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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Environmental life cycle assessment of drink and yoghurt products using non-nutritive sweeteners and sweetness enhancers in place of added sugar: the SWEET project

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Abstract

Purpose There are increasing concerns regarding detrimental health effects of added sugar in food and drink products. Non-nutritive sweeteners (NNS) and sweetness enhancers (SE) are seen as viable alternatives. Much work has been done on health and safety of NNS&SE when consumed in place of sugar, but very little on their sustainability. This work aims to bridge that gap with an environmental study of replacing added sugar with NNS&SE in the context of drink and yoghurt.

Methods A life cycle assessment (LCA) approach was used to compare environmental impact of a drink and yoghurt, sweetened with sucrose, to those sweetened with NNSs or an SE: stevia rebaudioside A, sucralose, aspartame, neotame, and thaumatin. Primary ingredients data were taken from preparation of foodstuffs for clinical trials. Results are reported via the ReCiPe 2016 (H) method, with focus on land use, global warming potential (GWP), marine eutrophication, mineral resource scarcity, and water consumption. Impacts are reported in terms of 1 kg product. Scenarios explore sensitivity of the LCA results to change in background processes, functional unit, and sweetener type. This research was conducted as part of the EU Horizon 2020 project SWEET (sweeteners and sweetness enhancers: impact on health, obesity, safety, and sustainability).

Results and discussion Replacing sugar with an NNS or part-replacing with an SE is shown to reduce environmental impact across most impact categories, for example, on a mass basis, GWP for a drink reduces from 0.61 to approx. 0.51 kgCO_2-eq/kg and for a yoghurt from 4.15 to approx. 3.73 kgCO_2-eq/kg. Variability in environmental impact is shown to be relatively small between the NNSs, indicating that choice of NNS is less important than the reformulation changes required to accommodate the loss of sugar. Reporting impact in terms of calorie density, instead of mass, shows greater reduction in environmental impact when using an NNS or SE and shows how important functional unit is when reporting impact of these products.

Conclusion This study is the first to compare food or drink products sweetened with sugar, NNS, or SE. Results show that there is great potential to reduce environmental impact of sweetened drinks and yoghurts. Moreover, the choice of NNS does not greatly affect the environmental impact of either product. Therefore, this research shows that choices relating to replacing added sugar may be based more upon health or formulation needs and less on environmental concerns.

Keywords Life cycle assessment · Non-nutritive sweeteners · Yoghurt · Drink · Added sugar

1 Introduction

There is much concern over the environmental impact of consumers' diets, leading to research on how dietary change may lead to reduction in environmental impact (Sun et al. 2022). In parallel, there is much concern over the healthiness of our diets and how excessive consumption of ingredients such as added sugar may adversely affect health (e.g., Johnson et al. 2017; Vaghela et al. 2020). Therefore, there is a need for research to understand how replacing a particular ingredient might affect both health and environmental impact. For instance, with regard to added sugar, one option is replacing its sweet taste using non-nutritive sweeteners (NNS) or sweetness enhancers (SE and collectively NNS&SE), thereby reducing dietary sugar intake.

To date, there has been much research into the health aspects of using NNS&SE (e.g., O'Connor et al. 2021;

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McGlynn et al. 2022), and this has been the subject of a systematic review and meta-analysis conducted by the World Health Organization (WHO) (Rios-Leyvraz and Montez 2022). Likewise, safety aspects of consuming NNS&SE are well understood, due to the necessity of rigorous research to underpin authorization for their use as ingredients in the European Union (European Union 2012). In terms of environmental studies, there are those for the individual NNS&SE: stevia derivatives (Gantelas et al. 2022; Milovanoff and Kicak 2022; Suckling et al. 2023b), aspartame (in the World Food LCA Database, Nemecek et al. 2019), aspartame and neotame (Suckling et al. 2023c), sucralose (Blenkley et al. 2023), and thaumatin (Suckling et al. 2023a). These studies offer comparison to sugar on both a mass and sweetness equivalence basis (i.e., the mass required to provide the same sweetness to 1 kg sugar). However, they stop short of incorporating the NNS&SE into foodstuff formulations. This is an important step as it is not often the case that sugar can simply be removed and replaced with a much smaller quantity of NNS or SE. Instead, further changes must be made to the formulations, and not looking at NNS&SE in context of reformulation may miss important changes to environmental impact. This study aims to fill that gap by being the first to attempt to understand what changes in environmental impact occur if added sugar is removed from a formulation and replaced with either an NNS or SE. This is an important step for supporting effective decisions regarding substitution of added sugar with NNS&SE in diets from all of health, safety, and environmental perspectives.

The foci for this study are a sweetened drink and a thick, sweetened, Greek-style, yoghurt. In terms of existing literature, the authors are aware of one study for a carbonated drink (Amienyo et al. 2013) and several for different types of yoghurts:

- Various yoghurts (including solid, stirred, and drinking) as produced in Portugal (Gonzalez-Garcia et al. 2013)
- Yoghurt (without further specification of type) produced from raw milk in Serbia (Djekic et al. 2014)
- Various yoghurts (Greek, set, liquid and ice cream) from raw milk in Spain (Vasilaki et al. 2016)
- Yoghurt (without further specification of type) from cows' milk in Turkey (Üçtuğ et al. 2019)
- Yoghurt (without further specification of type) from raw milk in Romania (Ghinea and Leahu 2020)
- Various yoghurts (without further specification of type) from cows' milk in Brazil (dos Santos et al. 2022)
- Greek yoghurt by different production methods, from milk in Quebec, Canada (Houssard et al. 2020)
- Various yoghurts (standard, Greek, drinking with and without fruits and aromas) from cows' milk in Canada in the ecoinvent 3.8 database (Wernet et al. 2016)

Further summary of these studies is given in Sect. 4.2 for comparative purposes to the present study. In each of the prior studies, the sweetener used is sugar, and they do not consider NNS or SE. Therefore, this study is the first comparative study of sweetened drinks and yoghurts using either sugar or NNS&SE.

Both the drinks and yoghurt in this study were developed as part of SWEET, a European Commission Horizon 2020 program project (grant no: 774293), to understand the ramifications of replacing added sugar with NNS&SE at product, dietary, and population scales. Both sugar- and NNS&SE-based versions were developed to be as similar as possible in terms of organoleptic qualities, for purposes of clinical trials, hedonic tests, and consumption studies. An outline of the studies and sensory attributes tested for are described in Supplementary Information, Sect. 3. Due to this development process, both versions have detailed lists of the ingredients required to make products which are similar as possible to each other. Such ingredient information is not available for similar, directly comparable commercial products, especially yoghurts.

The overarching aims of this study is to understand whether replacing added-sugar in a formulation with an NNS or SE causes environmental impact to increase or decrease and to attempt to quantify the contribution of the NNS in terms of an indicative total impact for the whole product. More specifically, the objectives of the presented study were to understand:

1. Net change in environmental impact of replacing added sugar with NNS&SE in drink and yoghurt formulations and the fraction of environmental impact change which may be attributable to the NNS&SE
2. Impact variation between different NNS-based formulations
3. The effect on the results of a mass-based or calorie density-based functional unit

2 Overview of the study and production processes

In this section, the key aspects of the LCA study will be described, and further overarching information relating to product reformulation is presented.

2.1 Functional unit, goal, and scope

The primary goal of this study was to understand the change in environmental impact from replacing added sugar with NNS&SE in 1 kg of non-carbonated sweetened drink and 1 kg Greek-style yoghurt. A second goal was to understand the variability between different NNS-based formulations in the context of a representative final product. Therefore, the functional unit for this study was 1 kg mass of each foodstuff, which is taken as equivalent to 1 L in the case of a drink. Mass is used as the functional unit for both sugar-based and NNS&SE-based formulations as this is the basis upon which they are sold and consumed. It also reflects that reducing energy intake can be achieved through reducing calorie density of foodstuffs while still maintaining mass of food consumed (Robinson et al. 2022). Therefore, no other aspects of the formulations are considered as part of the baseline functional unit, for instance, the presence of other nutrients, which may vary between sugar- and NNS&SE-based formulations. However, change in functional unit from mass-based to calorie density-based is explored in scenario modelling (Sect. 5.2).

Impact assessment was conducted using SimaPro 9.4 software and the ReCiPe 2016 Midpoint (Hierarchist) v1.07 method used (Huijbregts et al. 2016). Background data were drawn from the Agri-footprint 6.0 and ecoinvent 3.8 databases. Environmental impact within all impact categories of the ReCiPe 2016 method is reported, with focus given to global warming potential, land use, water consumption, and marine eutrophication. These impact categories allow for comparison between the NNS&SE and sugar and reflect the agricultural source of the sugar and dairy products. They also broadly align with the background studies for the SE (Suckling et al. 2023a) and the NNSs (Blenkley et al 2023; Suckling et al. 2023b, 2023c). However, it should be noted that this focus is purely for discussion of results, that impact data for all categories are given throughout, and that other impact categories are discussed when there are notable results.

The LCA was undertaken in line with the ISO 14040:2006 (ISO, 2010a) and ISO 14044:2006 (ISO 2010) guidelines.

2.2 System boundaries

The life cycles for both drink and yoghurt products are shown in Fig. 1. The production steps were identified through interviews with researchers who developed each of the foodstuffs. Only one production process is shown for each of drinks and yoghurts, because during product development, no discernable difference was found between the production processes for sugar-based and NNS&SE-based formulations. Likewise, researchers developing the formulations found no discernable difference in shelf-lives of the finished products. Finally, there were no differences in packaging requirements for either sugar- or NNS&SE-based formulations. Therefore, only one production process model is required, and ingredients can be changed to represent the different products.

The LCA focused on steps which are similar for both sets of products, so that reasonable comparison may be made: production of ingredients, production of formulations, packaging, and storage prior to shipping from the production site are in scope. However, at present, there is insufficient data on effects relating to change in consumption habits. Post-production steps, including transport to retail, consumption, and post-consumer waste disposal, were out of scope. Therefore, this study is cradle-to-factory-gate.

2.3 Allocation of impacts

All impacts were allocated to the final foodstuffs on an economic basis, as the only products of value from each

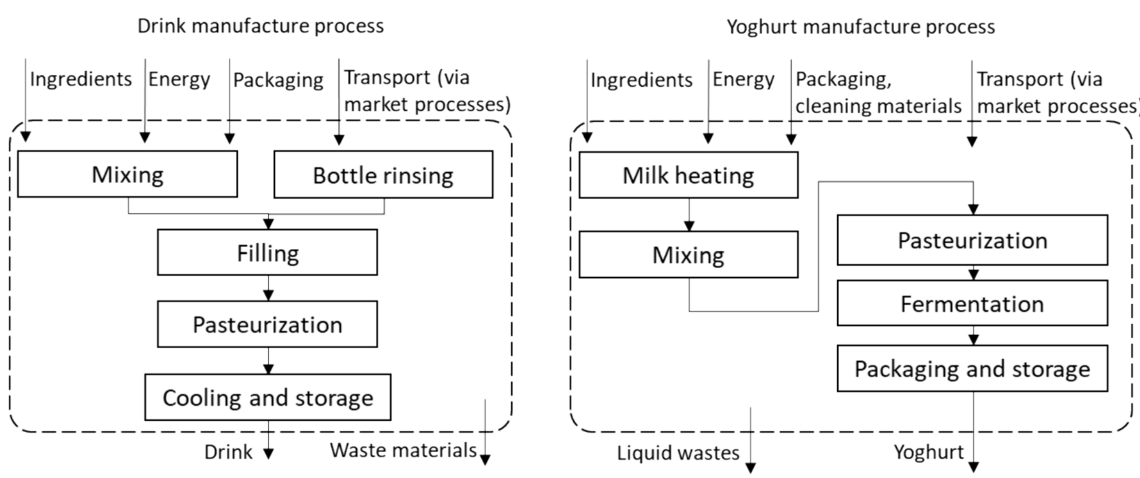

Fig. 1 Life cycle assessent process modelling steps and sytem boundaries (dashed box)

production system. Economic allocation models were also used for background processes to ensure consistency with preferred methodologies of the Agri-footprint and ecoinvent databases. However, it should be noted that the International Dairy Federation also recommends allocation for dairy products on a dry matter basis, because the solids are considered the components with the greatest economic value (IDF 2022). Cut-off criteria were applied to wastes or residues entering or leaving the system. In this regime, wastes or residues from the drink or yoghurt production processes carry no benefits if recycled, but impacts of wastes emitted to the environment (e.g., greenhouse gases) are accounted for.

