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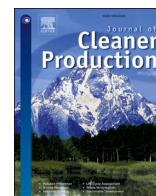
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Life cycle assessment of the sweetness enhancer thaumatin (E957) produced from *Thaumatococcus daniellii* fruit foraged from West Africa: The SWEET project

J. Suckling^{a,*}, S. Morse^a, R. Murphy^a, S. Astley^b, C. Boy^c, J.C.G. Halford^{d,e}, J.A. Harrold^e, A. Le-Bail^f, E. Koukouna^g, H. Musinovic^b, A. Raben^h, M. Roe^b, J. Scholten^g, C. Scottⁱ, C. Westbroek^g

^a Centre for Environment and Sustainability, University of Surrey, Guildford, UK

^b EuroFIR AISBL, Brussels, Belgium

^c Natex UK Ltd, Letchworth Garden City, UK

^d School of Psychology, University of Leeds, Leeds, UK

^e Department of Psychology, University of Liverpool, Liverpool, UK

^f ONIRIS, UMR GEPEA CNRS, 6144, Nantes, France

^g Blonk Consultants, Gouda, the Netherlands

^h Department of Nutrition, Exercise and Sports, University of Copenhagen, Copenhagen, and Clinical Research, Copenhagen University Hospital, Steno Diabetes Center Copenhagen, Herlev, Denmark

ⁱ Cargill, Plymouth, MN, USA

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ABSTRACT

Replacing added sugar with non-nutritive sweeteners and sweetness enhancers is of increasing interest due to the negative health effects of excess sugar consumption. Much has been done to understand health and safety of such sweetening additives, but little on their sustainability. This study, part of the Horizon 2020 SWEET project, presents results from the first life cycle assessment of the sweetness enhancer thaumatin, produced from *Thaumatococcus daniellii* fruit, from forests in West Africa and extracted in the United Kingdom. Thaumatin is used in formulations to increase perceived sweetness of added sugar, allowing some to be removed. Environmental impact is reported for multiple impact categories from the ReCiPe 2016 (H) method, focusing on global warming potential, land use, water consumption, and freshwater eutrophication. Impacts are expressed in terms of product mass and sweetness equivalence. Global warming potential for production of thaumatin is found to be 719.2 kgCO₂-eq/kg. When thaumatin replaces 20% of added sugar, environmental impact for a given sweetness is found to reduce by an average of 19.4% across all impact categories. International transport is a major contributor to global warming potential, as is aril removal from the fruit to freshwater eutrophication and water use, and fruit foraging to land use. However, land use is identified as a key area of future research to improve uncertainty in the data. Results show that thaumatin can be used to reduce the environmental impact of providing sweet taste in food and beverage products.

1. Introduction

There is concern of consumption of added sugar and its role in non-communicable diseases such as type 2 diabetes, obesity (Johnson et al., 2017), or tooth decay (Vaghela et al., 2020). As such, there is growing interest in the potential to use non-nutritive sweeteners (NNSs) or sweetness enhancers in place of added sugar and understand potential

benefits to health, such as weight control (O'Connor et al., 2021; McGlynn et al., 2022; Rios-Leyvraz and Montez, 2022). Both types of sweetness replacer are considered food additives, and as such, to be authorized in the European Union for use in food and beverage products they must undergo a rigorous approval process (Regulation EC 1333/2008) (EC, 2008).

One such authorized food additive is thaumatin, which can act both

* Corresponding author.

E-mail address: j.suckling@surrey.ac.uk (J. Suckling).

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as a sweetener or as a sweetness enhancer. On its own it has a sweetness approximately 3000-times greater than sugar (Aguilar et al., 2015; Wal et al., 2019). However, the taste profile is not considered to be well aligned with sugar, therefore, it's most common use is as a sweetness enhancer, and for this function it is used in quantities of 0.5 ppm to replace 200 g out of every 1 kg sugar to maintain perceived sweetness (interview data from producer). Thaumatin is a protein derived from the fruit of *Thaumatococcus daniellii* (*T. daniellii*, and herein referred to as Td) and accounts for 1–2% of aril mass, itself approximately 5% of the fresh fruit mass (Chinedu et al., 2014). Thaumatin is permitted for use in the EU as additive E957 (Lewis and Tzilivakis, 2021) and, recently, was found to require no numerical acceptable daily intake (ADI) (Younes et al., 2021). This sets thaumatin apart from sweeteners used in the EU market, especially regarding tracking of dietary intake (Le Donne et al., 2017; Martyn et al., 2018; Hafner et al., 2021). Td originated from West Africa, and has been introduced to other compatible climates, for example parts of Australia (Agha et al., 2022), or Malaya (POWO, 2023). The fruit is known locally in West Africa for its sweet taste (Lim, 2012). However, it is the leaves (not the fruit) that are most used for wrapping food or various kinds, preserving kolanuts, or fodder for animals, or even material for roofing (Arowosoge and Popoola, 2006). There is recognition that the fruit is an underutilized resource (Oluwatayo and Ojo, 2014) that remains largely unexploited. For instance, the total annual global market for thaumatin is approximately 1500 kg, for which there are two producers, both sourcing thaumatin from foraged fruit in West Africa, with no production known to occur from cultivated land (interview data, no other market data for thaumatin is available).

With regard to environmental impact, to the authors' knowledge, there are no life cycle assessments (LCAs) for thaumatin, nor for any sweetness enhancers. Therefore, this LCA of thaumatin is the first of that class of ingredient. Indeed, within the wider area of non-nutritive sweeteners (NNSs), the authors are only aware of six studies, and these only relate to NNSs, not sweetness enhancers; five for steviol glycosides (PureCircle, 2015; Cargill, 2021; Gantelas et al., 2022; Milovanoff and Kicak, 2022; Suckling et al., 2023) and one for aspartame in the World Food LCA database (Nemecek et al., 2019). The results of these studies shows that each of the NNSs can replace the sweet taste of sugar with a reduced environmental impact. With regard to thaumatin, there are economic studies (Arowosoge and Popoola, 2006; Oluwatayo and Ojo, 2014), and those relating to growth under certain conditions (Khairlani et al., 2020), but there are no LCAs of production of thaumatin from Td.

