food system.

Total GHG emissions (i.e., food system + anaerobic digestion emissions) were highest when assigning emissions from anaerobic digestion to the energy sector compared to assigning emissions from anaerobic digestion to the food system due to increased anaerobic digestion (Fig. 2) (Current-GHG: 318 vs. 329 kg CO_2e per capita per year; Circular-GHG: 149 vs. 173; Fig. 3). GHG emissions from anaerobic digestion were higher than GHG emission from compost. However, this comparison does not account for the contribution anaerobic digestion makes to biogas production, which will also reduce GHG emissions when replacing energy from fossil fuels. This was overcome by assigning emissions to the energy sector, which increased anaerobic digestion, total GHG emissions, and biogas production. Assigning anaerobic digestion emissions to the food system resulted in the lowest total GHG emissions, as residual streams were composted.

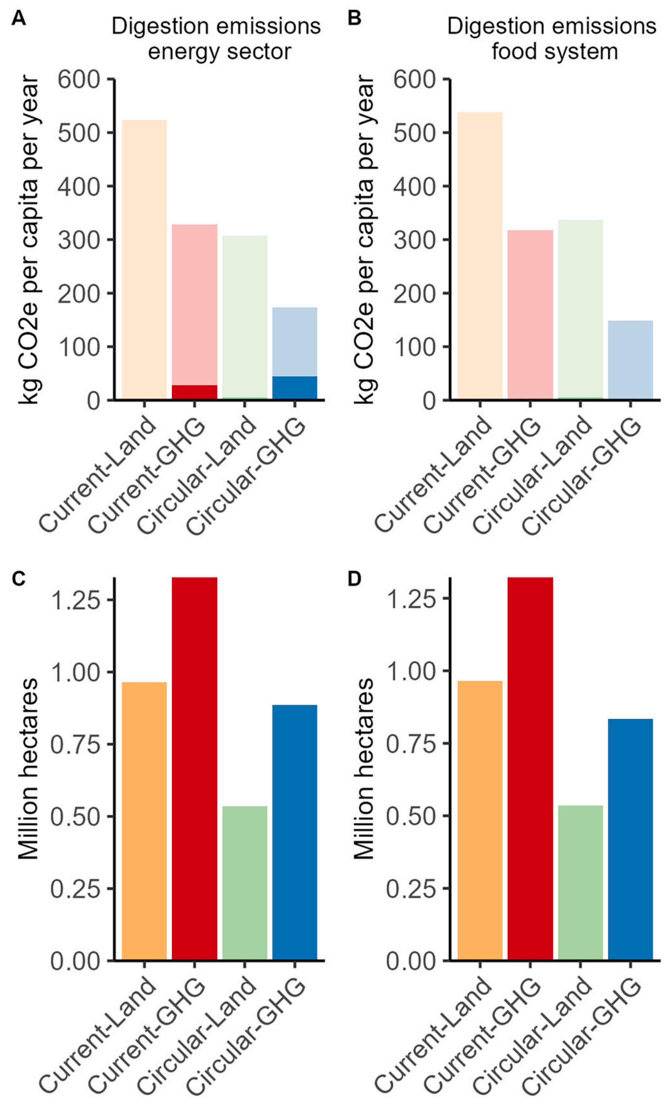


Fig. 3. A: GHG emissions (kg CO_2e per capita per year) for the four scenarios (Table 1) when emissions from anaerobic digestion are assigned to the energy sector. Shaded colours are emissions from the food system and solid colours are emissions from anaerobic digestion; B: GHG emissions (kg CO_2e per capita per year) when emissions from anaerobic digestion are assigned to the food system. Shaded colours are emissions are from the food system and solid colours are emissions from anaerobic digestion; C: Agricultural land use (million hectares per year) when GHG emissions from anaerobic digestion are assigned to the energy sector; D: Agricultural land use (million hectares per year) when GHG emissions from anaerobic digestion are assigned to the food system.

3.4. Nitrogen flows through the food system

Minimising GHG emissions reduced the flow of N through the food system compared to minimising land use (sizes of the flows shown on the left and right in Fig. 4). The overall N use efficiency of the food system (N output in food consumption and export as a percentage of N inputs, the latter including deposition, biological fixation and artificial fertiliser) was slightly higher when minimising GHG emissions (47 % vs. 44 %). Minimising GHG emissions ensured N was utilised more efficiently to reduce N losses and associated GHG emissions.