2.4 Data collection and sources

Foreground data relating to recipes were derived from interviews with the researchers responsible for developing the respective formulations. Following interviews, it was considered that there was not sufficient detailed data relating to production resource needs (e.g., energy consumption). Therefore, data relating to production were derived from literature: for drinks, Amienyo et al. (2013), and for yoghurt, Üçtuğ et al. (2019). Likewise, packaging used in experimental trials for yoghurt was in the form of a glass jar with a metal lid. This was driven by both the needs to deliver a safe product for consumption and availability of packaging equipment in the laboratory. However, it was felt that there is little value in presenting environmental impact information for unrepresentative packaging materials. Therefore, packaging data were derived from the same literature sources.

Data relating to background production of ingredients and other resources were taken from life cycle inventory databases. Where background processes did not exist, proxy processes were developed, and these are outlined in the Supplementary Information. Production is assumed to be within the EU, and therefore, European level processes are chosen where possible from background LCA data. Sugar is assumed to be from a commoditized market comprising 80% sugar from cane and 20% sugar from beet (ISO 2020; OECD et al. 2021). The mix of sugars is on a global basis, with contributions from individual countries listed in Supplementary Material, Table S14. For countries with regional variations (e.g., Brazil), average production as per the Agri-footprint database are used. Land use change is accounted for in sugar production. The use of sugar derived only from cane or beet is explored in Sect. 5.3.2.

2.5 Sugar replacement

Two methods of replacing the sweetness of added sugar were explored in this study: replacing all of the added sugar with an NNS (stevia rebaudioside A (Reb A), aspartame, neotame, or sucralose) and part replacing the added sugar with an SE (thaumatin).

When replacement is by NNS, the entirety of the sugar is removed and replaced with a much smaller quantity of NNS, an amount which is dependent upon the sweetness equivalence of the NNS in the context of the formulation. In contrast, when thaumatin (the SE) is used, it acts to make added sugar taste sweeter, allowing some, but not all of the sugar to be removed. Specifically, 20% of sugar is removed, and thaumatin is added at a rate of 0.5 ppm to the remaining 80% to achieve a similar sweetness to the original 100% (i.e., 800 g sugar mixed with 0.4 mg thaumatin is as sweet as 1 kg sugar by itself). Regardless, in both instances, the other remaining ingredients must be rebalanced to make up for any lost bulk due to sugar being removed.

The formulations include one in which both Reb A and thaumatin are used at the same time. Reb A is known to have a slightly bitter aftertaste, and thaumatin in this context is used due to its ability to mask bitter flavors. Therefore, the quantity of thaumatin used here is not indicative of how it may be used as a sweetness enhancer and is bespoke for purpose. Results are reported for this mixture and for Reb A alone separately in Sect. 4.2.

When sugar was removed from a formulation, rebalancing of ingredients was based upon sensory studies. In the case of the yoghurt, this meant that the rebalancing of milk, cream, and milk powder was to achieve similar organoleptic qualities as explored in sensory trials (outlined in more detail in Supplementary Information, Sect. 3). It was not the goal to match nutritional properties of the different formulations.

3 Life cycle inventory data

In this section, a description of each production process and the related life cycle inventory (LCI) data are given for each product developed within the SWEET project as a function of 1 kg of final food product. Packaging masses are in addition to product mass. There are instances when a blend of NNS&SE might be used or that the particular NNS&SE is not represented in existing LCA studies. Therefore, when an NNS&SE LCA is not available, it is replaced with a proxy, and the substitute highlighted.

3.1 Drink formulation preparation

Formulations for each of the drink types are given in Table 1 as a percentage of 1 kg liquid and derived from (Almiron-Roig et al. 2023). For the sugar-based drink, dry ingredients (sugar, potassium chloride, citric acid, sodium benzoate, flavoring, and sugar) are dissolved into water in batches of 50–100 L. This is decanted into 330-ml water bottles which have been pre-rinsed with 190 °C water. Filled bottles are

Table 1 Ingredients for non-carbonated drink as a fraction of 1 kg mass and sweetener type. Carbonated drink formulation from Amienyo et al. (2013) shown in brackets

Ingredient	Sugar[a,b]	Reb A	Reb A + thaumatin[a]	Neotame[d]	Aspartame[d]	Sucralose + Ace-K[a,d,e]	Thaumatin[d]
Water (%)	86.83 (85.00)	94.81	94.81	94.83	94.79	94.82	88.43
Potassium chloride (%)	1.04 (0.00)	1.04	1.04	1.04	1.04	1.04	1.04
Citric acid (%)	3.93 (3.00)	3.93	3.93	3.93	3.93	3.93	3.93
Sodium benzoate (%)[c]	2.00×10^{-2} (2.00×10^{-2})	2.00×10^{-2}	2.00×10^{-2}	2.00×10^{-2}	2.00×10^{-2}	2.00×10^{-2}	2.00×10^{-2}
Lemon/lime flavor (%)[c]	1.80×10^{-1} (2.00×10^{-2})	1.80×10^{-1}	1.80×10^{-1}	1.80×10^{-1}	1.80×10^{-1}	1.80×10^{-1}	1.80×10^{-1}
Sugar (%)	8.00 (11.00)	-	-	-	-	-	6.4
Sweetener (%)		2.4×10^{-2}	2.4×10^{-2} (Reb A) 1.20×10^{-4} (thaumatin)	5×10^{-4}	4.00×10^{-2}	1.00×10^{-2} (Ace-K) 1.00×10^{-2} (sucralose)	3.20×10^{-6}
Effective sucrose equivalence	1	333	333	16,000	200	400	N/A

[a]Quantites derived from Almiron-Roig et al. (2023)

[b]Quantities in brackets from Amienyo et al. (2013)

[c]No existing LCA data. Proxy process developed and data given in Supplementary Information, Sect. 1, Tables S1 and S2

[d]See Sect. 3.3, Assumptions

[e]Ace-K LCA data not available. Therefore, 0.02% sucralose is used as proxy for both NNSs

further heated to 190 °C for 15 s to pasteurize before being cooled in an ice bath for 5 min. The process is the same for the NNS&SE-based drinks, except that sugar is replaced by each respective NNS&SE and the fraction of water adjusted to account for the reduced ingredients' bulk. There were no significant differences between preparation of the different formulations and, likewise, packaging and storage needs. Resource demand in terms of energy was not well known for the laboratory production process. Therefore, background inventory data were used from Amienyo et al. (2013), which is for a carbonated drink, but otherwise has similar quantities of the other ingredients (denoted in brackets in Table 1 for the sugar-based drink). The drinks used for baseline impact results in this study were non-carbonated; however, results are also discussed for the same carbonation rate (from compressed CO_2) to Amienyo et al. (2013) in Sect. 4.1. Inventory data for production and packaging are shown in Table 2. As the study is cradle-to-gate, post-consumer drinks packaging waste are out of scope. However, manufacture waste packaging is included, but pallet waste treatment is omitted due to the small quantity of material.

3.2 Yoghurt formulation preparation

Formulations for each of the yoghurt products are given in Table 3 as a function of 1 kg yoghurt. Sugar-based yoghurts are made in batch size of 15.74 kg and NNS&SE-based yoghurt in 13.08 kg batches. Milk is first heated to 73 °C for

Table 2 Inventory data for 1 kg drink production. Data are the same for each formulation in Table 1. Derived from Amienyo et al. (2013)

Input per 1 kg drink	Value	Notes
Bottle and cap (polyethylene terephthalate) (g)	54.0	From Amienyo et al. (2013) for a 0.5 l carbonated drink
Label (polypropylene) (g)	7.00×10^{-1}	Electricity assumed to be European average mix (RER) from ecoinvent database
Energy (Wh)	304.0	
Corrugated board for delivery packaging (g)	1.78	
Pallet wrap (LDPE) (g)	1.23	
Secondary label (paper) (g)	2.00×10^{-3}	
Transport pallet (p)	2.99×10^{-6}	
Waste flows		
Waste plastic (g)	1.23	From Amienyo et al. (2013) for a 0.5 l carbonated drink
Waste cardboard (g)	1.78	

Table 3 Ingredients in yoghurt formulations as a function of fractional mass. Data shown for sugar-based (sugar), NNS-based (NNS), and thaumatin-based (SE) yoghurts

Ingredients	Sugar	NNS	SE
Milk (fresh) (%)	46.50 ± 1.27	63.00 ± 0.88	49.80 ± 1.27
Cream (fresh) (%)	41.00 ± 1.00	32.00 ± 1.00	39.20 ± 1.00
Sugar (%)	6.75	-	5.40
Milk powder (%)	5.73 ± 0.27	4.98 ± 0.12	5.58 ± 0.27
Live active yoghurt cultures (%)	2.00×10^{-2}	2.00×10^{-2}	2.00×10^{-2}
Total (%)	**100**	**100**	**100**
Reb A + thaumatin (%)		$2.00 \times 10^{-2} + 1.00 \times 10^{-4}$	
Neotame (%)		2.50×10^{-4}	
Sucralose + Ace-K (%)[A]		$7.00 \times 10^{-3} + 7.00 \times 10^{-3}$	
Aspartame (%)[B]		3.38×10^{-2}	
Reb A (%)[B]		2.70×10^{-2}	
Thaumatin (%)[B]			2.70×10^{-6}

[A] Ace-K LCA data not available. Therefore, 0.014% sucralose is used as proxy for both NNSs

[B] See Sect. 3.3, Assumptions

20 s and added the cream and milk powder. The mixture is heated to 90 °C for pasteurizing and the sugar or NNS&SE added. The mixture is then cooled to 40 °C and the yoghurt culture added. The batch is stored at 42 °C for 12 h to allow fermentation to complete, before being packaged and stored at 4 °C.

Unlike drinks, yoghurt is made using fresh ingredients (milk and cream), and their composition can vary between batches. Data in Table 3 shows the average fraction and associated uncertainty when balancing each ingredient to ensure a consistent final product. Variability in these ingredients is explored in sensitivity analysis (Sect. 4.3). Each of the NNS are listed below a base yoghurt, but these are added in separate formulations, not all at once. Therefore, there is in effect a slight error in the net total. For instance, the Reb A + thaumatin-based yoghurt has a net mass of 100.0201%, and not 100%. This is not accounted for in the results but would lead to an increased impact for NNS&SE-based yoghurts compared with sugar-based ones. Finally, the yoghurt culture is omitted from the LCA as it is derived from the final yoghurt product being investigated here and is only a small fraction of the total yoghurt formulation. Yoghurt culture is similarly omitted from all other studies apart from Üçtuğ et al. (2019), but it is worth noting that lactic acid bacteria may carry a significant environmental impact if used directly in yoghurt fermentation (Pénicaud et al. 2018).

Similar to the drinks, there was no significant difference between the production, packaging, or storage needs of sugar- and NNS&SE-based yoghurts. Again, energy consumption was not well known. In addition, cleaning of research equipment was considered to be much more resource intensive than at larger scale production and, therefore, not indicative. Instead, production data were derived from Üçtuğ et al. (2019) for pasteurization, filling, fermentation, and chilling production steps, being those in common with the process outlined in this study (Fig. 1). Production inventory data are given in Table 4. Packaging data is from measurement of retail packaging for a 500 g yoghurt. As the study is cradle-to-gate, post-consumer packaging waste flows are out of scope.