The research presented here aims to fill that gap with the first LCA on production of thaumatin, and the first LCA for any sweetness enhancer. The research further supports studies relating to replacement of sugar in foods or beverages. The thaumatin in this LCA is sourced from Td fruit which has been foraged in the forests in West Africa (particularly Cameroon, Cote D'Ivoire, Nigeria, and Ghana) and extracted in the United Kingdom by the case study business. Data presented are all provided by a thaumatin producer, who has oversight of, and is actively involved in the entire supply chain of thaumatin from fruit to final product. The research is aimed at practitioners within food production wishing to understand more of environmental impact of the ingredients they use and supports the producer's understanding of environmental impact within their supply chain. The research is part of the large EU project SWEET (Sweeteners and sweetness enhancers: Impact on health, obesity, safety and sustainability, www.sweetproject.eu).

This paper is organized as follows. An overview of the production process of thaumatin and the LCA methodology used is provided in Section 2. Detailed information and specific inventory data relating to the LCA are presented in Section 3. Results of the main LCA, and scenario analysis, are presented in Section 4. Sensitivity analysis of results to uncertainty in inventory data is presented in Section 5. Discussion, including comparison to sugar on a sweetness equivalence basis, is provided in Section 6. Finally, concluding remarks are made in Section 7.

2. Materials and methods

2.1. Supply chain description

The following is an overview of the thaumatin production process assessed in this study and is a summary of information provided during interviews with the thaumatin producer. Thaumatin is produced from Td that grows in the forests of West Africa. Communities living across the region practice forest agriculture, clearing underneath the trees to grow crops. Forests in the area are often secondary, i.e., re-grown after primary forest was cleared in preceding decades. However, Td is not a crop specifically produced by the communities. Rather, it is one of the first plants to return to the forest floor when agricultural production ceases and the land is left to become fallow for a period of time. Td spreads by rhizome, which helps its early reappearance on fallow land, as does its propensity to grow under forest canopy shade (Agha et al., 2022). The fruit that it produces is bright red when ripe, and grows at or just below ground level (POWO, 2023). Within the fruit are typically two or three seeds, to which is attached the aril, and it is in the aril that thaumatin is found (Khairlani et al., 2020).

Under normal circumstances, communities living there would not make use of Td fruit as a source of income (interview data), a finding echoed by Arowosoge and Popoola (2006). If no approach is made to purchase fruit by a thaumatin producer, the plant is left alone, and no activity undertaken to increase yield (e.g., fertilizer application, or plant breeding). Therefore, the land on which Td grows is considered fallow, and this indicates that Td fruit is harvested in a manner more akin to foraging than a formal agricultural processes. The fallow part of the forest is also used for other resources such as firewood, bushmeat, or medicinal plants (interview data). It should be noted that Td growth is included in this LCA, but since there is no activity undertaken to encourage growth (i.e., no resources used, or input, and no emissions created) there are no data which may be used in an environmental assessment.

Td fruit considered within this LCA is foraged from three broad areas within West Africa: Cote D'Ivoire, with some just across the border in Liberia; Ghana; and Cameroon, with some just across the border in Nigeria. For the purposes of environmental impact assessment, Td fruits are assumed processed in Cote D'Ivoire, Ghana and Cameroon (i.e., fruit foraged in Nigeria are assumed transported across the border to Cameroon). The total area foraged is not restricted by production, or natural habitat of the plant, but because it is sufficient to meet current market demands. The life cycle inventory is divided among the three regions to account for differing masses of fruit foraged, yields of thaumatin from Td fruit, building types and energy sources used for freezing aril. However, the exact mass of arils and thaumatin yield from each location is not reported here due to commercial sensitivity of the data.

Once foraged, fruit is taken to local market towns where it is purchased and transported to larger settlements in which there are 'cutting stations' where the aril can be removed (or 'cut'), from the fruit. The aril accounts for approximately 5% Td fruit mass (Chinedu et al., 2014). The rest of the fruit is discarded. Details of disposal are not fully known but it is thought that most is spread back to the land, and not formally composted, landfilled or otherwise treated (interview data).

Once removed, arils are frozen, which stabilizes the thaumatin, preventing degradation during transportation. Once enough arils are produced, they are shipped in insulated bags to operational centers at international airports in Abidjan (Cote D'Ivoire) and Douala (Cameroon). There, the arils are transferred from insulated bags to polystyrene boxes for air transport to Brussels (Belgium).

From Brussels, they are shipped in refrigerated, articulated lorry to Kent (United Kingdom), where they are stored until needed by the extraction facility. The growing season for Td is from November until April and, therefore, arils are cold stored to even out extraction and supply rates over the year. Finally, the arils are transported to Letchworth Garden City (UK), where thaumatin is extracted.

2.2. Goal and scope

The goal of the LCA was to assess the environmental impact of producing 1 kg purified thaumatin (E957) extracted from the fruit (specifically the aril) of *Thaumatococcus daniellii* (Td), sourced and processed in West Africa, and extracted in the UK, as described above.

The study includes all foreground activities associated with plant growth and fruit forage, processing of the fruit to remove arils, extracting the thaumatin and transport between locations. Background activities are also included for inputs such as energy, infrastructure, and materials. Waste disposal is also included.

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

2.3. System boundaries

The LCA boundary is shown in Fig. 1 and includes phases: plant growth and fruit forage from the forest; cutting and freezing of the aril; transport to airports within West Africa; transport into Europe (Belgium); transport to the UK; cold storage in the UK; and extraction and purification of thaumatin from aril in the UK. Also shown Fig. 1 is the geographical locations of key points of the supply chain. All upstream inputs, such as electricity, and other energy inputs, and machinery production are included. Outputs, such as by-products and wastes are also included.

The assessment was conducted using SimaPro 9.3 software with the ecoinvent 3.8 and Agri-footprint 6.1 databases. The characterization method used was ReCiPe 2016 Midpoint (Hierarchist) (Huijbregts et al., 2016). Results for all impact categories of the ReCiPe 2016 method are reported, with focus on global warming potential, water consumption, land use and freshwater eutrophication due to their relevance in production of such a plant-based ingredient.

Primary data were collected through interview with a producer of thaumatin, one of two, and the largest by market share (interview data, thaumatin market data not otherwise available). The producer has

oversight of the entire supply chain and primary data for all locations. Health restrictions due to COVID-19 prevented visits to many of the sites, aside from the extraction facility in the UK, which is also the main location of the thaumatin producer. Thus, any further familiarization of inaccessible locations and processes were conducted via literature survey and internet.

2.4. Functional unit

The LCA study is cradle-to-factory-gate, and the functional unit is “production of 1 kg purified thaumatin”. In this case the gate is exit from the thaumatin factory in the UK. Transport of the thaumatin to customers and its use in food and beverage products was out of scope for this study because of the number and variety of formulations in which thaumatin might be used.