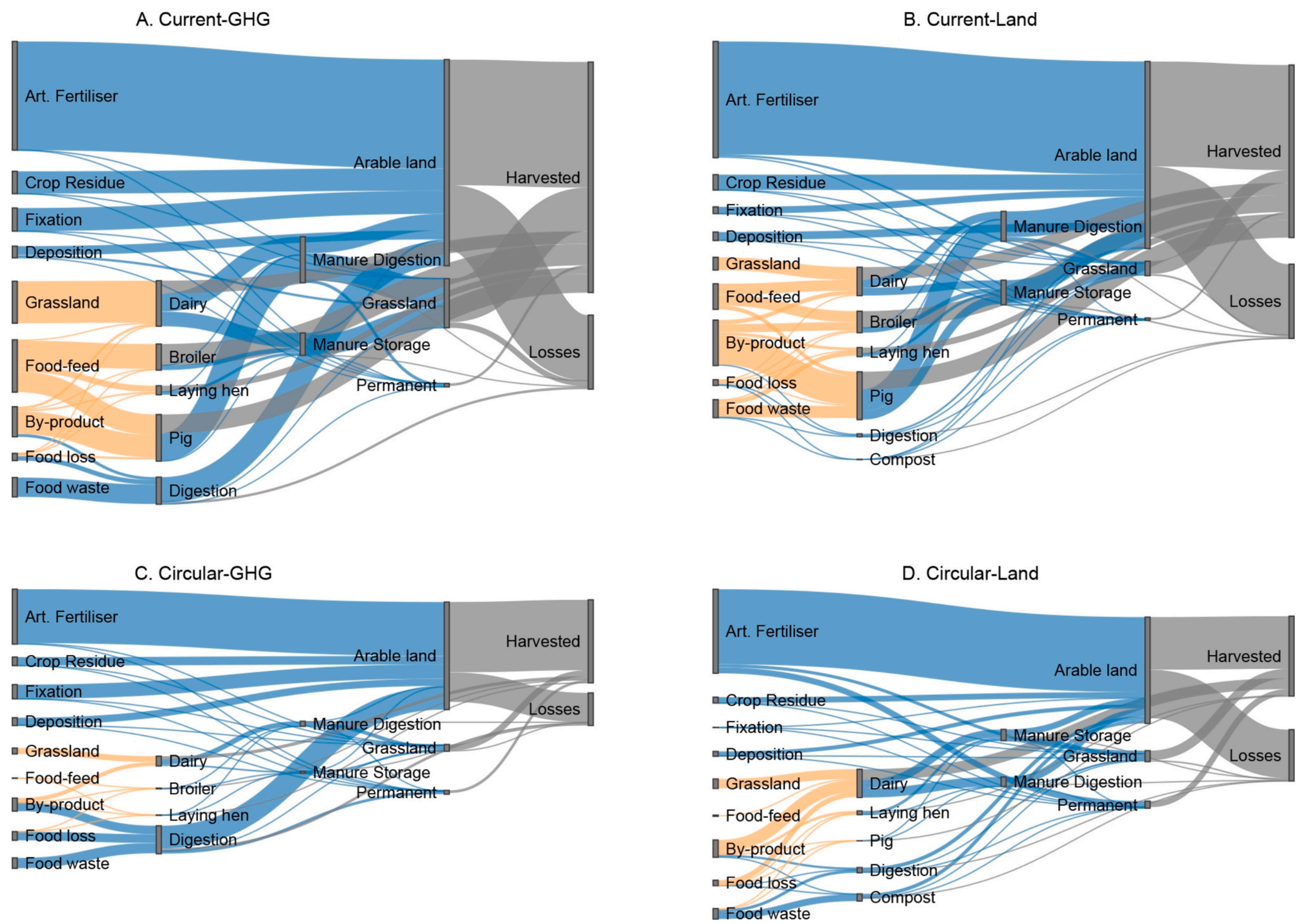


Fig. 4. Nitrogen (N) flows through the food system for feed (orange flows) and fertiliser (blue flows). Animal feed (food feed, grassland) is fed to livestock while residual streams are either fed to livestock, composted, or digested. Livestock produce manure which is digested or used as fertiliser on arable land and grassland. Arable land and grassland are also fertilised with compost, digestate, artificial fertiliser and crop residues. N deposition and fixation also contribute to fertilisation. Harvested N includes feed, food and by-products including food losses and waste. Labels refer to vertical grey bars. In this figure GHG emissions from anaerobic digestion are assigned to the energy sector. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The flow of N through the food system was substantially lower in the circular diet than in the current diet (sizes of the flows shown at the top and bottom of Fig. 4), primarily due to less demand for animal-sourced food and therefore less demand for animal feed. Consequently, the N use efficiency of the food system was higher with a circular diet compared to the current diet (48 % vs. 43 %) due to lower N losses from livestock. In the current diet, livestock consumed larger quantities of all feed categories. Production and availability of by-products was not only driven by demand for the main food product, but also by demand for animal feed. As a result, in our model the main product was exported, and the by-product remained in the Netherlands as animal feed. Due to an increase in the production of animal feed, the quantity of N applied to the soil also increased (Fig. 4).