3.3 Assumptions

In addition to assumptions stated already, the following further assumptions were made during the study:

- Environmental impact of the individual NNS&SE are taken from individual LCA conducted within the SWEET project (Blenkley et al. 2023; Suckling et al. 2023a, b, c). In each instance, reported baseline impacts from the references were used in this study. Where variation in impacts is presented in the individual LCA studies, these will be discussed when it may influence the results presented here. Impact data for each NNS&SE are reproduced in Supplementary Information, Table S4.
- Not all formulations were developed with every NNS&SE. These are denoted by footnotes in Tables 1 and 3. In these instances, the NNS&SE has been added according to typically quoted sweetness equivalence values and the formulation verified with the researchers developing the other NNS-based formulations for representativeness. When thaumatin is used on its own as an SE (as opposed to alongside Reb A), it was assumed that 0.5 ppm thaumatin could replace 20% sugar within a formulation, and other ingredients were rebalanced accordingly: for the drink, the fraction of water was increased; for yoghurts, a linear interpolation was taken between respective milk, cream, and protein powder quantities used in the sugar- and NNS-based yoghurts. The rebal-

Table 4 LCI for production 1 kg of yoghurt and cleaning of yoghurt making equipment. Data derived from Üçtuğ et al. (2019)

Input per 1 kg yoghurt	Value	Notes
Electricity (kWh)	2.20×10^{-1}	Derived from Üçtuğ et al. (2019) for filling, pasteurization and fermentation steps
Heating (kWh)	7.37×10^{-1}	Electricity assumed to be European average mix (RER) from ecoinvent database
Water for cleaning (l)	1.60	
Cleaning H_2O_2 (mg)	1.50	
Cleaning nitric acid (g)	1.35	
Cleaning NaOH (mg)	1.50×10^{-2}	
Electricity (kWh)	1.14	Derived from Üçtuğ et al. (2019) for cooling and storage steps
Plastic carton (g)	18.00	Measured data from retail 500 g yoghurt pot
Cardboard jacket (g)	14.00	
Plastic lid (polyethylene terephthalate) (g)	6.20	
Aluminum foil (g)[a]	1.80	
Waste flows		
Wastewater treatment (l)	1.60	Derived from Üçtuğ et al. (2019) for pasteurization, filling and fermentation steps. Cleaning agents assumed treated as part of wastewater

[a]Proxy process used, and outlined in Supplementary Information, Sect. 1, Table S3

anced formulations were again verified by the researchers developing the non-sugar-based products.

4 Results

The results of the LCA are presented in this section, first in terms of impact of the whole product, and then in finer detail to understand the sources of impact, and changes thereof. Overview results are presented in terms of all impact categories, with additional focus given to global warming potential (GWP), land use (LU), water consumption (WC), and marine eutrophication (MEu). In Sect. 2.2, the system boundary showed the production processes involved for purposes of identifying appropriate proxy data from literature. But because an objective of this study was to explore the environmental impact change from replacing added sugar and that there was no discernable difference in production methods for sugar- or NNS&SE-based formulation, it is change in ingredient ratios which are likely to drive environmental impact change. Therefore, data are presented in terms of ingredients (and not individual production steps) to facilitate better exploration of impact change.

4.1 Drink results

Figure 2 shows the environmental impact for each ReCiPe impact categories for producing 1 kg non-carbonated drink as a function of sweeteners, sugar (black), Reb A + thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (orange), and SE thaumatin (grey). Data are normalized to the drink with the greatest impact within a given impact category; hence, the maximum relative impact is 1. Absolute environmental impact data are given in Table 5.

In terms of GWP, the sugar-based drink has the greatest impact with 6.15×10^{-1} kgCO_2-eq/kg, whereas all NNS-based drinks (which includes Reb A + thaumatin) have impacts ranging between 81.5 and 83.3% of sugar-based drink. The SE-based drink has an impact of 96.3% of the sugar-based drink. For MEu, the sugar-based drink has the greatest impact with 2.14×10^{-4} kgN-eq/kg, whereas NSS-based drinks are 36.3 to 39.0%, and the SE-based drink 87.3% of that impact. For LU, the Reb A and thaumatin-based drink has the greatest impact with 4.07×10^{-1} m^2acrop-eq, whereas the sugar-based drink has an impact of 1.55×10^{-1} m^2acrop-eq/kg. The other NNS-based drinks are 28.5 to 34.3% of the sugar-based drink, and SE-based drink is 91.8% of that impact. The greater LU of the Reb A + thaumatin-based drink is due to assumptions used in the background thaumatin LCA (Suckling et al. 2023a). Thaumatin is produced from foraged *Thaumatococcus daniellii* fruit from the forests in West Africa, but the yield per hectare is not known, and the yield value used in that LCA was considered to be greatly underestimated. In addition, no account was taken for other uses of that forest land, such as medicinal plants, firewood, or other forage crops. Therefore, no allocation was made between thaumatin and other potential produce of the land. It was anticipated that with better data, the LU impact of thaumatin would greatly decrease. Finally for WC, the sugar-based drink has the greatest impact with

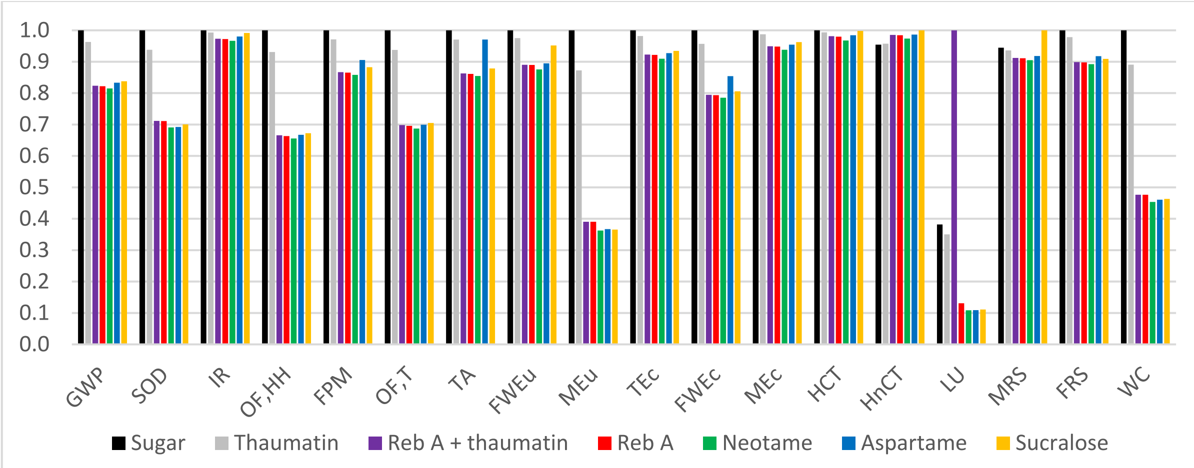

Fig. 2 Relative impacts of 1 kg sweetened drink for all ReCiPe 2016 (H) impact categories. Sweeteners shown are sugar (black), Reb A + thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (orange), and SE thaumatin (grey). Maximum impact in a given category equals 1. GWP, global warming potential; SOD, stratospheric ozone depletion; IR, ionizing radiation; OF,HH, ozone formation, human health; FPM, fine particulate matter; OF,T, ozone formation, terrestrial; TA, terrestrial acidification; FWEu, freshwater eutrophication; MEu, marine eutrophication; TEc, terrestrial ecotoxicity; FWEc, freshwater ecotoxicity; MEc, marine ecotoxicity; HCT, human carcinogenic toxicity; HnCT, human non-carcinogenic toxicity; LU, land use; MRS, mineral resource scarcity; FRS, fossil resource scarcity; WC, water consumption

Table 5 Absolute environmental impact data for 1 kg sweetened drinks as a function of both sweetening ingredient and impact category. Data supports Fig. 2. Impact categories defined in Fig. 2

Impact category	Sugar	Thaumatin	Reb A + thaumatin	Reb A	Neotame	Aspartame	Sucralose
GWP (kgCO_2-eq)	6.15×10^{-1}	5.92×10^{-1}	5.07×10^{-1}	5.06×10^{-1}	5.01×10^{-1}	5.13×10^{-1}	5.15×10^{-1}
SOD (kgCFC11-eq)	2.37×10^{-6}	2.23×10^{-6}	1.69×10^{-6}	1.69×10^{-6}	1.64×10^{-6}	1.64×10^{-6}	1.66×10^{-6}
IR (kBqCo-60-eq)	3.13×10^{-2}	3.11×10^{-2}	3.04×10^{-2}	3.04×10^{-2}	3.02×10^{-2}	3.07×10^{-2}	3.10×10^{-2}
OF,HH (kgNOx-eq)	1.83×10^{-3}	1.70×10^{-3}	1.22×10^{-3}	1.21×10^{-3}	1.20×10^{-3}	1.22×10^{-3}	1.23×10^{-3}
FPM (kgPM2.5-eq)	1.02×10^{-3}	9.92×10^{-4}	8.85×10^{-4}	8.84×10^{-4}	8.76×10^{-4}	9.25×10^{-4}	9.01×10^{-4}
OF,T (kgNOx-eq)	1.79×10^{-3}	1.68×10^{-3}	1.25×10^{-3}	1.24×10^{-3}	1.23×10^{-3}	1.25×10^{-3}	1.26×10^{-3}
TA (kgSO_2-eq)	2.59×10^{-3}	2.51×10^{-3}	2.23×10^{-3}	2.23×10^{-3}	2.21×10^{-3}	2.51×10^{-3}	2.27×10^{-3}
FWEu (kgP-eq)	2.35×10^{-4}	2.30×10^{-4}	2.10×10^{-4}	2.09×10^{-4}	2.06×10^{-4}	2.11×10^{-4}	2.24×10^{-4}
MEu (kgN-eq)	2.14×10^{-4}	1.87×10^{-4}	8.35×10^{-5}	8.35×10^{-5}	7.76×10^{-5}	7.86×10^{-5}	7.82×10^{-5}
TEc (kg1,4-DCB)	2.78	2.73	2.57	2.57	2.53	2.58	2.60
FWEc (kg1,4-DCB)	3.32×10^{-2}	3.18×10^{-2}	2.64×10^{-2}	2.64×10^{-2}	2.61×10^{-2}	2.84×10^{-2}	2.68×10^{-2}
MEc (kg1,4-DCB)	3.63×10^{-2}	3.58×10^{-2}	3.44×10^{-2}	3.44×10^{-2}	3.40×10^{-2}	3.46×10^{-2}	3.49×10^{-2}
HCT (kg1,4-DCB)	2.71×10^{-2}	2.69×10^{-2}	2.66×10^{-2}	2.65×10^{-2}	2.62×10^{-2}	2.66×10^{-2}	2.70×10^{-2}
HnCT (kg1,4-DCB)	5.85×10^{-1}	5.87×10^{-1}	6.04×10^{-1}	6.04×10^{-1}	5.97×10^{-1}	6.05×10^{-1}	6.13×10^{-1}
LU (m^2acrop-eq)	1.55×10^{-1}	1.43×10^{-1}	4.07×10^{-1}	5.33×10^{-2}	4.42×10^{-2}	4.45×10^{-2}	4.51×10^{-2}
MRS (kgCu-eq)	2.10×10^{-3}	2.08×10^{-3}	2.03×10^{-3}	2.03×10^{-3}	2.01×10^{-3}	2.04×10^{-3}	2.22×10^{-3}
FRS (kg-oil-eq)	1.89×10^{-1}	1.85×10^{-1}	1.70×10^{-1}	1.69×10^{-1}	1.68×10^{-1}	1.73×10^{-1}	1.72×10^{-1}
WC (m^3)	2.61×10^{-2}	2.32×10^{-2}	1.24×10^{-2}	1.24×10^{-2}	1.18×10^{-2}	1.20×10^{-2}	1.21×10^{-2}

2.61×10^{-2} m^3/kg, whereas NNS-based drinks are 45.3 to 47.7%, and SE-based drink is 89.1% of that impact. For MEu, LU, and WC, the NNS-based drinks containing neotame, aspartame, or sucralose have smaller impacts than Reb A and Reb A + thaumatin. This shows that artificially produced NNS have the potential to reduce agriculturally related impacts which are still present for plant-based ones. Finally, across all of the impact categories, the average impact of the Reb A + thaumatin-based drink is 82.2% that of the sugar-based drink, and likewise, Reb A is 77.3%, sucralose is 78.7%, aspartame is 78.5%, neotame is 76.1%, and thaumatin is 95.5%.