Mass is the primary functional unit because it is an internationally recognized standard. However, it does not represent the primary functional use of thaumatin in formulations, which is to enhance sweetness of sweet molecules. When used as a sweetness enhancer, thaumatin is used in 0.5 ppm amounts, reducing sugar use by ca. 20%, i.e., 200 g in every 1 kg sugar, whilst maintaining subjective sweetness. Therefore, LCA results are also presented in terms of partial replacement of sugar (0.4 mg thaumatin added to 800 g sugar) in the Discussion, Section 6.

In addition to the functional unit, reference units have been used throughout the life cycle for transitions between phases: 20 kg Td fruit and 1 kg arils.

2.5. Allocation

The only product of value from the production process is purified thaumatin, therefore all impacts are allocated to it. Any plant residues or other outputs are returned to the land, composted, treated in wastewater plants, or landfilled.

Cut-off criteria are applied to materials entering or leaving the system, so no burden is allocated to wastes or residues from thaumatin

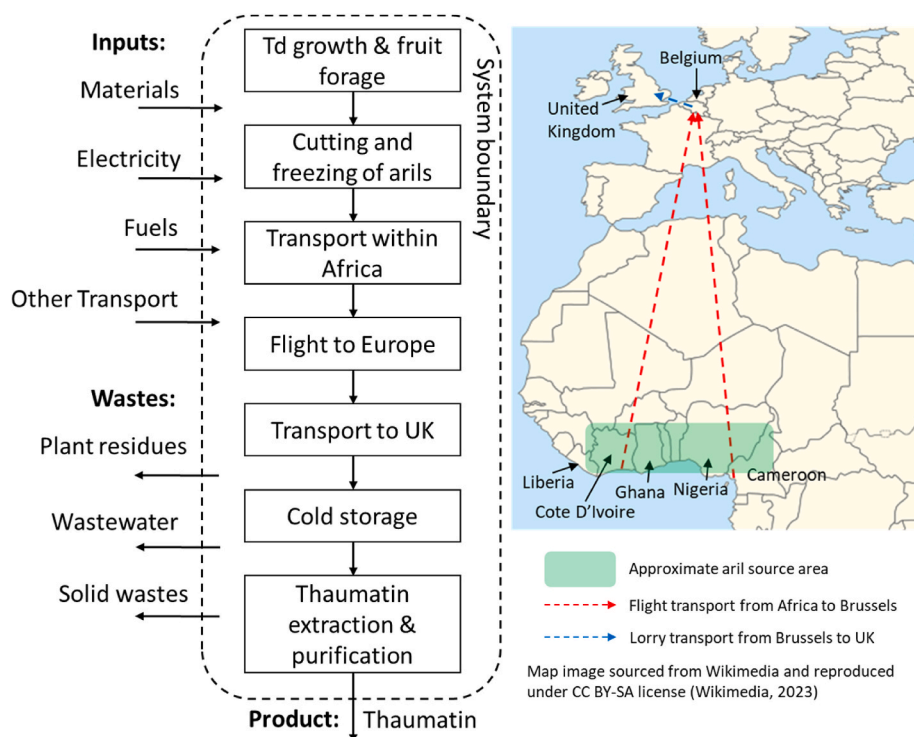


Fig. 1. System boundaries for the life cycle assessment of thaumatin production with main flows crossing the boundary (left) and locations of key points in the supply chain (right). Map image reference: [Wikimedia Commons \(2021\)](#).

production, nor do they carry benefits if recycled.

3. Life cycle inventory data

As previously indicated, Td fruit is sourced from Cameroon, Cote D'Ivoire and Ghana (and associated border areas, Section 2). Forage, methods to obtain the aril, freezing, and transport are assumed to be the same in all three areas. Differentiators among the regions are thaumatin yield from arils, what building types are used for cutting, and energy source used for freezing. Therefore, life cycle data are presented as though for all areas, unless otherwise specified. Complete life cycle inventory data are given in supplementary information, Tables S8–S16.

3.1. Phase: plant growth and fruit forage

For this phase, inputs and outputs are described as in reference to 20 kg fruit, the mass assumed collected by an individual villager undertaking foraging. Data relates to annual production of thaumatin and are not derived from individual samples of fruit collected from the regions. *T. daniellii* grows under the forest canopy (Khairani et al., 2020) and arise after an area used for forest agriculture is left fallow. The plant produces fruit between November and April annually (interview data and Agha et al., 2022). Local communities who forage Td fruit for the thaumatin production outlined in this study, are not known to otherwise make use of the fruit (or any other part of the plant) for economic gain, unless approached by those wishing to purchase it (interview data; Arowosoge and Popoola, 2006). The forest is not managed during the fallow period, other than to forage harvest of Td fruit for thaumatin production, or for items such as firewood, bushmeat, medicines (FAO, 2017, 2021). No inputs are made to grow the plant; no fertilizers are applied, no tillage or weeding is undergone, nor any form of propagation. Therefore, no data could be collected for use within the LCA relating to plant growth. Similarly, no biogenic carbon is assumed taken up as IPCC accounting for an annual crop are used in this instance (IPCC et al., 2019). Foraging is not by a standardized method, with villagers free to use whichever method is suitable to them, but it is not thought to include any mechanization (interview data). Therefore, for the purposes of this LCA, it is assumed that fruits are manually foraged.

At present there is no information about the yield of fruit per unit area of the forest. Villagers do not report the area over which they roam during each forage period. The only information relating to yield is a paper-based study conducted by the collaborating company, which estimated that 120 t of aril could be obtained from the whole of Cote D'Ivoire. The exercise was based upon scribing logistics circles on maps around market towns. Areas within which villagers operated, and the masses foraged, agree with that study. However, precise foraged area is not known by the company, and it is considered that it is not possible to know this data due to the nature of the fruit foraging. Therefore, an indicative quantity of 2000 kg_{fruit}/ha is used, which is the lower bound of 2–8 t/ha reported for active cultivation of Td fruit (Firsov et al., 2018). However, it should be noted that the reference is not representative of this study or supply chain but is the only known reference of yield. This uncertainty in land use will be explored in sensitivity analysis for a range of yields from 500 to 4000 kg/ha. Land occupation and transformation are for extensive forest, given that the type of forest agriculture practiced is not intensive in the way that wheat might be cultivated.

It is estimated that 20 kg of fruit is transported to local market towns by foot for 3.5 km on average. At the market town, fruit are put into 75 kg capacity bags made from woven polypropylene and to cutting stations (75 km) by a variety of transport means. This is approximated as a total of 1.5 t.km by 3.5–7.5 t freight lorry. The woven polypropylene bags are thought to be reused indefinitely within the market towns, but an indicative mass of 11.5 g polypropylene, with corresponding waste treatment, is allocated to each 1 kg aril.