3.5. Livestock diets

Livestock diets and consumption of feed-food crops were influenced by the environmental objective minimised (land use or GHG emissions). Poultry diets were dominated by feed-food crops when minimising GHG emissions (broiler: 79 %; laying hen: 86 %), but feed-food crops were partially or fully replaced with residual streams when minimising land use. Producing feed-food crops increased land use while processing residual streams increased GHG emissions. Dairy cow diets contained more conserved grassland products (e.g., grass silage) when minimising GHG emissions and more feed-food crops (e.g., maize silage) when minimising agricultural land use. Pigs were not selected when minimising GHG emissions with the circular diet while broiler chickens were not selected when minimising land use in the circular diet. Broiler chickens had a lower GHG emission intensity, while pigs were more efficient at utilising residual streams as feed which reduced land use.

The current diet, representing current demand for animal-sourced food in the human diet, resulted in different livestock diets and animal numbers than the circular diet (Fig. 5 & Supplementary Material S5). Livestock diets contained relatively more residual streams in the circular diets because less animals were kept, this enabled feed-food crops to be replaced with residual streams. Residual streams were available in limited quantities, and consuming less animal-sourced food allows residual streams to make a greater contribution to livestock diets. By-products and high-quality food losses (e.g., waste from grains) were suitable substitutes for feed crops. Poultry diets were dominated by food losses in the Circular-GHG scenario, while laying hen diets were dominated by food waste in the Circular-Land scenario. The food waste consisted of high-quality distribution waste that had not been diluted with lower quality food products.

3.6. Fertilisation

The way residual streams are utilised in the food system impacted the types of fertiliser and organic amendments applied to the soil (Fig. 6). Minimising GHG emissions increased the percentage of residual streams being digested (Fig. 1), which in-turn increased the percentage of digestate applied to the soil (Min GHG: 19 %; Min land: 3 %) (Fig. 6).

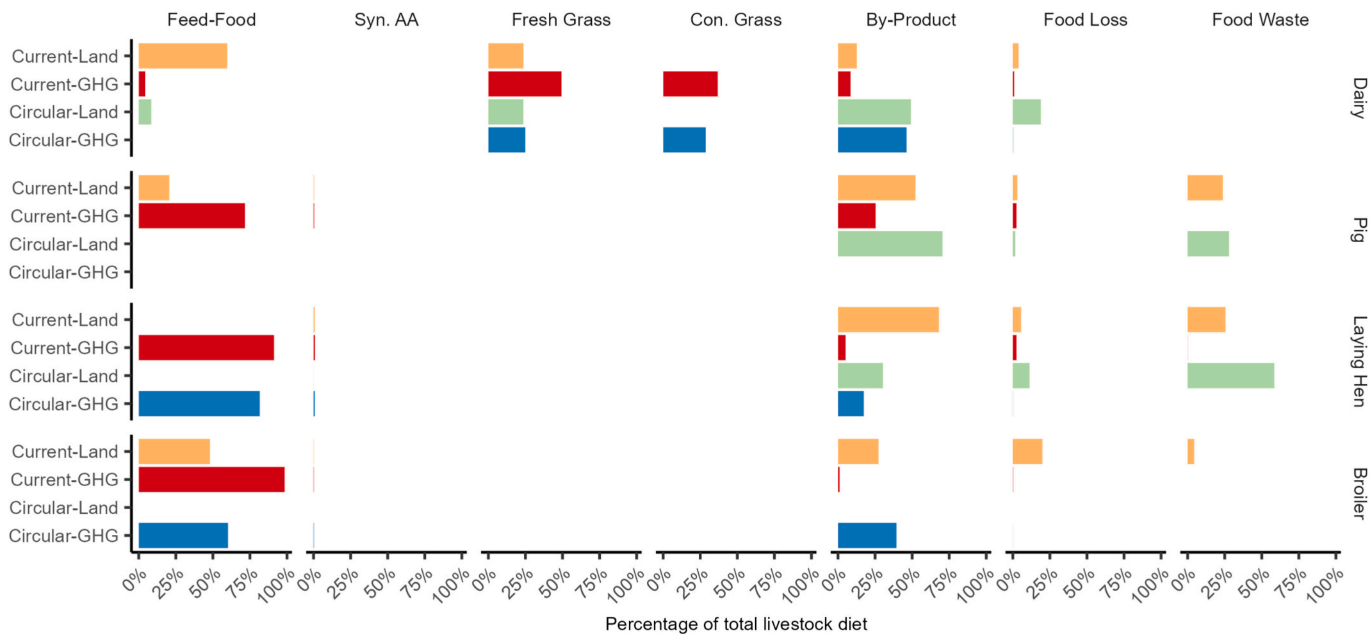


Fig. 5. Feed intake of each feed category per livestock category and scenario. Beef cattle were not selected in any scenario. Results are shown as percentage of total dry matter intake. In these scenarios GHG emissions from anaerobic digestion are assigned to the energy sector. Results showing emissions assigned to the food system are available in the supplementary material S1.