For the remaining impact categories, NNS- and SE-based drinks have a lower impact except for within human non-carcinogenic toxicity (HnCT). For this category, sugar is modelled in the Agri-footprint database as having negative impact due to a net absorption of toxic minerals into plant material which is not released back to the environment. (The effect of sourcing background data from the ecoinvent 3.8 database instead are explored in Sect. 5.3.) In terms of sucralose mineral resource scarcity (MRS), greater impact is due to life cycle data relating to material consumption as derived from patent literature. However, the original sucralose study highlighted that this result was likely due to excessive use of phosphorus chloride in the background literature source and that process optimization might reduce impact or sucralose MRS by 44.7%. This might reduce the impact of the sucralose-based drink to below that of the sugar-based one in this study.

For comparison, Amienyo et al. (2013) calculates an impact of 2.93×10^{-1} $kgCO_2$-eq/l for a 0.5 l PET bottled drink using the CML method. However, it should be noted that their LCA includes waste disposal of all materials and that a credit is applied when those materials are recycled, which was not assumed in this study. For completeness, provided in Supplementary Information, Table S5, is the impact across all impact categories if the drinks modelled in this study are carbonated using 0.6 gCO_2/kg_{drink}, as per Amienyo et al. (2013), in place of the same mass water. The results show that impact is increased across all categories, with the smallest increase being 0.04% for stratospheric ozone depletion and the greatest 1.82% for ionizing radiation.

4.1.1 Source of impact change in drinks

The results presented in Fig. 2 show that environmental impact changes when sugar is replaced by NNS&SE, but do not show how that change occurs. Therefore, Fig. 3 shows the contribution to environmental impact of different components of the drinks for (A) GWP, (B) LU, (C) MEu, and (D) WC as a function of processing and packaging (black), flavorings (green), sugar (red), water (orange), and NNS&SE (blue). In this context, flavorings are all the minor ingredients in Table 1 which do not change between formulations. Numerical data are given in Table 6. It is shown that, for these four impact categories, all of the change in environmental impact is simply attributable to the removal of sugar and replacement with NNS&SE and water. Sugar has a larger environmental impact per unit mass than the combination of water and NNS used in its place. Hence, the change is

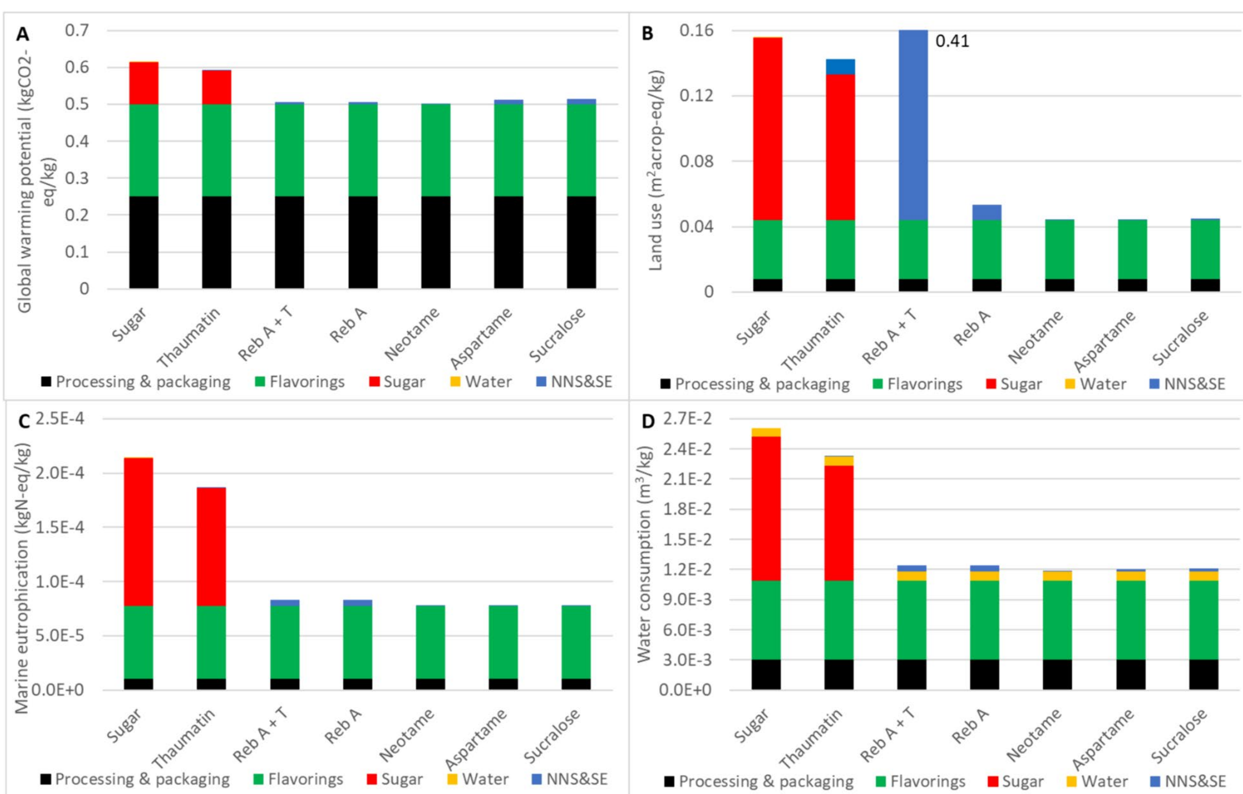

Fig. 3 Environmental impact contribution to 1 kg sweetened drinks from processing and packaging (black), flavorings (green), sugar (red), water (yellow), and individual NNS&SE (blue), as a function of **A** GWP, **B** LU, **C** MEu, and **D** WC. Reb A + thaumatin shown as "Reb A & T." LU max for Reb A + T is above scale max at 0.41 m^2acrop-eq/kg

Table 6 Contribution of components to impact per 1 kg of the sweetened drinks for GWP, LU, WC, and MEu. Data supports Fig. 3. Impact categories defined in Fig. 2. Percentage contribution data given in Supplementary Information, Table S15

Impact category		Processing and packaging	Flavorings	Sugar	Water	NNS&SE
GWP ($kgCO_2$-eq)	Sugar	2.51×10^{-1}	2.49×10^{-1}	1.14×10^{-1}	2.86×10^{-4}	
	Thaumatin	2.51×10^{-1}	2.49×10^{-1}	9.14×10^{-2}	2.91×10^{-4}	2.31×10^{-5}
	Reb A + T	2.51×10^{-1}	2.49×10^{-1}		3.12×10^{-4}	5.72×10^{-3}
	Reb A	2.51×10^{-1}	2.49×10^{-1}		3.12×10^{-4}	4.86×10^{-3}
	Neotame	2.51×10^{-1}	2.49×10^{-1}		3.12×10^{-4}	2.17×10^{-4}
	Aspartame	2.51×10^{-1}	2.49×10^{-1}		3.12×10^{-4}	1.17×10^{-2}
	Sucralose	2.51×10^{-1}	2.49×10^{-1}		3.12×10^{-4}	1.44×10^{-2}
LU (m^2acrop-eq)	Sugar	7.83×10^{-3}	3.64×10^{-2}	1.11×10^{-1}	7.74×10^{-6}	
	Thaumatin	7.83×10^{-3}	3.64×10^{-2}	8.90×10^{-2}	7.88×10^{-6}	9.44×10^{-3}
	Reb A + T	7.83×10^{-3}	3.64×10^{-2}		8.45×10^{-6}	3.63×10^{-1}
	Reb A	7.83×10^{-3}	3.64×10^{-2}		8.45×10^{-6}	9.08×10^{-3}
	Neotame	7.83×10^{-3}	3.64×10^{-2}		8.45×10^{-6}	5.41×10^{-6}
	Aspartame	7.83×10^{-3}	3.64×10^{-2}		8.45×10^{-6}	2.35×10^{-4}
	Sucralose	7.83×10^{-3}	3.64×10^{-2}		8.45×10^{-6}	9.01×10^{-4}
WC (m^3)	Sugar	3.01×10^{-3}	7.87×10^{-3}	1.44×10^{-2}	8.73×10^{-4}	
	Thaumatin	3.01×10^{-3}	7.87×10^{-3}	1.15×10^{-2}	8.89×10^{-4}	4.96×10^{-8}
	Reb A + T	3.01×10^{-3}	7.87×10^{-3}		9.54×10^{-4}	6.10×10^{-4}
	Reb A	3.01×10^{-3}	7.87×10^{-3}		9.54×10^{-4}	6.08×10^{-4}
	Neotame	3.01×10^{-3}	7.87×10^{-3}		9.54×10^{-4}	2.77×10^{-6}
	Aspartame	3.01×10^{-3}	7.87×10^{-3}		9.53×10^{-4}	1.96×10^{-4}
	Sucralose	3.01×10^{-3}	7.87×10^{-3}		9.54×10^{-4}	2.57×10^{-4}
MEu (kgN-eq)	Sugar	1.03×10^{-5}	6.73×10^{-5}	1.36×10^{-4}	1.95×10^{-8}	
	Thaumatin	1.03×10^{-5}	6.73×10^{-5}	1.09×10^{-4}	1.98×10^{-8}	1.21×10^{-9}
	Reb A + T	1.03×10^{-5}	6.73×10^{-5}		2.13×10^{-8}	5.98×10^{-6}
	Reb A	1.03×10^{-5}	6.73×10^{-5}		2.13×10^{-8}	5.93×10^{-6}
	Neotame	1.03×10^{-5}	6.73×10^{-5}		2.13×10^{-8}	1.43×10^{-8}
	Aspartame	1.03×10^{-5}	6.73×10^{-5}		2.13×10^{-8}	1.02×10^{-6}
	Sucralose	1.03×10^{-5}	6.73×10^{-5}		2.13×10^{-8}	6.75×10^{-7}

most marked for when neotame is used to replace sugar. This is due to the very small mass of neotame required, thanks to its extremely high sucrose equivalence (approx. 8000 times that of sugar). There is no change in the processing and packaging and flavorings environmental impact.

4.2 Yoghurt results

Figure 4 shows the environmental impact for all ReCiPe impact categories for producing 1 kg yoghurt as a function of sweeteners, sugar (black), Reb A + thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (orange), and SE thaumatin (grey). Data are normalized to the yoghurt with the most impact within a given impact category; therefore, maximum relative impact = 1. Absolute environmental impact data are given in Table 7.

In terms of GWP, the sugar-based yoghurt has the greatest impact with 4.15 $kgCO_2$-eq/kg, whereas all NNS-based yoghurts (which includes Reb A + thaumatin) have impacts ranging between 89.7 and 89.9% of sugar-based yoghurt. The SE-based yoghurt has an impact of 97.9% of the sugar-based yoghurt. For MEu, the sugar-based yoghurt has the greatest impact with 3.82×10^{-3} kgN-eq/kg, whereas NSS-based drinks are 87.1 to 87.3%, and the SE-based drink 97.4% of that impact. For WC, the sugar-based drink has the greatest impact with 4.56×10^{-2} m^3/kg, whereas NNS-based drinks are 68.4 to 69.9%, and SE-based drink is 93.7% of that impact. Finally, for LU, the Reb A + thaumatin-based yoghurt has the greatest impact with 1.64 m^2acrop-eq, whereas the sugar-based yoghurt is 96.6% of this impact, and the other NNS-based yoghurts are 81.6 to 82.2%. Again, the increased LU for Reb A + thaumatin is due to assumptions made during the background thaumatin LCA (Suckling et al. 2023a). In general, the sugar-based yoghurt has the greatest impact.