3.2. Phase: Aril cutting

For this phase, inputs and outputs are described in reference to 1 kg aril. Arils are removed by manual labor at dedicated cutting stations, which are not used for any other purpose. Therefore, all impacts are allocated to thaumatin production. The aril accounts for approximately 4.9% of the fresh fruit mass. Producing 1 kg of aril requires 20.4 kg fruit and creates 19.4 kg fruit waste, which is spread to land. A range of 4.8–5% for aril percentage of Td fruit is used for sensitivity.

Arils are laid out on plastic trays and frozen in chest freezers. The trays are assumed to be made of 500 g glass reinforced plastic (GRP) and used for five years and, therefore, 0.0056 kg is allocated to each 1 kg of aril produced. The energy required for freezing arils is not known precisely but is estimated to be between 0.115 kWh/kg_{aril} and 2.474 kWh/kg_{aril} in Cote D'Ivoire, where energy is drawn from the electricity grid. The lower figure relates to interview data for electrical energy consumed by the freezer per kg aril while the upper figure is based upon interview data for total energy consumed in a cutting center over the course of a year, both inside and outside the growing season. However, the upper value was derived from supply chain negotiations relating to energy costs and assumed to be exaggerated. Therefore, a default value of 90% of the higher value is assumed (2.226 kWh/kg_{aril}).

For Cameroon and Ghana, electricity is produced by 100 kW diesel generators, with an assumed efficiency of 39% (FW Power, 2022). Therefore, values equate to 0.306 kWh/kg_{aril} and 6.582 kWh/kg_{aril} from diesel respectively, and a default of 5.924 kWh/kg_{aril} is applied.

Once frozen, arils are stored for approximately two weeks before being transferred to insulated bags for transport to nearby international airports (see Section 3.3). Woven polypropylene is used as proxy for the insulated bag and a mass of 11.5 g used per 1 kg of aril.

Fruit are discarded by spreading back to the land. The carbon within them is assumed to be returned to the atmosphere. IPCC accounting for biogenic carbon of annual crops is used in this instance, and is therefore not accounted for in either growth, or decomposition, of Td fruit (IPCC et al., 2019). Emission of N-compounds is accounted for because nitrogen is taken up during plant growth, even if only from natural sources. However, they are not included in the main calculation due to the foraged nature of the fruit: if it were not foraged it would still grow and decay in the forest. In that regard, the activity undertaken as part of thaumatin production is, in effect, only moving the location of a natural process. However, this is acknowledged as a methodological choice and, therefore, direct and indirect emissions of nitrates and N₂O from discarded fruit are accounted for using the Agri-footprint 6.0 methodology (Blonk et al., 2022) as a scenario in Section 6.2. For this, fruit composition data were derived from a combination of references due to a lack of sufficient data from one single source (Elemo et al., 1999; Chinedu et al., 2014; Krul, 2019). Emissions are 0.14965 kg nitrate and 0.0035133 kg N₂O. Emission inventory data are also given in supplementary information, Table S9.

The buildings used for the cutting stations vary. However, the footprint for each is assumed to be 12 m by 12 m (144 m²). In this space 24 cutters work, producing 100 kg of aril each per season, giving an indicative conversion of 16.67 kg_{aril}/m² building per year. The floor area is concrete to a depth of 10 cm. Three tables and six benches are allocated for cutting staff, and one for aril weighing equipment. All have a lifetime of 25 years.

3.2.1. Cutting station: Cote D'Ivoire

The roof is made of corrugated metal sheet, with some part covering the sides for protection from the weather; lifetime is 10 years. There is a 2.5 m tall concrete block wall along the back and 3 m walls along each side; lifetime is 25 years. The rest of the area is open, with wooden supports and rafters supporting the roof. A total of 27 uprights are used, each 2.5 m tall, and 0.15 m in width. There are four rafters, each 12 m long and 0.15 m wide. All are assumed to be sawn wood with a lifetime of 25 years.

3.2.2. Cutting station: Ghana

The specifications for the Ghana cutting stations are the same as for Cote D'Ivoire, except the uprights and beams are steel. There are 12 uprights, each 2.5 m tall and weighing 13 kg/m. There are four beams, each 12 m long and assumed 13 kg/m. Lifetime is 25 years.

3.2.3. Cutting station: Cameroon

Cuttings stations in Cameroon have a different configuration. The concrete floor area is the same, but the superstructure is different. There is a room occupying 72 m² (12 m × 6 m) of floor space and with 2.5 m tall concrete block walls; lifetime is 25 years. The room has a corrugated metal sheet roof as per the Cote D'Ivoire cutting station. The rest of the area is covered with a plastic roof, made from PVC sheet with mass of 110 g/m² and a lifetime of two years.

3.3. Phase: Transport within Africa

For this phase, and other transport phases, inputs and output are described in reference to 1 kg aril. Frozen arils are transported to international airports (Douala for Cameroon, and Abidjan for Cote D'Ivoire and Ghana) at an approx. distance of 300 km (0.3 t.km/kg_{aril}) by 7.5–16 t lorry with equivalent to EURO 5 emissions controls. The arils are transported in insulated bags, and the lorry is not refrigerated.

Arils are delivered to a depot at the airport and stored until a flight to Europe is available. Storage times are typically one week and consumes 0.05657 kWh/kg_{aril} of electricity. Electricity for the freezers is sourced from the national grid at all locations. At the depot, arils are transferred from the insulated bags to expanded polystyrene boxes for air freight transport. The depots are assumed to process large quantities of air freight, of which the arils form a negligible part of the total. Therefore, infrastructure at this point is not included. The arils are put into two different sized boxes; 20 kg aril per box in Cameroon and 25 kg per box in Cote D'Ivoire and Ghana. This equates to 0.0175 kg_{polystyrene}/kg_{aril} from Cameroon, and 0.022 kg_{polystyrene}/kg_{aril} from Cote D'Ivoire and Ghana. These figures are based upon indicative boxes having volumes of 0.0239 m³ (JBP, 2022a) and 0.037 m³ (JBP, 2022b) polystyrene at a density of 15 kg/m³. The arils are placed inside polythene bags within the boxes to an approximate mass of 4 g_{polythene}/kg_{aril}. Finally, the boxes are placed on to a pallet and wrapped in a low-density polythene plastic film, such that 1 g_{film}/kg_{aril} is used.