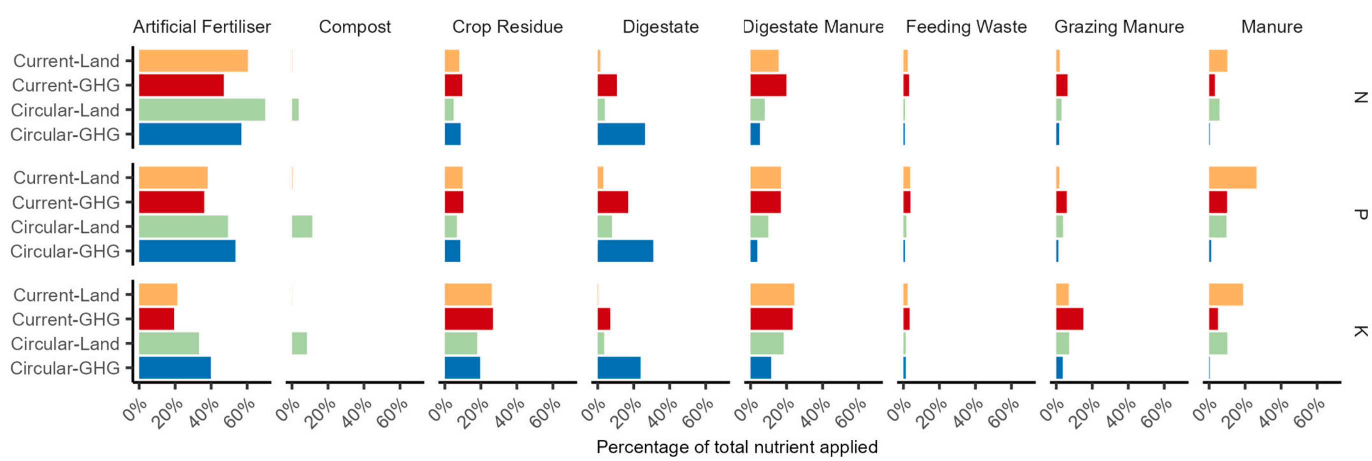


Fig. 6. Nutrients applied to the soil per fertiliser category and scenario. Results are shown as percentage of total amount of nutrient applied. In these scenarios anaerobic digestion emissions are assigned to the energy sector. Results showing emissions assigned to the food system are available in the supplementary material S2.

Overall, minimising GHG emissions inadvertently minimises N losses from livestock and fertilisation by minimising N_2O emissions, which also reduced demand for artificial fertiliser (Min Land: 65 %; Min GHG: 52 %; Fig. 4). On the other hand, minimising agricultural land use increased the share of artificial fertiliser, manure, and digestate from anaerobically digested manure applied to the soil (Fig. 6). Nutrient intake in livestock diets was higher, which increased nutrient excretion and nutrients in manure when minimising land use (Fig. 4). This increased the quantity of nutrients applied in manure as digestate manure or directly as manure.

The larger quantity of animal-sourced food in the current diet resulted in more animals being kept (Fig. 1 & Supplementary Material S6), which increased the percentage of digested manure (Current diet: 20 %; Circular diet: 9 %) being applied to the soil compared to the circular diet. In the circular diet, less animal-sourced food was consumed, and relatively more artificial fertiliser (Current diet: 50 %; Circular diet 37 % of kg N, P and K applied) was applied to compensate for a reduction in (digested) animal manure. A small amount of compost was applied, only when minimising land use with a circular diet.

4. Discussion

Our results show that prioritising the use of by-products for animal feed minimises both agricultural land use and GHG emissions. Our results also show that prioritising the use of food loss and waste for animal feed minimises agricultural land use, but that prioritising the use of food loss and waste for compost or anaerobic digestion minimises GHG emissions.

Currently in the Netherlands, an estimated 16 % of food loss and waste is fed to animals, 12 % is digested and 36 % is composted (Soethoudt and Vollebregt, 2020). The remainder (36 %) is burnt for electricity generation. Achieving the level of food loss and waste utilisation shown in our study requires an important change in legislation. Current legislation prescribes food loss and waste can only be fed to animals when it can be demonstrated that there is no risk of contamination with animal derived products. However, it has been shown that pigs, poultry, and fish can upcycle contaminated food loss and waste without compromising food safety (El Boushy and van der Poel, 2000; zu Ermgassen et al., 2016).