Yoghurt is a more difficult product to compare than a drink. Yoghurts come in many forms, with different viscosities, sweetening agents (e.g., sugar, or fruits, or honey), and last but not least the least geographical source of the dairy ingredients. All these factors affect impact, as do the

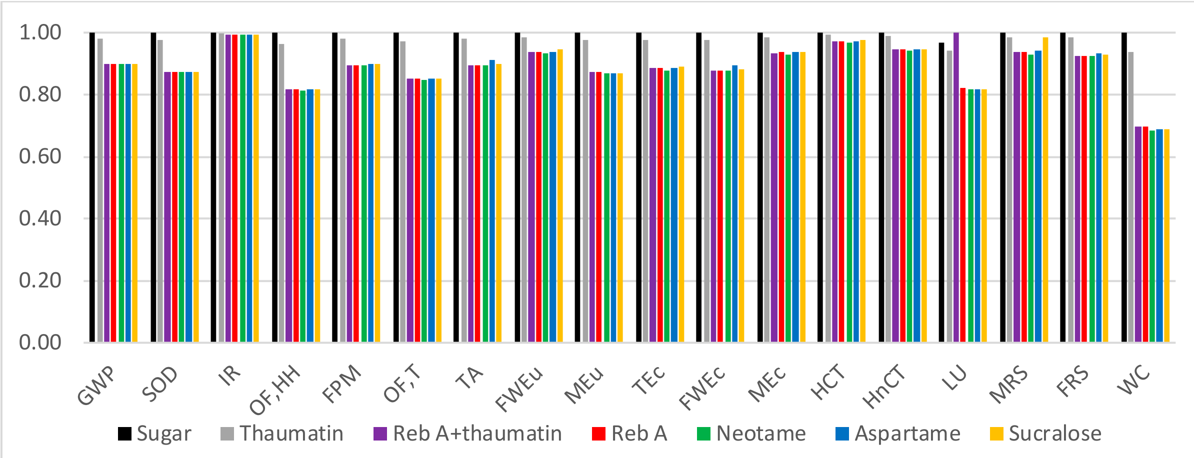

Fig. 4 Relative impacts of 1 kg sweetened yoghurt for all ReCiPe 2016 (H) impact categories. Sweeteners shown are sugar (black), Reb A + thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (orange), and SE thaumatin (grey). Maximum impact in a given category equals 1. Impact categories defined in Fig. 2

Table 7 Absolute environmental impact data for 1 kg sweetened yoghurts as a function of both sweetening ingredient and impact category. Data supports Fig. 4. Impact categories defined in Fig. 2

Impact category	Sugar	Thaumatin	Reb A + thaumatin	Reb A	Neotame	Aspartame	Sucralose
GWP (kgCO$_2$-eq)	4.15	4.06	3.73	3.73	3.72	3.73	3.73
SOD (kgCFC11-eq)	1.97×10^{-5}	1.92×10^{-5}	1.72×10^{-5}	1.73×10^{-5}	1.72×10^{-5}	1.72×10^{-5}	1.72×10^{-5}
IR (kBqCo-60-eq)	3.16×10^{-1}	3.15×10^{-1}	3.13×10^{-1}	3.13×10^{-1}	3.13×10^{-1}	3.13×10^{-1}	3.13×10^{-1}
OF,HH (kgNOx-eq)	4.09×10^{-3}	3.93×10^{-3}	3.34×10^{-3}	3.34×10^{-3}	3.33×10^{-3}	3.34×10^{-3}	3.35×10^{-3}
FPM (kgPM2.5-eq)	1.39×10^{-2}	1.36×10^{-2}	1.25×10^{-2}	1.25×10^{-2}	1.25×10^{-2}	1.25×10^{-2}	1.25×10^{-2}
OF,T (kgNOx-eq)	5.97×10^{-3}	5.79×10^{-3}	5.09×10^{-3}	5.09×10^{-3}	5.07×10^{-3}	5.09×10^{-3}	5.09×10^{-3}
TA (kgSO$_2$-eq)	1.52×10^{-2}	1.48×10^{-2}	1.36×10^{-2}	1.36×10^{-2}	1.36×10^{-2}	1.38×10^{-2}	1.36×10^{-2}
FWEu (kgP-eq)	1.05×10^{-3}	1.04×10^{-3}	9.87×10^{-4}	9.88×10^{-4}	9.85×10^{-4}	9.88×10^{-4}	9.97×10^{-4}
MEu (kgN-eq)	3.82×10^{-3}	3.72×10^{-3}	3.33×10^{-3}	3.33×10^{-3}	3.32×10^{-3}	3.33×10^{-3}	3.33×10^{-3}
TEc (kg1,4-DCB)	3.55	3.46	3.14	3.15	3.11	3.15	3.16
FWEc (kg1,4-DCB)	1.10×10^{-1}	1.07×10^{-1}	9.66×10^{-2}	9.66×10^{-2}	9.63×10^{-2}	9.82×10^{-2}	9.68×10^{-2}
MEc (kg1,4-DCB)	7.36×10^{-2}	7.26×10^{-2}	6.89×10^{-2}	6.90×10^{-2}	6.85×10^{-2}	6.90×10^{-2}	6.91×10^{-2}
HCT (kg1,4-DCB)	6.25×10^{-2}	6.21×10^{-2}	6.07×10^{-2}	6.07×10^{-2}	6.03×10^{-2}	6.07×10^{-2}	6.09×10^{-2}
HnCT (kg1,4-DCB)	2.11	2.09	1.99	2.00	1.99	2.00	2.00
LU (m^{2}acrop-eq)	1.59	1.55	1.64	1.35	1.34	1.34	1.34
MRS (kgCu-eq)	2.69×10^{-3}	$2.65\times10-^{3}$	2.52×10^{-3}	2.52×10^{-3}	2.50×10^{-3}	2.53×10^{-3}	2.65×10^{-3}
FRS (kg-oil-eq)	4.48×10^{-1}	4.42×10^{-1}	4.15×10^{-1}	4.15×10^{-1}	4.14×10^{-1}	4.18×10^{-1}	4.16×10^{-1}
WC (m^3)	4.56×10^{-2}	4.27×10^{-2}	3.17×10^{-2}	3.19×10^{-2}	3.12×10^{-2}	3.14×10^{-2}	3.14×10^{-2}

assessment methods used, their versions, and the dates of the studies. Previous LCAs of yoghurt have reported the following:

- Üçtuğ et al. (2019): Cradle-to-grave LCA of yoghurt made from raw milk in Turkey. GWP calculated at 4.2 kgCO$_2$-eq/kg using the CML2001 method. In that study, 23 kg of cream is removed for every 1672 kg raw milk used, but it is not clear whether this is treated as a waste or carries any impact allocation.
- Gonzalez-Garcia et al. (2013): Cradle-to-grave LCA of 1 t yoghurts as a group, comprising 21.0% solid, 43.2% stirring, and 35.8% drinking yoghurts. Ingredients include raw, powdered, and concentrated milks, sugar, aromas, and fruits. Milk produced in Portugal.

GWP calculated to be 1.776 $kgCO_2$-eq/kg using the CML2001 method.

- Djekic et al. (2014): Cradle-to-grave LCA of yoghurt produced from raw milk in Serbia. GWP calculated to be 1.46–2.63 $kgCO_2$-eq/kg using the CCaLC method.
- dos Santos et al. (2022): Cradle-to-gate LCA of yoghurt produced in Brazil using the CML2001 method. GWP calculated to be 1.82 $kgCO_2$-eq/kg using the CML-IA method.
- Vasilaki et al. (2016): a cradle-to-gate LCA-based water and carbon footprint study for yoghurt produced in Spain. GWP calculated to be 1.94 $kgCO_2$-eq/kg using the ReCiPe 2008 method.
- Ghinea and Leahu (2020): Cradle-to-gate LCA for yoghurt produced from raw milk in Romania using various methods. GWP of 2.92 CO_2-eq/kg is reported using the ReCiPe v1.08 method.
- Houssard et al. (2020): Cradle-to-gate study of 5 Greek yoghurt production systems in Quebec, Canada. GWP of ~ 2.5 $kgCO_2$-eq/kg is reported using the IMPACT WORLD + method.
- Finally, there is a native yoghurt process in the ecoinvent 3.8 database. GWP for this is 2.00 $kgCO_2$-eq/kg when using the ReCiPe v1.07 method; however, it should be noted that it is an aggregate process for multiple types of yoghurt, that packaging is not included (but is for the other studies), and that the background dairy and sugar processes are from ecoinvent, whereas in this study, they are from the Agri-footprint 6 database.

In general, the impacts reported from other sources are lower than those in this study. The yoghurt in this study was designed as a thick Greek-style yoghurt (but is not specifically a Greek yoghurt) with cream and milk powder used during manufacture (see Table 3 for fractions of each ingredient). Therefore, the yoghurt in this study is most similar to the Greek yoghurt produced by Houssard et al. (2020) using fortification with protein powder (~ 2.9 $kgCO_2$-eq/kg in that study). However, a greater proportion of milk powder (~ 5 to 6% vs ~ 3% by mass), and cream was used in this study, whereas cream was not listed as a separate ingredient by Houssard et al. (2020). Both powder and cream carry a greater environmental impact than milk (see Table 9).

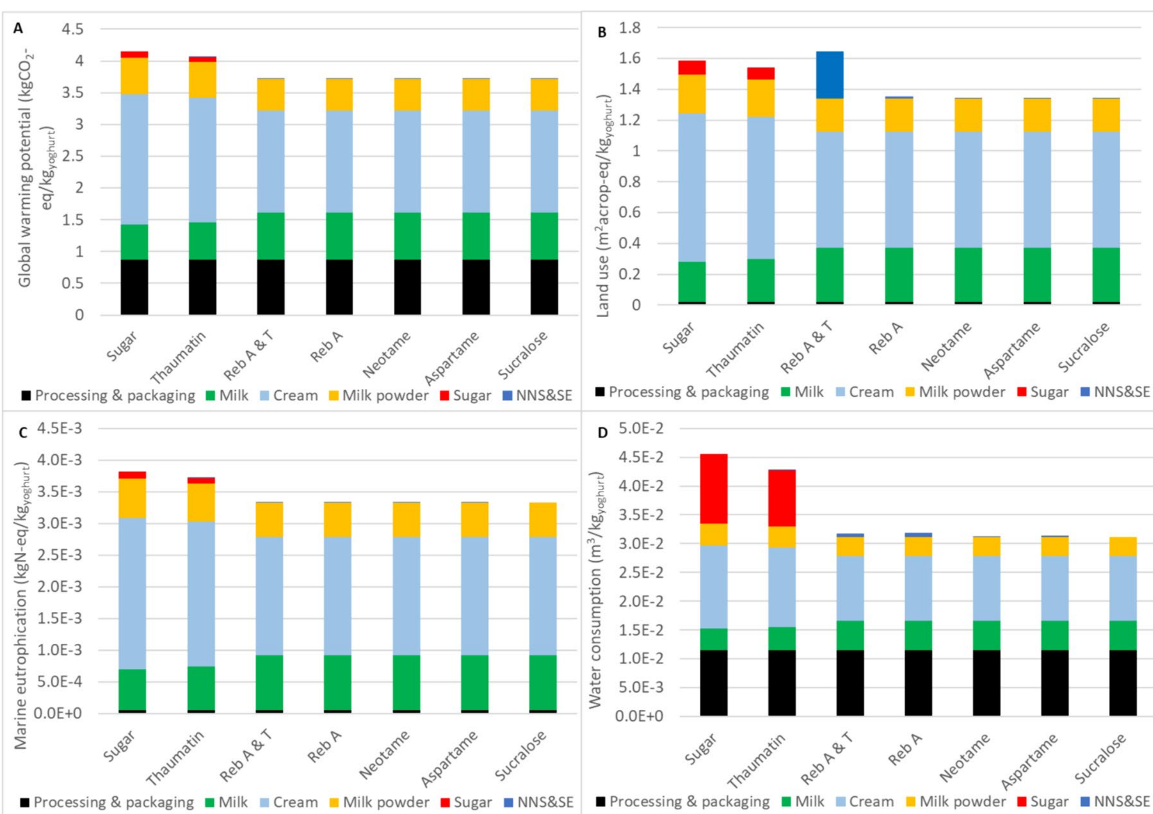

Fig. 5 Environmental impact contribution to 1 kg yoghurt from processing and packaging (black), milk (green), cream (light blue), milk powder (orange), sugar (red), and individual NNS and SE (blue), as a function of **A** GWP, **B** LU, **C** MEu, and **D** WC. Reb A + thaumatin shown as "Reb A & T"