3.4. Phase: Transport into Europe and the UK

The arils are transported into Europe via commercial flights, stowed in the aircraft hold. The holds are unheated and are therefore sufficiently cold to not require refrigeration. Arils arrive at Brussels from Abidjan and Douala on consecutive days. Distances are taken to be 5125 km between Abidjan and Brussels, and 5232 km between Douala and Brussels. Accounting for both arils and packaging mass, air transport becomes 5.2634 t.km and 5.3262 t.km per kg_{aril} respectively, modelled as air freight.

Due to the arrival of flights on consecutive days, half of the aril mass is stored for 12 h, leading to 0.5 kg.day storage in a reefer cooled by CO₂ refrigerant (assumed as exact details of the storage conditions were not known). From Brussels, the arils are transported in a half-full refrigerated, articulated lorry to Feltham (London) for import checks and from there to a storage facility in Kent. This equates to 0.75 t.km lorry transport within the EU, 0.051 t.km transport by train (Eurotunnel), and 0.21 t.km lorry transport in the UK.

3.5. Phase: Cold storage in the UK

For this phase, inputs and outputs are described in reference to 1 kg aril. Frozen arils are not extracted immediately upon arrival in Kent. The fruit forage period is from November to April, but extraction occurs throughout the year. Therefore, approximately half the total mass of

arils is stored for half the year. This leads to a storage of 91 kg.day, with a reefer with CO₂ as the refrigerant used as a proxy for the storage conditions. After storage, the arils are transported from Kent to the extraction facility by a 7.5 t refrigerated lorry for 130 km (0.133 t.km/kg_{aril} including the mass of transport packaging).

3.6. Phase: Thaumatococcus extraction

For this phase, inputs and outputs are described as a function of 1 kg purified thaumatococcus. Arils contain 1–2% thaumatococcus, and for this study an average of approx. 1.28% was used, based upon interview data for specific yields from each country. Yield tends to be greater from Ghana than the other two countries, but finer detail of yields is subject to commercial sensitivity. Variation of ±0.25% is explored in the sensitivity analysis. Thaumatococcus is extracted from arils by steeping in hot water, flocculation, filtering, and ultrafiltration, before drying to a purified powder, which is stable for several years.

Arils are first removed from the packaging, which is disposed of via a mixture of landfill and incineration; recycling not being an option for the company at present. For the extraction process, the following materials are used: sodium hydroxide (NaOH) solution (0.833 kg/kg_{thaumatococcus}); 14% hydrochloric acid (HCl) solution (8.33 kg/kg_{thaumatococcus}); 48 kg filter material per 600 kg arils (approx. 5.3–8 kg/kg_{thaumatococcus} depending on yield in the aril); polyethersulfane filters (approx. 2.78 g/kg_{thaumatococcus}); and 666.67 l/kg_{thaumatococcus} of water. Waste aril material is discarded to landfill, as other options for disposal are not available currently.

The thaumatococcus powder product is packaged in polypropylene bottles for transport. Mass of bottles is 0.10 g/kg_{thaumatococcus}. Disposal of the bottles occurs at the food producer site and is, therefore, out of scope for this LCA.

Finally, 150 kg/year of caustic cleaner and 300 kg/year of bleach (hydrogen peroxide and sodium hypochlorite in equal quantities) are used for cleaning. This equates to 125 g/kg_{thaumatococcus} for each of the cleaning products.

In total 63.8 kWh of electricity is used during extraction and is sourced from the UK National Grid. A total of 44 kWh of natural gas is used specifically for heating steeping water.

There are several waste streams from processing, including 651.19 kg of water sent to a wastewater treatment plant (WWTP). This water is a combination of steeping water and that in the acid or alkali solutions. A further 20 kg of water is lost to the atmosphere from drying. A total of 0.94 kg/kg_{thaumatococcus} HCl is also sent to WWTP; this amount being the remainder of that added after neutralization with NaOH has occurred. No NaOH is emitted, as it is all neutralized by the HCl, meaning 36.53 g sodium chloride is also sent to a WWTP. Finally, 76.9 kg of arils are sent to landfill, as there is other option for waste disposal available.

3.7. Assumptions

The following assumptions were made for the LCA:

1. Biogenic carbon was not accounted for, in line with IPCC recommendations for annual crops (IPCC et al., 2019). Therefore, it is assumed that all carbon absorbed during growth is re-emitted to the atmosphere on timescales shorter than the 100-years of the impact assessment.
2. Processes and infrastructure described are indicative for individual locations in West Africa.
3. Emissions of nitrogen-based compounds from waste fruit were omitted as these are considered the same as if the fruit are not foraged and, instead, decompose on the forest floor. The effect on LCA results of including N-emissions is reported in Section 6.2.

4. Results

Results are presented as a function of production of 1 kg thaumatococcus.

Select impact categories are discussed in detail, namely global warming potential, freshwater eutrophication, land use and water consumption. Full results for all ReCiPe impact categories are given in Table S1 in the supplementary information.

Fig. 2 shows the relative impact of life cycle phases of thaumatin extraction (black), cold storage in UK (red), transport to EU and UK (green), transport within Africa (blue), cutting and freezing of aril (orange), and Td fruit growth and forage (purple, abbreviated to 'forage'). Similarly, Fig. 3 shows the relative importance of each phase as compared to the most impactful phase for each category. The color coding is the same as Fig. 2, and numerical data given in Supplementary Information Table S2.

Global warming potential (GWP) is 719.2 kgCO₂-eq/kg. The main sources of impact are air and refrigerated ground freight transport into the EU and UK (48.6%), aril cutting and freezing (25.4%), and extraction and purification (14.7%). Within transport to EU and UK, the main sources of impact are flights from Douala (20.5%), and Abidjan for arils from Cote D'Ivoire (20.2%) and Ghana (2.9%), and transport from the EU to the UK (4.9%). For freezing and cutting of arils, main impacts are freezing energy from diesel in Cameroon (10.4%), and Ghana (1.5%), and electricity from Cote D'Ivoire (6.6%). Within the extraction phase, main impacts are disposal of waste aril material to landfill (6.6%) and electricity to run equipment (2.8%).

Total water consumption (WC) is 1.55 m³/kg. The main sources of impact are cutting and freezing of arils (35.5%), extraction and purification (36.1%), and transport to the EU and UK (12.3%). For cutting and freezing of arils, the main sources are diesel used for freezing energy in Cameroon (5.2%), and electricity in Cote D'Ivoire (5.8%). Within extraction and purification, water used for steeping the arils is the main contributor (43.7%), as well as polyethylene used for thaumatin packaging (12.9%), but these are largely offset by water returned to the environment via wastewater treatment (-37.4%).