Separation of food loss and waste increases flexibility and the opportunity to feed animals. Food loss (i.e., post-harvest and processing and packaging losses) occurs at an industrial scale, which allows for the separation of individual food loss streams. On the other hand, food waste (i.e., distribution and consumption waste) occurs in the supermarket or in the household which limits the ability to separate food waste streams. In this study, we assumed post-harvest, processing and packaging losses were separated into individual residual streams (e.g., wheat waste or wheat flour waste), distribution waste was separated at a food group level (e.g., grain waste), and finally, consumption waste could not be separated and was treated as a single residual product. Our results suggest that post-harvest, processing and packaging losses, and distribution losses must be fed to animals when minimising land, while consumption or household waste better be composted or digested (especially in circular diets). The higher the level of separation of food losses, the more flexibility the product has to be utilised as animal feed. Each animal has a unique biological ability to up-cycle waste streams. Some animals require high-quality (i.e., nutrient dense) residual streams (e.g., poultry), while others can consume lower quality residual streams (e.g., ruminants or pigs) (van Selm et al., 2022). Yet, separating food waste at a household level can be challenging. Alternatively, drying food waste could also increase the utilisation of food waste as animal feed, however this process is energy intensive (Salemdeeb et al., 2017). Alternative ways to collect and process food waste into animal feed must be found that are not GHG emission intensive.

Currently, anaerobic digestion in the Netherlands is limited. Since our study explores future scenarios we did not consider if the current anaerobic digestion capacity would be sufficient to digest the quantities suggested in our analysis. Furthermore, we did not consider feeding rates and the ratio of manure to residual streams in this analysis. However, our results fit well with the ambition of the Netherlands to increase anaerobic digestion capacity in the future (Winquist et al., 2021).

During the composting and digestion processes, nutrients (especially N) are lost to the atmosphere. Uncertainty exists in the quantity of N lost and the resulting GHG emissions produced during composting and anaerobic digestion (Boldrin et al., 2009; Mayer et al., 2021). This uncertainty primarily impacts the GHG emission estimates. In the present exercise, the decision to compost was determined by where the emissions from digestate are assigned to i.e., the energy sector or the food system (Fig. 2). It should also be noted we did not consider the feeding rates of the digester or the ratios of manure to residual streams in the feedstock. Suboptimal feeding rates and ratios will reduce the efficiency of anaerobic digestion but will not influence the choice to compost or digest residual streams. That choice was determined by the assignment of emissions from anaerobic digestion and not efficiency gains or losses from compost or anaerobic digestion. Assigning emissions from anaerobic digestion to the food system favours composting food waste (absolute GHG emissions of composting is lower than GHG emissions from anaerobic digestion), but this fails to acknowledge that energy is produced from anaerobic digestion, which will contribute to reducing GHG emissions because of substitution of fossil fuels (Farghali et al., 2022). Including these avoided emissions in the model optimisation would result in by-products and food losses being digested while livestock are fed with feed-food crops. In this case it might be better to anaerobically digest the feed-food crops directly instead, however more research is needed to understand the implications for the food system, energy systems, and agricultural land use. Circularity principles argue that biomass and agricultural land use should be prioritised for basic human needs (food, pharmaceuticals, clothing) (Muscat et al., 2021). Based on these principles energy should be produced from alternative renewable options (e.g., wind, solar). The primary product of anaerobic digestion is biogas (latter burned to produce energy); therefore it seems most appropriate to assign emissions from anaerobic digestion to the energy sector. Digesting manure rather than applying it as a fertiliser will always result in the lowest GHG emissions, no matter to where the GHG emissions are assigned because emissions from anaerobic digestion are lower than from current manure management systems.

When minimising land use the decision to compost or digest food waste is less certain than when minimising GHG emissions. If large quantities of animal-sourced food are required food waste should be fed to animals, but when lower quantities are required (i.e., with a circular diet) the decision is less certain (e.g., Fig. 1, Circular-Land: food waste). The model's preference to digest or compost in the circular diet when minimising agricultural land use was only determined by favourable N:P:K ratios better meeting crop fertilisation requirements. The portion of residual streams to be either composted or digested can therefore be based on minimising GHG emissions.

In our study fertilisation focused on the application of N, P, and K to meet crop requirements. However, applying organic amendments (e.g., compost, manure, digestate) provides benefits beyond N, P, K, which can be difficult to quantify (Hijbeek et al., 2017). For example, organic amendments can potentially increase soil carbon content, provide micronutrients, improve soil structure, increase soil microbial activity and water holding capacity (Hoffland et al., 2020). Other organic amendments could also be used to increase soil carbon, e.g. sewage sludge to cropland and grassland. Sewage sludge derived from human excreta was not considered in this study, but could partially replace artificial fertiliser and result in further closing of nutrient cycles (Van Kernebeek et al., 2018) and higher nutrient use efficiency of the food system. However, the potential of human excreta as a fertiliser is affected mostly by, energy requirements, the risk of contamination, and legislation issues.

5. Conclusions

In this study we show the optimal use of residual streams of food loss, food waste, and by-products in circular food systems, depending on the environmental objective, human diet, and assignment of GHG emissions to the food system or the energy sector. By-products such as wheat bran should always be fed to livestock. Food loss and waste is best fed to livestock when minimising land use, but is best composted to replace fertilisers or digested to replace fossil energy when minimising GHG emissions. The decision to compost or digest depends on where the emissions from anaerobic digestion are assigned to. Assigning to the biogas (energy sector) rather than to the digestate (food system) favoured anaerobic digestion, which can be considered most appropriate because energy is the primary product. More optimum use of food loss and waste can be achieved with higher levels of separation of food loss and waste in different categories, to tailor the use of different types of animal feed and to avoid problems with contamination.