Table 8 Contribution of components to impact for 1 kg of sweetened yoghurt for GWP, LU, WC, and MEu. Data supports Fig. 5. Impact categories defined in Fig. 2. Percentage contribution data given in Supplementary Information, Table S16

Impact category		Processing and packaging	Milk	Cream	Milk powder	Sugar	NNS&SE
GWP ($kgCO_2$-eq)	Sugar	8.70×10^{-1}	5.50×10^{-1}	2.05	5.80×10^{-1}	9.64×10^{-2}	
	Thaumatin	8.70×10^{-1}	5.89×10^{-1}	1.96	5.64×10^{-1}	7.71×10^{-2}	1.95×10^{-5}
	Reb A & T	8.70×10^{-1}	7.46×10^{-1}	1.60	5.04×10^{-1}		4.77×10^{-3}
	Reb A	8.70×10^{-1}	7.46×10^{-1}	1.60	5.04×10^{-1}		5.47×10^{-3}
	Neotame	8.70×10^{-1}	7.46×10^{-1}	1.60	5.04×10^{-1}		1.09×10^{-4}
	Aspartame	8.70×10^{-1}	7.46×10^{-1}	1.60	5.04×10^{-1}		9.87×10^{-3}
	Sucralose	8.70×10^{-1}	7.46×10^{-1}	1.60	5.04×10^{-1}		1.01×10^{-2}
LU (m^2acrop-eq)	Sugar	1.94×10^{-2}	2.59×10^{-1}	9.67×10^{-1}	2.49×10^{-1}	9.38×10^{-2}	
	Thaumatin	1.94×10^{-2}	2.78×10^{-1}	9.25×10^{-1}	2.43×10^{-1}	7.51×10^{-2}	7.97×10^{-3}
	Reb A & T	1.94×10^{-2}	3.51×10^{-1}	7.55×10^{-1}	2.16×10^{-1}		3.03×10^{-1}
	Reb A	1.94×10^{-2}	3.51×10^{-1}	7.55×10^{-1}	2.16×10^{-1}		1.02×10^{-2}
	Neotame	1.94×10^{-2}	3.51×10^{-1}	7.55×10^{-1}	2.16×10^{-1}		2.70×10^{-6}
	Aspartame	1.94×10^{-2}	3.51×10^{-1}	7.55×10^{-1}	2.16×10^{-1}		1.98×10^{-4}
	Sucralose	1.94×10^{-2}	3.51×10^{-1}	7.55×10^{-1}	2.16×10^{-1}		6.31×10^{-4}
WC (m^3)	Sugar	1.14×10^{-2}	3.85×10^{-3}	1.44×10^{-2}	3.82×10^{-3}	1.21×10^{-2}	
	Thaumatin	1.14×10^{-2}	4.13×10^{-3}	1.37×10^{-2}	3.72×10^{-3}	9.69×10^{-3}	4.18×10^{-8}
	Reb A & T	1.14×10^{-2}	5.22×10^{-3}	1.12×10^{-2}	3.32×10^{-3}		5.08×10^{-4}
	Reb A	1.14×10^{-2}	5.22×10^{-3}	1.12×10^{-2}	3.32×10^{-3}		6.84×10^{-4}
	Neotame	1.14×10^{-2}	5.22×10^{-3}	1.12×10^{-2}	3.32×10^{-3}		1.38×10^{-6}
	Aspartame	1.14×10^{-2}	5.22×10^{-3}	1.12×10^{-2}	3.32×10^{-3}		1.65×10^{-4}
	Sucralose	1.14×10^{-2}	5.22×10^{-3}	1.12×10^{-2}	3.32×10^{-3}		1.80×10^{-4}
MEu (kgN-eq)	Sugar	5.26×10^{-5}	6.41×10^{-4}	2.39×10^{-3}	6.16×10^{-4}	1.15×10^{-4}	
	Thaumatin	5.26×10^{-5}	6.87×10^{-4}	2.29×10^{-3}	6.00×10^{-4}	9.21×10^{-5}	1.02×10^{-9}
	Reb A & T	5.26×10^{-5}	8.69×10^{-4}	1.87×10^{-3}	5.35×10^{-4}		4.98×10^{-6}
	Reb A	5.26×10^{-5}	8.69×10^{-4}	1.87×10^{-3}	5.35×10^{-4}		6.67×10^{-6}
	Neotame	5.26×10^{-5}	8.69×10^{-4}	1.87×10^{-3}	5.35×10^{-4}		7.15×10^{-9}
	Aspartame	5.26×10^{-5}	8.69×10^{-4}	1.87×10^{-3}	5.35×10^{-4}		8.61×10^{-7}
	Sucralose	5.26×10^{-5}	8.69×10^{-4}	1.87×10^{-3}	5.35×10^{-4}		4.73×10^{-7}

4.2.1 Source of impact change in yoghurt

As per drinks, the results shown in Fig. 4 show the change in environmental impact, but not what causes the change. Therefore, Fig. 5 shows the contribution to environmental impact of different components of the yoghurts for (A) GWP, (B) LU, (C) MEu, and (D) WC as a function of processing and packaging (black), milk (green), cream (light blue), milk powder (orange), sugar (red), and NNS&SE (blue). Numerical impact data are given in Table 8. In contrast to the results for drinks, it is shown that removal of sugar can only account for the majority environmental impact change within WC. For GWP, LU, and MEu, sugar's contribution to environmental impact is smaller than the change incurred when it is removed. Instead, environmental impact change arises from the rebalancing of the other yoghurt ingredients once sugar is removed: milk, cream, and milk powder. Table 3 shows that fraction of milk was increased when sugar was removed, and fractions of cream and milk powder were decreased. The reason for this change was in response to the organoleptic studies outlined in Sect. 1 and Supplementary Information, Sect. 3. Data in Table 9 shows that impact per 1 kg of milk is lower than it is for cream, milk powder, and sugar. Therefore, it is the increase in milk and decrease in cream and milk powder fractions which also drive environmental impact reduction when the sugar is removed from a yoghurt, and not removal of sugar by itself. Data for all impact categories for these ingredients are given in Supplementary Information, Table S6. It should be noted that the results for environmental impact change presented here may be for this specific type of yoghurt and cannot be guaranteed to be indicative of all types of yoghurts.

Table 9 Data for environmental impact of milk, cream, and milk powder per 1 kg of each ingredient from the Agri-footprint database. Impact categories defined in Fig. 2

Impact category (unit)	Milk	Cream	Milk powder	Sugar
GWP (kgCO_2-eq)	1.18	5.01	10.11	1.43
LU (m^2acrop-eq)	5.57×10^{-1}	2.36	4.35	1.39
WC (m^3)	8.28×10^{-3}	3.51×10^{-2}	6.67×10^{-2}	1.79×10^{-1}
MEu (kgN-eq)	1.38×10^{-3}	5.84×10^{-3}	1.07×10^{-2}	1.71×10^{-3}

4.3 Sensitivity to fresh ingredient variability

The results for yoghurt showed that additional rebalancing of milk, cream, and milk powder was an important contributor to environmental impact change. In Table 3, it was shown that the quantities of milk, cream, and milk powder needed to be adjusted for different batches to account for the inherent variability of the fresh ingredients (e.g., fat content in milk and cream) when producing a consistent end product. Therefore, in this section, sensitivity of the results to change in fractions of the fresh ingredients used in the yoghurt formulation is explored.

In reality, properties of milk and cream can vary randomly, but this is not possible to model using LCA software which only reports impact in terms of mass, and not, for example, fat content. Instead, it was assumed that the mass fraction of milk in the formulation was inversely proportional to both cream and milk powder and calculated as per:

$$f_{x,milk} = f_{0,milk} - s\Delta_{cream} - s\Delta_{powder} \quad (1)$$

where f_x is the adjusted fraction of milk in the recipe, f_0 is the baseline fraction, and s is the amount of change (Δ_{cream} or Δ_{powder}) from the baseline value for each of cream and milk powder, respectively. The amount of change is defined as the variability given in Table 3. For example, Δ_{cream} for the sugar-based yoghurt is up to 1% either side of 41%, and therefore, $s=0$ means a cream content of 41%, and $s=\pm1$ means a cream content of 40% or 42%. In all cases, the net fraction of milk, cream, and powder stays the same for each formulation regardless of the value of s. Both positive and negative values of s are possible. Using this formula, it is possible to use the comparative Monte Carlo simulation function within SimaPro to explore sensitivity of the baseline impact results (as a function of mass) to change in ingredient balance in the yoghurts. To perform the calculation, unique parameters in Eq. 1 were defined for each of a sugar-, Reb A-, and thaumatin-based yoghurts. This allows SimaPro to align background parameters and only explore the effect of ingredient variation for the individual yoghurts separately. The parameter, s, was assumed to have a triangular distribution between ±1, which provides a similar

Table 10 Comparison of impact for 1 kg a sugar-based yoghurt to, separately, a Reb A- and thaumatin-based yoghurt. Impact categories defined in Fig. 2

Impact category	Sugar-based yoghurt impact	#iterations thaumatin < sugar (%)	Average % difference (thaumatin)	#iterations Reb A < sugar (%)	Average % difference (Reb A)
GWP (kgCO_2-eq)	4.15	99.26	−2.06	99.98	−10.34
SOD (kgCFC11-eq)	1.97×10^{-5}	99.40	−2.55	99.94	−13.07
IR (kBqCo-60-eq)	3.16×10^{-1}	99.34	−0.16	99.84	−0.78
OF,HH (kgNOx-eq)	4.09×10^{-3}	99.98	−3.77	99.98	−18.41
FPM (kgPM2.5-eq)	1.39×10^{-2}	98.02	−2.07	99.96	−10.74
OF,T (kgNOx-eq)	5.97×10^{-3}	99.98	−3.04	100.00	−15.15
TA (kgSO_2-eq)	1.52×10^{-2}	99.16	−2.11	99.96	−10.78
FWEu (kgP-eq)	1.05×10^{-3}	99.82	−1.32	99.94	−6.72
MEu (kgN-eq)	3.82×10^{-3}	99.30	−2.58	99.94	−13.51
TEc (kg1,4-DCB)	3.55	99.98	−2.49	99.96	−11.70
FWEc (kg1,4-DCB)	1.10×10^{-1}	99.98	−2.49	99.96	−12.48
MEc (kg1,4-DCB)	7.36×10^{-2}	99.88	−1.40	99.96	−6.55
HCT (kg1,4-DCB)	6.25×10^{-2}	99.74	−0.68	99.36	−2.88
HnCT (kg1,4-DCB)	2.11	95.52	−1.20	99.66	−9.02
LU (m^2acrop-eq)	1.59	94.96	−1.97	99.96	−15.51
MRS (kgCu-eq)	2.69×10^{-3}	99.98	−1.44	99.98	−6.37
FRS (kg-oil-eq)	4.48×10^{-1}	99.98	−1.54	99.98	−7.55
WC (m^3)	4.56×10^{-2}	99.98	−6.33	100.00	−30.19

distribution profile to a Gaussian, but with hard limits placed on the minimum and maximum bounds, which is necessary for effective use of Eq. 1. It should be noted that this calculation assumes that the environmental impact of producing the fresh ingredients does not change regardless of how they might vary. It should be further noted that if the environmental impact does indeed change, then this calculation is not possible given the current availability of background impact data for either ingredient, which is as a function of mass, and not fat content, for example.