Total freshwater eutrophication (FWEu) is 1.53×10^{-1} kgP-eq/kg. The main source of impact is transport to the EU and UK (32.6%), cutting and freezing of arils (30.7%), and extraction and purification (15.6%). Within cutting and freezing, Cameroon accounts for 19.5%, and Cote D'Ivoire 8.2%. For Cameroon, diesel used in the generators is the main source (8.8%), whereas for Cote D'Ivoire it is manufacture of the aril freezing equipment (3.1%). Within transport to the EU and UK, flights account for most impact (12.8% for arils from Cote D'Ivoire, and 13.0% for arils from Cameroon). Within extraction and purification, it is due to landfill of organic wastes (6.3%).

Total land use (LU) is estimated to be 2.95×10^5 m²acrop-eq/kg. It should be stressed that the results as presented are estimated and assumptions made will be discussed in Section 6.3. The main source of impact is forage, which accounts for 99.99% of total impact (given to 2

decimal places to avoid rounding to 100%). All of this impact is related to the estimated yield of Td fruit per hectare (2000 kg/ha), the mass of Td fruit required per 1 kg purified thaumatin (approx. 1630 kg Td fruit) and the fact that extensive forest is the assumed land use and transformation.

4.1. Scenario analysis

Two scenarios are explored to understand their effects upon calculated environmental impact:

1. Source country for arils.
2. Total energy required to freeze arils.

For the first scenario, key differences between the countries were identified in Sections 3.2 and 3.6. In particular, yield of thaumatin within the Td fruit and fuel sources used for freezing arils is different between locations. Other differences are the transport distances by air freight from Africa to Europe, and the construction of buildings at the aril cutting centers. These factors are explored in the first scenario by assuming the entire supply of arils comes from each of Cameroon, Cote D'Ivoire or Ghana individually (and associated neighboring areas across national borders, as described in Section 2.1).

The second scenario related to the total energy required for freezing arils. It was discussed how there was uncertainty in the quantity of energy consumed in freezing arils (Section 3.2) and the contribution to net environmental impact was reported (Section 4). Therefore, this scenario explores change in net environmental impact of 1 kg thaumatin due to variation in freezing energy from minimum to maximum bounds. Results are compared to the environmental impact of the base case which assumed a freezing energy of 90% the upper limit in each location.

Fig. 4 shows the effect of sourcing all arils from each country individually and data are shown as relative impact to the default case. Supporting data are given in Supplementary Information Table S3. No one country is best or worst for all impact categories, but results indicate that arils sourced from Cameroon tend to carry the most environmental impact: relative change averaged across all impact categories is 1.16. For Cote D'Ivoire and Ghana, the averaged relative changes are 0.86 and 0.89 respectively. For Ghana, a greater yield of thaumatin within the arils compared with Cameroon or Cote D'Ivoire offsets the more polluting source of energy for aril freezing (diesel) compared with Cote D'Ivoire (electricity).

Total energy needed to freeze the arils is not known exactly, and a range was specified in Section 3.2. Effects of taking the minimum and maximum bounds is shown in Fig. 5. Supporting data are given in Supplementary Information Table S4. The results show a skew to

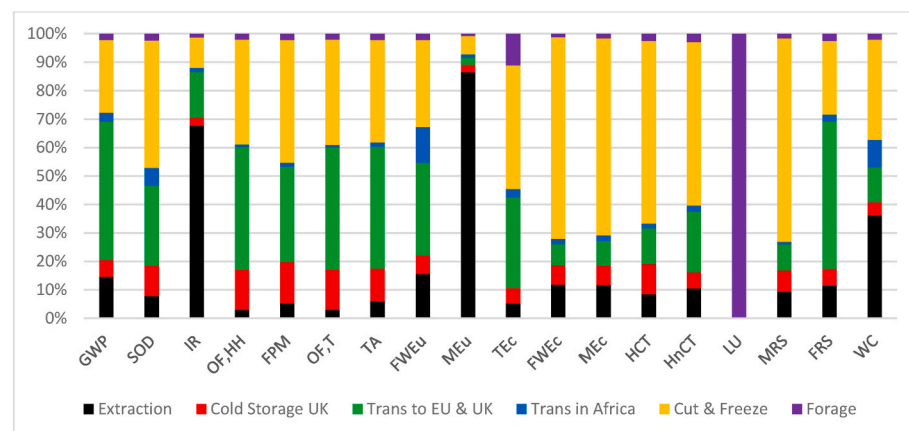


Fig. 2. Relative impacts of each life cycle phase for all ReCiPe 2016 (H) impact categories. Phases shown are thaumatin extraction (black), cold storage in UK (red), transport to EU and UK (green), transport within Africa (blue), cutting and freezing of aril (orange), and Td fruit growth and forage (purple, abbreviated to 'forage'). 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. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

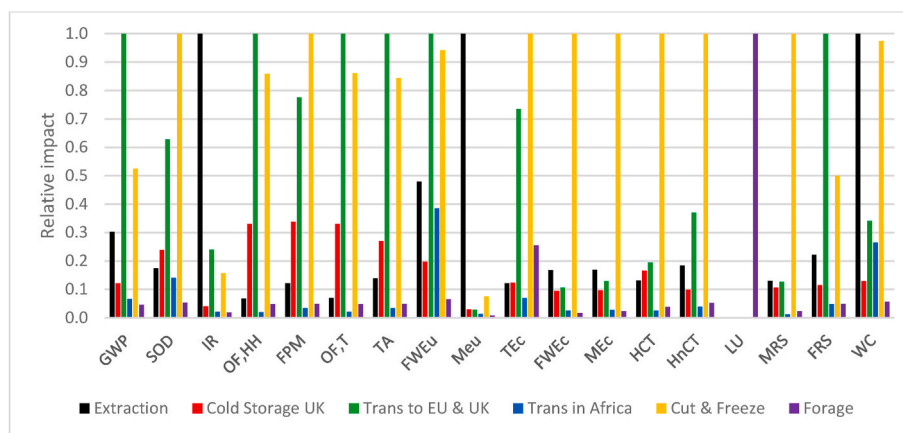


Fig. 3. Impact of each life cycle phase normalized to the most impactful, for all ReCiPe 2016 (H) impact categories. Phases shown are thaumatin extraction (black), field cold storage in UK (red), transport to EU and UK (green), transport within Africa (blue), cutting and freezing of aril (orange), and Td fruit growth and forage (purple). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