CRediT authorship contribution statement

Benjamin van Selm: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Conceptualization. **Renske Hijbeek:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Corina E. van Middelaar:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Imke J.M. de Boer:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Martin K. van Ittersum:** Writing – review & editing, Supervision, Methodology, Conceptualization.

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 supported by the Dutch Ministry of Agriculture, Nature and Food Quality via the knowledge and innovation Connected Circularity programme (Grant Number KB-40-001-001). We thank Laura Stoll for her role in adding digestion as a processing option to FOODSOM.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2024.104185.

References

Billen, G., Aguilera, E., Einarsson, R., Garnier, J., Gingrich, S., Grizzetti, B., Lassaletta, L., Le Noë, J., Sanz-Cobena, A., 2021. Reshaping the European agro-food system and closing its nitrogen cycle: the potential of combining dietary change, agroecology, and circularity. One Earth (Cambridge, Mass.) 4, 839–850. https://doi.org/10.1016/j.oneear.2021.05.008.

Boldrin, A., Andersen, J.K., Møller, J., Christensen, T.H., Favoino, E., 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 800–812. https://doi.org/10.1177/0734242X09345275.

Brink, E., van Rossum, C., Postma-Smeets, A., Stafleu, A., Wolvers, D., van Dooren, C., Toxopeus, I., Buurma-Rethans, E., Geurts, M., Ocké, M., 2019. Development of healthy and sustainable food-based dietary guidelines for the Netherlands. Public Health Nutr. 22, 2419–2435. https://doi.org/10.1017/S1368980019001435.

van Bruggen, C., Bannink, A., Groenestein, C.M., Lagerwerf, L.A., Luesink, H.H., Velthof, G.L., Vonk, J., Zee, T.V.D., 2021. Emissies Naar Lucht uit de Landbouw Berekend met NEMA voor 1990-2019, p. 238.

Caldeira, C., De Laurentiis, V., Corrado, S., van Holsteijn, F., Sala, S., 2019. Quantification of food waste per product group along the food supply chain in the European Union: a mass flow analysis. Resour. Conserv. Recycl. 149, 479–488. https://doi.org/10.1016/j.resconrec.2019.06.011.

CBS, 2019. CBS StatLine. Statistics Database.

Cortés, A., Oliveira, L.F.S., Ferrari, V., Taffarel, S.R., Feijoo, G., Moreira, M.T., 2020. Environmental assessment of viticulture waste valorisation through composting as a biofertilisation strategy for cereal and fruit crops. Environ. Pollut. 264, 1–8. https://doi.org/10.1016/j.envpol.2020.114794.

De Boer, I.J.M., Van Ittersum, M.K., 2018. Circularity in Agricultural Production, Wageningen University & Research. Wageningen University & Research, Wageningen.

De Ruijter, F.J., Van Dijk, W., Van Geel, W.C.A., Holshof, G., Postma, R., Wilting, P., Van Middelkoop, J.C., 2020. Actualisatie van Stikstof- en Fosfaatgehalten van Akkerbouwgewassen Met EEN Groot Areaal. https://doi.org/10.18174/520624.

El Boushy, A.R.Y., van der Poel, A.F.B., 2000. Handbook of Poultry Feed from Waste. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-017-1750-2.

FAO, 1996. Technical Conversion Factors for Agricultural Commodities. Food and Agriculture Organization of the United Nations.

Farghali, M., Osman, A.I., Umetsu, K., Rooney, D.W., 2022. Integration of biogas systems into a carbon zero and hydrogen economy: a review. Environ. Chem. Lett. https://doi.org/10.1007/s10311-022-01468-z.

Frehner, A., Cardinaals, R.P.M., de Boer, I.J.M., Muller, A., Schader, C., van Selm, B., van Hal, O., Pestoni, G., Rohrmann, S., Herrero, M., van Zanten, H.H.E., 2022. The compatibility of circularity and national dietary recommendations for animal products in five European countries: a modelling analysis on nutritional feasibility, climate impact, and land use. Lancet Planet. Health 6, e475–e483. https://doi.org/10.1016/S2542-5196(22)00119-X.

Haberl, H., Erb, K.H., Krausmann, F., 2014. Human appropriation of net primary production: patterns, trends, and planetary boundaries. Annu. Rev. Environ. Resour. 39, 363–391. https://doi.org/10.1146/annurev-environ-121912-094620.

Hijbeek, R., van Ittersum, M.K., ten Berge, H.F.M., Gort, G., Spiegel, H., Whitmore, A.P., 2017. Do organic inputs matter a meta-analysis of additional yield effects for arable crops in Europe. Plant Soil 411, 293–303. https://doi.org/10.1007/s11104-016-3031-x.