The results of the comparative sensitivity analysis are shown in Table 10 for a sugar-based yoghurt compared separately with a Reb A-based and, separately, a thaumatin-based yoghurt. Data shown are the baseline environmental impact for a sugar-based yoghurt, the percent of iterations that the NNS or SE-based yoghurts have a lower environmental impact (columns titled "#iterations thaumatin < sugar" and "#iterations Reb A < sugar"), and the average difference of the two environmental impacts as a function of impact category. As an example of interpreting the data, within GWP, a thaumatin-based yoghurt is shown to have a lower environmental impact than a sugar-based yoghurt for 99.26% of the 5000 calculation iterations for different values of s: i.e., for only 37 calculation iterations was the thaumatin-based yoghurt found to have a higher environmental impact than the sugar-based yoghurt. In addition, across all 5000 calculations, the average GWP for the thaumatin-based yoghurt is 2.06% lower than the sugar-based one. Therefore, the results show that both NNS&SE-based yoghurts show a significantly lower (confidence interval > 95%) environmental impact across all impact categories after accounting for a degree of variability in the fresh ingredients.

A similar comparison is offered in Supplementary Information, Table S7, for when the distribution of s is instead assumed to be uniform between the bounds of ± 1. The results show that for Reb A, the environmental impact is still significantly lower across all impact categories. However, for thaumatin, the results are not significant (a confidence interval > 95%) for fine particular matter (FPM, 91.6%), terrestrial acidification (TA, 94.8%), HnCT (87.1%), and LU (89.1%). This shows that the nature of the variability of the fresh ingredients and how it is accounted for in the formulations is important to determining significance of environmental impact reduction of replacing sugar with NNS&SE in yoghurts.

5 Discussion

The results show that environmental impact of both a drink and yoghurt is reduced when replacing added sugar with either NNS or SE. In this section, further discussion of the results and their ramifications for reformulation of drink and yoghurt products is given.

5.1 Variability of impact due to NNSs

Figure 6 shows the difference between the NNS-based product with the largest and smallest impact as a percentage of the product with the smallest impact for, separately, drinks (black), and yoghurts (red). Note: the graph is not comparing drink to yoghurt, and instead, they are shown on the same axes for brevity. The data shown is the percentage difference of the absolute values of impact. Numerical data are given in Supplementary Information, Table S8. The results indicate that the choice of NNS has relatively little effect upon the impact of the reformulated product. This is particularly true of yoghurt, which has a larger environmental impact than a drink, and therefore, the contribution to total impact from the NNS is smaller. This leads to a smaller variability between the NNS-based yoghurt formulations. For instance, for GWP, variability in NNS-based drinks impact is 2.3%, and for yoghurt, it is only 0.3%. Many of the instances of greater variability in impact are due to assumptions made in the background LCAs for the NNSs. The most notable exception is LU, for which variability within the drinks is 820% and yoghurt is 22.6%. Both are due to the Reb A + thaumatin mix and are due to the background thaumatin LCA, as discussed in Sects. 4.1 and 4.2. If the

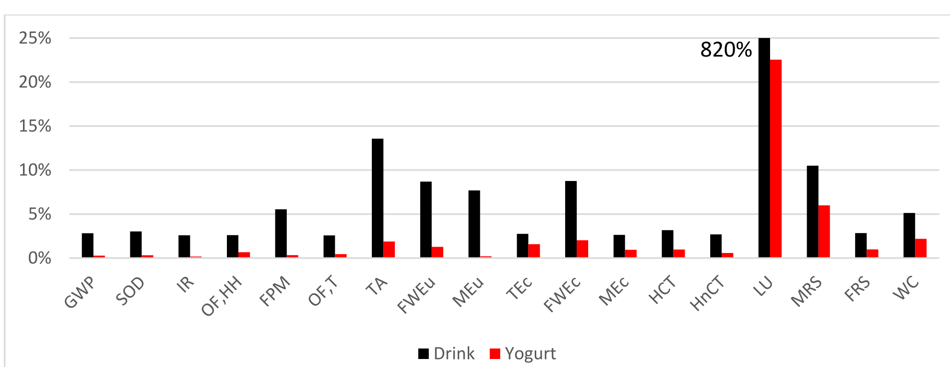

Fig. 6 Difference in impact between the NNS-based drink with highest and lowest impact (black) and separately the NNS-based yoghurt with highest and lowest impact (red). Drink LU difference is above scale max at 820%. Impact categories defined in Fig. 2

Reb A + thaumatin mix is omitted from the comparison, the variability reduces to 20.5% (from 820%) and 0.6% (from 22.6%) for drink and yoghurt, respectively. For TA and freshwater ecotoxicity (FWEc), the drink with greatest impact is one based upon aspartame, for which impact in these categories was linked to emission of production process waste material directly to the environment without treatment (Suckling et al. 2023c). For MRS, sucralose-based formulations showed the greatest impact, for which issues with inventory data derived from literature were identified (Blenkley et al. 2023) and discussed in Sect. 4.1. Therefore, it may also be anticipated that variability between reformulated products' environmental impact will also reduce. The results in this section are an important finding from the study. They indicate that the particular choice of NNS is not critical for environmental impact of the final reformulated foodstuff across the majority of impact categories. Therefore, focus may instead be given to other drivers, such as health, technical function, or organoleptic qualities of the new products being developed.

5.2 Impact change due to reference unit

Results presented in Sect. 4 all focused on mass as the primary functional unit. This reflects how the products are purchased and consumed. However, the purpose of reformulating the drinks and yoghurts was to reduce their calorie density in order to understand potential for reduction of obesity through consumption of NNS&SE sweetened products as opposed to sugar-sweetened ones. Therefore, another perspective on environmental impact may be offered by comparing the sugar-sweetened and NNS&SE-sweetened products on the basis of calorie density or kcal/100 g. Table 11 shows the kcal/100 g for the ingredients used in this study and the net kcal/100 g for each of the final products.

Figure 7 shows the results for 1 kg drinks as a function of calorie density, for drinks sweetened using sugar (black), Reb A + thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (orange), and SE thaumatin (grey). Supporting numerical data are given in Supplementary Information, Table S10. The results show that all of the trends are the same as when comparing formulations

Table 11 Nutritional information for ingredients used in drink and yoghurt formulations. Also given, resulting kcal/100 g for each of sugar-, NNS-, and thaumatin-based drinks and yoghurts

Ingredient/recipe	kcal/100 g	Reference
Water	0	
Potassium chloride	0	ReciPal (2023a)
Citric acid	300	EU Labelling factor for organic foods
Sodium benzoate	0	ReciPal (2023b)
Lemon/lime flavor	0	PHE (2021), using lime cordial, undiluted as a proxy
Sugar	394	PHE (2021)
Milk	66	
Cream	467	
Protein powder	35	
Foodstuff	kcal/100 g	Source
Drink (sugar)	44.2	SWEET project recipe data and above nutritional information
Drink (NNS)	12.7	
Drink (thaumatin)	37.9	
Yoghurt (sugar)	155.0	
Yoghurt (NNS)	118.8	
Yoghurt (thaumatin)	147.8	

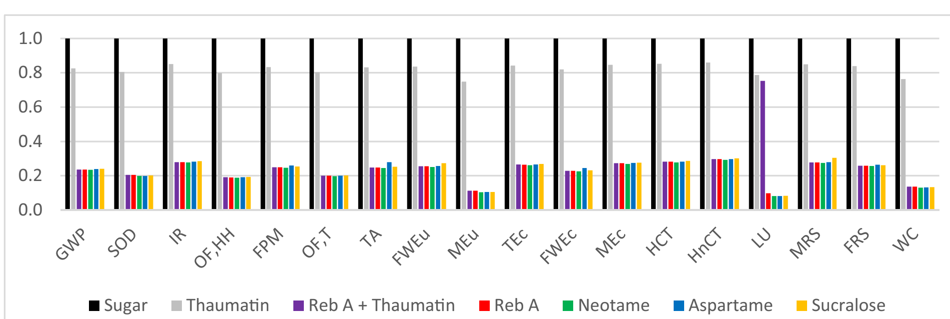

Fig. 7 Relative impacts of 1 kg sweetened drink for all ReCiPe 2016 (H) impact categories when assessed as a function of calorie density (kcal/100 g). Sweeteners shown are sugar (black), Reb A + thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (yellow), and SE thaumatin (grey). Impact categories defined in Fig. 2

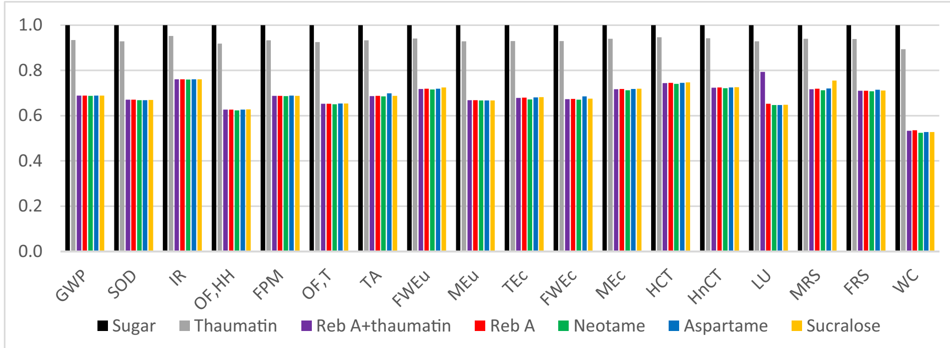

Fig. 8 Relative impacts of 1 kg sweetened yoghurt for all ReCiPe 2016 (H) impact categories when assessed as a function of calorie density (kcal/100 g). Sweeteners shown are sugar (black), Reb A + thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (yellow), and SE thaumatin (grey). Impact categories defined in Fig. 2

on a weight basis: replacing added sugar with NNS or SE reduces environmental impact. However, when considering impact in terms of calorie density, the differences are more marked. A thaumatin-based drink now has an average impact of 82.2% that of the sugar-based drink across all impact categories (down from 95.5%). Drinks using NNS have an impact ranging from 22.3% (neotame, down from 76.1%) up to 26.4% (Reb A + thaumatin, down from 82.2%). Moreover, the impact categories in which there was an increased impact (HnCT, MRS, and LU), are now, without exception, lower than the sugar-based drink.

Figure 8 shows the same results for yoghurt products, with numerical data given in Supplementary Information, Table S11. Again, the trends are the same as when comparing formulations on a weight basis: replacing added sugar with NNS or SE reduces environmental impact. But again, the differences are more marked. A thaumatin-based yoghurt now has an impact of 93.3% that of the sugar-based yoghurt (down from 97.6%). NNS-based yoghurts have an impact ranging from 68.1% (neotame, down from 88.7%) up to 69.2% (Reb A + thaumatin, down from 90.0%).

This comparison demonstrates how choice of functional unit in this setting can have a marked effect upon reported environmental impact. However, it should be noted that selecting calorie density as a single reference point might be over-simplistic if expanding the practice to include multiple foodstuffs. For instance, the role of food is not only to supply calories, but also many other nutrients. It is not guaranteed that replacing sugar with NNS&SE will only reduce calories without affecting other nutritional qualities of the food. Therefore, at a dietary level, it may also be necessary to identify key nutrients to include in a functional unit.

5.3 Choice of background ingredient processes

5.3.1 Background process database

In this study, the baseline environmental impact of yoghurt is built upon background processes for sugar and dairy (specifically cows' milk, cream from cows' milk, and milk protein powder) from the Agri-footprint database. This was because there was no milk powder process available in the ecoinvent 3.8 database and it was desirable to have consistency across the primary ingredients. However, in Sect. 4.2, results from other studies were presented, one of which was a native process for yoghurt within the ecoinvent database, which uses background ingredient data also from the ecoinvent database. Therefore, it is prudent to verify that the findings of this study are the same when using background processes for milk, cream, and sugar from the ecoinvent database, in place of those from Agri-footprint. Yoghurt formulations given in Table 3 are reproduced in Supplementary Information, Table S9. The ecoinvent database does not have a single milk powder process. Instead, it has two processes for reducing water content of milk: an evaporation process to increase dry matter content from 9 to 50% and a spray drying process to further increase dry matter content from 50 to 96.5%. Both of these steps are included in the model and are listed as part of the ingredients in Table S9 with appropriate mass balance applied to account for removed water.