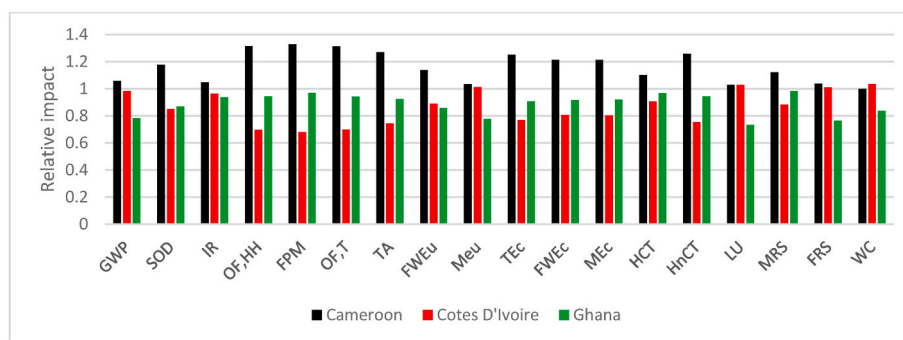


Fig. 4. Change in environmental impact by sourcing all arils from each country individually. Relative impact compared to the default assumed values is shown for Cameroon (black), Cote D'Ivoire (red), and Ghana (green) for each impact category. Default case values for each impact category are equal to 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

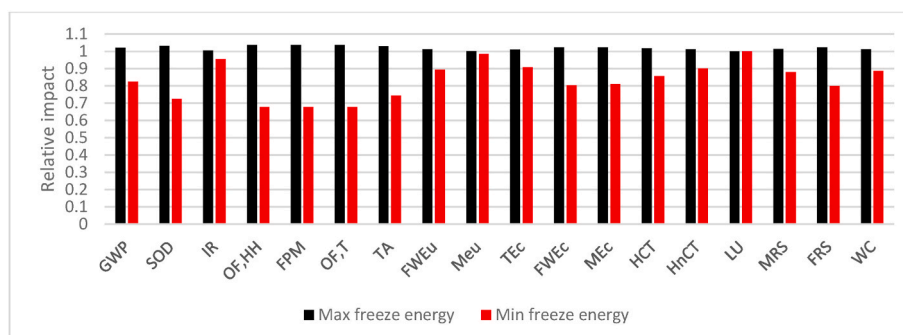


Fig. 5. Change in environmental impact due to variation in energy required to freeze arils. Effect of maximum (black) and minimum (red) bounds shown. Default case values for each impact category are equal to 1. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

reduction in impact because the default assumed freezing energy is 90% of maximum.

5. Sensitivity analysis

Sensitivity analysis is conducted on uncertainty within the life cycle inventory data. Uncertainty in both foreground and background data are modelled using the Monte Carlo method. Results are shown in Table 1. Original impact data are shown alongside the mean of the sensitivity analysis, standard deviation, and relative standard deviation (standard

deviation as a percentage of the mean). Two impact categories have higher sensitivity to uncertainty: water consumption and ionizing radiation. Regarding ionizing radiation, more than half of net impact derives from electricity consumed in the UK, a significant proportion of which is from nuclear power (IEA, 2019). Conducting a sensitivity analysis of background processes for electricity supply in the UK yields a similar relative standard deviation of 136, indicating that uncertainty here is due to background processes and not uncertainty in foreground data. Water consumption sensitivity is due to flows into and out of the life cycle system which are larger than net consumption but act partially

Table 1

Sensitivity of results to uncertainty within the process data. Abbreviations of impact categories as per caption for Fig. 2.

Impact category	Unit	Original	Mean	Standard deviation	Relative standard deviation
GWP	kgCO ₂ -eq	719.21	667.75	57.84	8.66
SOD	kgCFC11-eq	3.39×10^{-4}	2.92×10^{-4}	5.31×10^{-5}	17.76
IR	kBqCo-60-eq	22.19	21.69	24.41	121.76
OF,HH	kgNO _x -eq	3.97	3.43	0.51	14.83
FPM	KgPM2.5-eq	1.06	0.91	0.16	17.89
OF,T	kgNO _x -eq	4.01	3.47	0.51	14.78
TA	kgSO ₂ -q	2.41	2.16	0.27	12.65
FWEu	kgP-eq	0.15	0.15	2.49×10^{-2}	16.96
MEu	kgN-eq	3.77×10^{-2}	3.77×10^{-2}	2.61×10^{-3}	6.92
Tec	kg1,4-DCB	2.76×10^3	2.67×10^3	617.32	23.12
FWEc	kg1,4-DCB	27.64	25.47	7.44	39.20
Mec	kg1,4-DCB	36.04	33.32	9.28	27.84
HCT	kg1,4-DCB	27.49	26.11	9.28	58.52
HnCT	kg1,4-DCB	392.37	378.33	104.10	27.52
LU	m2acrop-eq	2.95×10^5	6.70×10^5	3.07×10^5	45.78
MRS	kg-Cu-eq	2.03	1.95	0.27	13.79
FRS	kg-oil-eq	217.29	199.33	20.80	10.44
WC	m ³	1.55	1.50	263.17	1.76×10^4

to cancel one another out. Small changes in either input or output flows result in large uncertainty in the result, in this case a net flow of water into the environment.

6. Discussion

6.1. Sweetness equivalence

Results presented so far are for production of 1 kg thaumatin. However, thaumatin's main use as a sweetness enhancer means it is used in quantities of 0.5 ppm to replace 200 g of every 1 kg sugar, in effect replacing 500,000-times the mass of sugar. The thaumatin enhances the sweetness of the remaining sugar, to taste as though the full mass were present.