Hoffland, E., Kuyper, T.W., Comans, R.N.J., Creamer, R.E., 2020. Eco-functionality of organic matter in soils. Plant Soil 455, 1–22. https://doi.org/10.1007/s11104-020-04651-9.

Krausmann, F., Erb, K.H., Gingrich, S., Haberl, H., Bondeau, A., Gaube, V., Lauk, C., Plutzar, C., Searchinger, T.D., 2013. Global human appropriation of net primary production doubled in the 20th century. Proc. Natl. Acad. Sci. USA 110, 10324–10329. https://doi.org/10.1073/pnas.1211349110.

Kromhout, D., Spaaij, C.J.K., De Goede, J., Weggemans, R.M., Brug, J., Geleijnse, J.M., Van Goudoever, J.B., Hoes, A.W., Hopman, M.T.E., Iestra, J.A., Mensink, R.P., Pijl, H., Romijn, J.A., Schols, A.M.W.J., Seidell, J.C., Veer, P.V.T., Visser, M., Zwietering, M.H., 2016. The 2015 Dutch food-based dietary guidelines. Eur. J. Clin. Nutr. 70, 869–878. https://doi.org/10.1038/ejcn.2016.52.

Lagerwerf, L.A., Bannink, A., van Bruggen, C., Groenestein, C.M., Huijsmans, J.F.M., van der Kolk, J.W.H., Luesink, H.H., van der Sluis, S.M., Velthof, G.L., Vonk, J., 2019. Methodology for estimating emissions from agriculture in the Netherlands - update 2019. Res. Tasks Unit Nat. Environ. Wageningen. https://doi.org/10.18174/383679.

Lun, F., Liu, J., Ciais, P., Nesme, T., Chang, J., Wang, R., Goll, D., Sardans, J., Peñuelas, J., Obersteiner, M., 2018. Global and regional phosphorus budgets in agricultural systems and their implications for phosphorus-use efficiency. Earth Syst. Sci. Data 10, 1–18. https://doi.org/10.5194/essd-10-1-2018.

Mayer, F., Bhandari, R., Gäth, S.A., 2021. Life cycle assessment on the treatment of organic waste streams by anaerobic digestion, hydrothermal carbonization and incineration. Waste Manag. 130, 93–106. https://doi.org/10.1016/j.wasman.2021.05.019.

Melse, R.W., Groenestein, C.M., 2016. Emissiefactoren Mestbewerking: Inschatting van Emissiefactoren voor Ammoniak en Lachgas uit Mestbewerking. https://doi.org/10.18174/386801.

Muscat, A., de Olde, E.M., de Boer, I.J.M., Ripoll-Bosch, R., 2020. The battle for biomass: a systematic review of food-feed-fuel competition. Glob. Food Sec. 25, 100330. https://doi.org/10.1016/j.gfs.2019.100330.

Muscat, A., de Olde, E.M., Ripoll-Bosch, R., Van Zanten, H.H.E., Metze, T.A.P., Termeer, C.J.A.M., van Ittersum, M.K., de Boer, I.J.M., 2021. Principles, drivers and opportunities of a circular bioeconomy. Nat. Food 2, 561–566. https://doi.org/10.1038/s43016-021-00340-7.

O'Connor, J., Hoang, S.A., Bradney, L., Dutta, S., Xiong, X., Tsang, D.C.W., Ramadass, K., Vinu, A., Kirkham, M.B., Bolan, N.S., 2021. A review on the valorisation of food waste as a nutrient source and soil amendment. Environ. Pollut. 272, 115985. https://doi.org/10.1016/j.envpol.2020.115985.

O'Connor, J., Mickan, B.S., Rinklebe, J., Song, H., Siddique, K.H.M., Wang, H., Kirkham, M.B., Bolan, N.S., 2022. Environmental implications, potential value, and future of food-waste anaerobic digestate management: a review. J. Environ. Manag. 318. https://doi.org/10.1016/j.jenvman.2022.115519.

PBL, 2020. Availability and Applications of Sustainable Biomass. Report on a Search for Shared Facts and Views, p. 35.

Röös, E., Patel, M., Spångberg, J., Carlsson, G., Rydhmer, L., 2016. Limiting livestock production to pasture and by-products in a search for sustainable diets. Food Policy 58, 1–13. https://doi.org/10.1016/j.foodpol.2015.10.008.

van Rossum, C.T.M., Buurma-Rethans, E.J.M., Dinnissen, C.S., Beukers, M.H., Brants, H.A.M., Dekkers, A.L.M., Ocké, M.C., 2020. The Diet of the Dutch - Results of the Dutch National Food Consumption Survey 2012-2016, p. 384.

Salemdeeb, R., Ermgassen, Z., Erasmus, K.H.J., Kim, M.H., Balmford, A., Al-Tabbaa, A., 2017. Environmental and health impacts of using food waste as animal feed: a comparative analysis of food waste management options. J. Clean. Prod. 140, 871–880. https://doi.org/10.1016/j.jclepro.2016.05.049.