Figure 9 shows the relative environmental impact of sugar-based and NNS&SE-based yoghurts when reproducing the results using background processes for milk, cream, powder, and sugar from the ecoinvent database instead of those from Agri-footprint. The presentation mimics that of Fig. 4, wherein the results are normalized within a given impact category to the yoghurt with the greatest environmental impact. Numerical impact data are given in Supplementary Information, Table S12. The environmental impact of all of the NNS&SE-based yoghurts are shown to be lower than the sugar-based yoghurt, a finding which is in accordance with those in Fig. 4. However, the reduction in environmental impact is smaller for models using the ecoinvent database processes. For instance, for GWP a sugar-based yoghurt is 3.90 kgCO_2-eq/kg, whereas for thaumatin, it is 3.87 kgCO_2-eq/kg, and for the NNS-based yoghurt, it ranges from 3.74 to 3.75 kgCO_2-eq/kg. This smaller difference is due to the environmental impact for the ecoinvent sugar and dairy models being closer in impact than the Agri-footprint equivalents are to each other

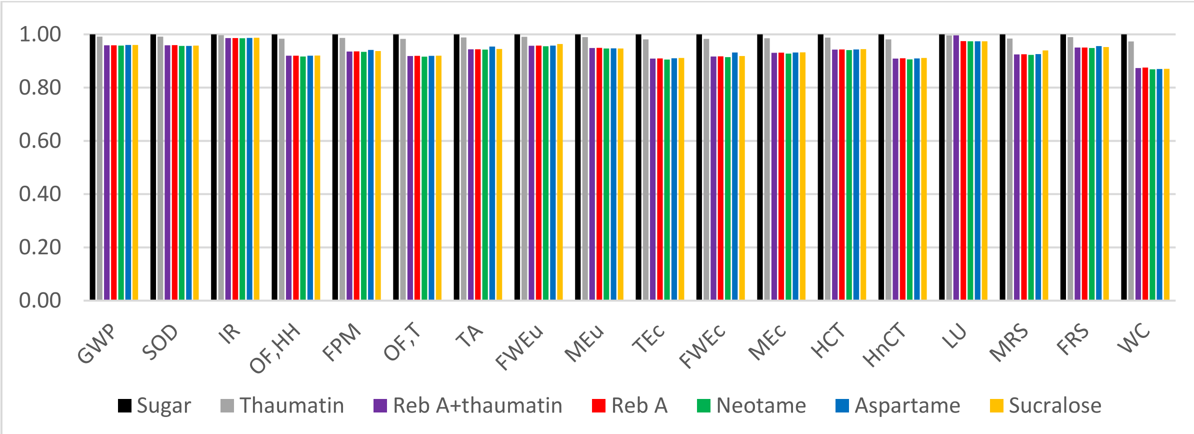

Fig. 9 Relative impacts of 1 kg sweetened yoghurt for all ReCiPe 2016 (H) impact categories for models using background data from the ecoinvent 3.8 database. Sweeteners shown are sugar (black), Reb A+thaumatin (purple), Reb A (red), neotame (green), aspartame (blue), sucralose (yellow), and SE thaumatin (grey). Maximum impact within a category equals 1. Impact categories defined in Fig. 2

(given in Supplementary Information, Table S13, for comparison to Table 9). For the baseline results (in Sect. 4.2), reduction in environmental impact when replacing sugar was shown to be in part due to milk having a lower environmental impact than sugar (and also reduction in cream and milk powder fractions in the formulations). However, in the case of the ecoinvent background processes, milk tends to have a *greater* environmental impact than sugar (in GWP, LU, and MEu, Table S13), while still having a lower environmental impact than cream and the proxy milk powder process. Therefore, when using ecoinvent background processes, reduction in environmental impact is not because milk has lower environmental impact than sugar, but because less cream and milk powder are used when sugar is replaced.

When comparing the impact of a sugar-based yoghurt with ecoinvent background processes to those with Agri-footprint background processes, the GWP is slightly lower for ecoinvent (3.90 kgCO_2-eq/kg vs 4.15 kgCO_2-eq/kg). This is simply because the fractions of ingredients and the individual ingredients' environmental impact means that yoghurt with ecoinvent background processes have a marginally lower impact. The NNS-based yoghurts have very similar impacts, with GWP of approx. 3.73 kgCO_2-eq/kg for ecoinvent-based models and approx. 3.74 kgCO_2-eq/kg for Agri-footprint based models. Again, this is just down to the fraction of ingredients and their individual impacts. In terms of comparison to the native ecoinvent model, the impact of the yoghurt in this study is still greater (3.90 kgCO_2-eq/kg vs 2.00 kgCO_2-eq/kg), and this is again due to the nature of the models: the native model being a mixture of yoghurt types, whereas this study focusing on a thick Greek-style yoghurt. This highlights how choice in background models can affect results of the assessment.

5.3.2 Sugar source

The baseline results were for a drink or yoghurt formulation sweetened with a global mix of cane and beet sugar. However, the environmental impact of each type of sugar is different. Therefore, this section explores the effect of assuming all the sugar is sourced either from just cane or just beet. New background processes were created in which the global mix of sugar was re-normalized assuming that it was only made of cane or beet (Supplementary Information, Table S14). These new sugar mixes were used in place of the global mix in the yoghurt and drinks models. The new environmental impacts are reported in Supplementary Information Tables S17 (for 1 kg drink) and S18 (for 1 kg yoghurt). New environmental impact data are shown for each of the sugar-based formulations (columns headed "Sugar cane only" or "Sugar beet only" and for SE-based (thaumatin) formulations. However, the data for the NNS-based formulations are the same as those shown in Table 5 (drink) and Table 7 (yoghurt) because they have no sugar which can be changed. The data are color coded to highlight which NNS&SE-based formulations have most impact compared to the sugar-based ones. Amber colored cells show when SE- or NNS-based formulations have a greater impact than the sugar-based ones, but were shown to have a greater impact already in baseline comparison (i.e., no relative change). Red shows when impact of the NNS-based formulation is now worse, and green shows when impact is now better. No color indicates no change in relative impact compared to baseline results. For SE-based formulations, they are compared with the sugar-based formulation using the same sugar type (i.e., cane vs cane and beet vs beet). For NNS-based formulations they are compared with the sugar-based formulation with the lowest impact out of cane or beet.

The results show that in the majority of cases, there is no change in relative impact of sugar-, SE-, or NNS-based formulations. There are two exceptions to this. First, for an aspartame-based drink, impact is now marginally worse for TA compared with the sugar-based drink. However, the shift is minor: in baseline results, aspartame was 2.9% lower impact than the sugar-based drink, and in this instance, it is 0.1% higher than the sugar-based drink using beet. Second, for an SE-based drink using beet sugar, impact is now marginally better HnCT than a sugar-based drink using beet. For baseline results, it was 0.4% higher, and in this instance, it is 1.3% lower. Therefore, the results show that the source of sugar has little effect on the relative change in impact when replacing sugar with either an SE or NNS.

5.4 Whole life cycle

The focus of this study was the production of 1 kg of either a drink or a yoghurt and do not include the rest of the life cycle of the product. This is an area for further investigation, but one which may be reflected upon here as a function of life cycle phase:

1) *Consumption*: In theory, an NNS&SE-based product should have different health outcomes for the consumer in terms of obesity or diabetes. Such differences would only be apparent in a consequential LCA when including any changes in demand for support services, such as health care, which may arise as a consequence of removing sugar. This study is attributional. However, the World Health Organization (WHO) recently published a large meta-study into the health effects of NNS upon humans (Rios-Leyvraz and Montez 2022). The findings were not conclusive and indicated that more research was required in order to identify significant health changes. Therefore, until better data are available, it may be difficult to conduct a meaningful comparative LCA including consumption of sugar- or NNS&SE-based foodstuffs.
2) *Waste disposal*: In terms of waste disposal, the key differentiator between the sugar-based and NNS&SE-based products is at wastewater treatment plants. There are studies which seek to understand the potential for NNS to cause harm to the environment (e.g., Luo et al. 2019). But at present, these studies have not translated into measurable impacts at LCA levels in methods such as ReCiPe 2016. For instance, aspartame is present in the ecoinvent database as an emission but is yet to have any associated impacts upon release into the environment.

Therefore, the authors consider that, at present, it would be difficult to conduct an LCA study of NNS&SE-based foodstuffs which included phases beyond production.

5.5 Limitations and further research

This study focused on the production of sugar-based and NNS&SE-based drinks and yoghurts produced for research purposes within the SWEET project. There are limitations to the study which might be explored in future research:

- Both sugar-based and NNS&SE-based yoghurts were developed in a laboratory setting. This was useful in enabling identification of similarities and differences in the production processes. However, there were challenges relating to collection of production data (e.g., electricity consumption), and it was therefore incomplete. Instead, data was included from literature sources to give perspective of environmental impact change of a whole product and to allow exploration of impact of NNS in a more realistic context (the production of the ingredients themselves already being at industrial scale in the background processes). Future research into industrially manufacturing versions of the products studied here would give a more representative impact. This is especially true of the NNS-based yoghurt for which there is currently no larger scale production data of any kind. A detailed projection of future potential environmental impacts (e.g., van der Giesen et al. 2020; Erakca et al. 2024) was outside the scope of this study, but is an area for future research.
- The present study was limited to the thick, sweetened Greek-style yoghurt developed for the SWEET project. However, there are many types of yoghurt available, such as those containing fruit, low fat varieties, or drinking yoghurts. It would be beneficial for future studies to expand to include those other types of yoghurts. This also applies to the wide variety of sweetened drinks available on the market.
- The present study assumed that the sourcing of the milk, cream, and milk powder does not change during reformulation (i.e., environmental impact of the ingredients do not change). However, it is possible that sourcing of ingredients might change, and therefore, changes in impact due to regional differences in ingredient production may also play a role in environmental impact change of a reformulated product.

6 Conclusions

There is increasing concern over excessive consumption of added sugar and the resulting adverse health effects. Therefore, NNS&SE are seen as alternative ingredients which might be used to provide the sweet taste of sugar, but without the associated calories. Previous studies have focused on the environmental impact of producing the individual NNS&SE. This study is the first which has extended the research to include production of drink and yoghurt foodstuffs using them. The study used sugar- and NNS-based formulations, developed as part of the SWEET project and designed to be as similar as possible in terms of consumption perceptions.

An LCA was conducted for production of 1 kg sugar-based and NNS&SE-based drinks and yoghurts in order to understand the ramifications for replacing added sugar with NNS&SE. The results showed that products which used NNS&SE had a lower environmental impact across most of the ReCiPe impact categories than the equivalent sugar-based products. Exceptions to this were mineral resource scarcity for a sucralose-based drink, land use for a Reb A + thaumatin-based drink, human non-carcinogenic toxicity for all NNS&SE-based drinks, and land use for a Reb A + thaumatin-based yoghurt. Change in the environmental impact of drinks was driven primarily by the difference in environmental impact of the sugar removed, and the water and NNS added. For yoghurts, the findings were more nuanced, wherein rebalancing of the dairy ingredients also contributed to reduction in environmental impact.

It was shown that there is relatively little difference in environmental impact between NNS-based formulations. This is an important finding, as it shows that choice of NNS may be driven by needs of technical function, or consumption (such as clean labeling), and not by concerns over environmental impact. Finally, challenges were identified of extending the work to include the whole life cycle, wherein there is currently a lack of strong evidence for differences between consumption of foodstuffs sweetened with sugar and those sweetened with NNS or SE.

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Data availability All data relating to this research are available in this document and supporting material.

Declarations

Conflict of interest The authors declare that they have no conflict of interest, except for A. Raben, who has received honoraria from Nestle, Unilever, and the International Sweeteners Association, and J.C.G Halford and J.A Harrold who have received project funds from the American Beverage Association.

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