Schievano, A., D'Imporzano, G., Salati, S., Adani, F., 2011. On-field study of anaerobic digestion full-scale plants (part I): an on-field methodology to determine mass, carbon and nutrients balance. Bioresour. Technol. 102, 7737–7744. https://doi.org/10.1016/j.biortech.2011.06.006.

van Selm, B., Frehner, A., de Boer, I.J.M., van Hal, O., Hijbeek, R., van Ittersum, M.K., Talsma, E.F., Lesschen, J.P., Hendriks, C.M.J., Herrero, M., van Zanten, H.H.E., 2022. Circularity in animal production requires a change in the EAT-lancet diet in Europe. Nat. Food 3, 66–73. https://doi.org/10.1038/s43016-021-00425-3.

van Selm, B., Hijbeek, R., van Ittersum, M.K., van Hal, O., van Middelaar, C.E., de Boer, I.J.M., 2023a. Recoupling livestock and feed production in the Netherlands to reduce environmental impacts. Sci. Total Environ. 165540. https://doi.org/10.1016/j.scitotenv.2023.165540.

van Selm, B., van Zanten, H.H.E., Hijbeek, R., van Middelaar, C.E., Schop, M., van Ittersum, M.K., de Boer, I.J.M., 2023b. Interventions to increase circularity and reduce environmental impacts in food systems. Ambio. https://doi.org/10.1007/s13280-023-01953-x.

Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., Azapagic, A., 2019. Environmental sustainability of anaerobic digestion of household food waste. J. Environ. Manag. 236, 798–814. https://doi.org/10.1016/j.jenvman.2019.02.001.

Soethoudt, H., Vollebregt, M., 2020. Monitor Voedselverspilling: Update 2009–2019: Hoeveel kilo gaat er in Nederland verloren? https://doi.org/10.18174/558030.

Spek, J.W., Van Wesemael, D., 2021. CVB Feed Table 2021 (no. August). Federatie Nederlandse Diervoederketen.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018a. Options for keeping the food system within environmental limits. Nature 562, 519–525. https://doi.org/10.1038/s41586-018-0594-0.

Springmann, M., Wiebe, K., Mason-D'Croz, D., Sulser, T.B., Rayner, M., Scarborough, P., 2018b. Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail. Lancet Planet. Health 2, e451–e461. https://doi.org/10.1016/S2542-5196(18)30206-7.

Van Hal, O., De Boer, I.J.M., Muller, A., de Vries, S., Erb, K.-H., Schader, C., Gerrits, W.J.J., van Zanten, H.H.E., 2019. Upcycling food leftovers and grass resources through livestock: impact of livestock system and productivity. J. Clean. Prod. 219, 485–496. https://doi.org/10.1016/j.jclepro.2019.01.329.

Van Kernebeek, H.R.J., Oosting, S.J., Van Ittersum, M.K., Ripoll-Bosch, R., De Boer, I.J. M., 2018. Closing the phosphorus cycle in a food system: insights from a modelling exercise. Animal: Intern. J. Animal Biosci. 12, 1755–1765. https://doi.org/10.1017/S1751731118001039.

Vasco-Correa, J., Khanal, S., Manandhar, A., Shah, A., 2018. Anaerobic digestion for bioenergy production: global status, environmental and techno-economic implications, and government policies. Bioresour. Technol. 247, 1015–1026. https://doi.org/10.1016/j.biortech.2017.09.004.

Vellinga, T.V., Blonk, H., Marinussen, M., van Zeist, W.J., de Boer, I.J.M., Starmans, D., 2013. Methodology used in feedprint: a tool quantifying greenhouse gas emissions of feed production and utilization. Livestock Res. 121. Report 674.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S.J., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene: the EAT-lancet commission on healthy diets from sustainable food systems. Lancet (Lond., Engl.) 393, 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Winquist, E., Van Galen, M., Zielonka, S., Rikkonen, P., Oudendag, D., Zhou, L., Greijdanus, A., 2021. Expert views on the future development of biogas business branch in Germany, the Netherlands, and Finland until 2030. Sustainability 13, 1148. https://doi.org/10.3390/su13031148.

van Zanten, H.H.E., Simon, W., van Selm, B., Wacker, J., Maindl, T.I., Frehner, A., Hijbeek, R., van Ittersum, M.K., Herrero, M., 2023. Circularity in Europe strengthens the sustainability of the global food system. Nat. Food. https://doi.org/10.1038/s43016-023-00734-9.

Zu Ermgassen, E.K.H.J., Phalan, B., Green, R.E., Balmford, A., 2016. Reducing the land use of EU pork production: where there's swill, there's a way. Food Policy 58, 35–48. https://doi.org/10.1016/j.foodpol.2015.11.001.