Fig. 6 shows the effect of using 0.4 mg thaumatin mixed with 800 g sugar compared with impact data for 1 kg sugar from ecoinvent 3.8 (black bars) and Agri-footprint 6.1 (red) databases. Sugar data are based

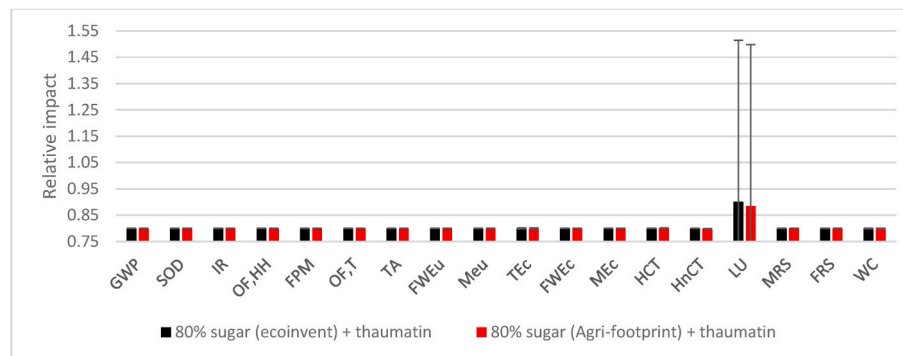


Fig. 6. Relative impact of a mixture of 0.4 mg thaumatin and 800 g sugar to produce equivalent sweetness of 1 kg sugar. Data compared to environmental impact for 1 kg sugar as per the ecoinvent 3.8 (black bars) and Agri-footprint 6.1 (red) databases. Note the vertical axis scale. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

on a global mix of 80% sugar from cane and 20% sugar from beets (ISO, 2020; OECD/FAO, 2021). Standard deviation from the thaumatin sensitivity data is shown by the error bars. Supporting data are given in Supplementary Information, Tables S5 and S6. The impact across all categories is reduced to an average of 80.59% (ecoinvent 3.8) and 80.49% (Agri-footprint 6.1) for 1 kg of sugar. Considering that removing 20% sugar should reduce impact to 80%, this shows how little the thaumatin contributes to the sweetness equivalent mixture (0.59%–0.49%). This shows that using thaumatin to replace sugar partially will significantly reduce environmental impact.

It is worth noting that thaumatin has a sweet taste that is 3000-times that of sugar (Aguilar et al., 2015; Wal et al., 2019). However, thaumatin organoleptic qualities are not like sugar (the onset of sweet taste does not align well with expectation from sugar consumption), and thaumatin is not often used in isolation (interview data). If interpreting the LCA results in terms of sweetening potency only, data for environmental impact of 1 kg thaumatin can be divided by 3000 to arrive at an environmental impact equivalent to the sweetness of 1 kg sugar. More details are given in the Supplementary Information, Table S5.

6.2. Waste disposal of waste Td fruit

Thaumatin is a low yield product comprising approximately 0.06–0.07% the mass of the whole Td fruit. More specifically, production of 1 kg thaumatin requires approximately 1500 kg fruit. What happens to waste fruit is, therefore, important in understanding contribution to net impact. For instance, it is assumed that Td fruit are spread back to land and decompose in the same way as on the forest floor (if not foraged). Therefore, emissions of nitrogen-based compounds are

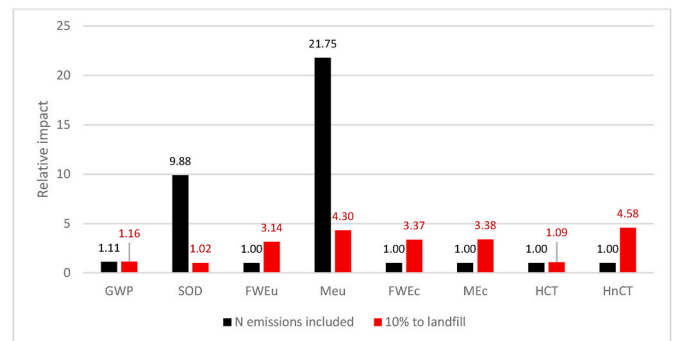


Fig. 7. Change in environmental impact due to disposal method assessment. Effect of including N-emissions from discarded fruit (black) and sending waste fruit to landfill (red) shown. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

omitted from the main LCA impact calculation. Fig. 7 shows the relative change in environmental impact of including N-emissions in the impact calculation (black bars), and, separately, the effect of sending 10% of waste fruit to municipal landfill in Africa (red). Nitrogen emissions are calculated as per crop residues in Blonk et al. (2022), and described in Section 3.2. Impact categories with less than 1% change are omitted from Fig. 7, but full data are given in Supplementary Information, Table S7. GWP increases in both scenarios (11% and 16% respectively), and SOD and MEu show greatest change. However, in context of the comparison to sugar (Fig. 6 and Table S5), such changes are minor.

The results highlight that improved understanding of disposal routes will not only ensure that this part of the life cycle is modelled accurately, but afford better understanding and exploitation of opportunities. For example, fruit waste might be fed to cattle (Elemo et al., 1999. Note: reference focuses on chemical composition of Td and not feeding trials), or anaerobically digested and the biogas used to offset diesel consumption for aril freezing (e.g., Ardolino et al., 2018, but reference not specific to Td). Further research within the locales of waste production would enable both a better understanding of the disposal routes and the opportunities for better use available to each location.

6.3. Land use

The land use impact is highlighted multiple times in this study as a large contributor to environmental impact. However, there is uncertainty in the data, and further investigation is required: it is possible that the impact reported here is greatly overestimated. Three issues underpin the uncertainty, specifically lack of information describing 1) Td fruit yield per unit area of forest, 2) other uses for the land, and 3) type of land transformation taking place.

Regarding point 1), yield is estimated to be 2000 kg fruit per hectare for foraging on fallow land. However, the only known value published is for managed cultivation (2 t/ha to 8 t/ha, Firsov et al. (2018)). A study conducted by the thaumatin producer (discussed in Section 3.1) was for the total tonnage within a given country. That study needed to factor in accessibility to the forest across the region, and not just yield of fruit per unit area. Accessibility included factors such as settlement locations, road conditions, and land topography. As a study, it was not conducted to understand how much land is foraged for a given mass of fruit.

Compounding this is the lack of information regarding other uses for the fallow forest (point 2), e.g., firewood, medicine, or bushmeat (FAO, 2017, 2021). Each of these needs a fair allocation of impact for their respective provisions, which would reduce the land use impact allocated to thaumatin in this study.

Finally, more detail is required for transformation of the land. In this study, cultivated crops and fallow land were assumed to represent extensive forest, i.e., no land use change. However, fallow forest might support more biodiversity than formally cultivated land. If this were the case, it would count in favor of the thaumatin production, again reducing impact.

If thinking in terms of land use alone, maximizing yield of fruit would be attractive. However, it might be advantageous overall to maintain a low yield and minimize intrusion of people into the forest, maximizing potential use of the land for biodiversity and sustainability benefits. All the above are areas for further investigation, and best conducted in the locales of the fruit foraging and aril cutting.

6.4. Scope to upscale thaumatin production

Sourcing Td fruit from fallow land in West African forests offers an opportunity to land spare from sugar production if thaumatin production is upscaled using the same forage methods. For instance, it has been shown that 0.4 mg of thaumatin might replace 200 g of sugar (or 1 kg thaumatin and 500 t sugar). For comparison, the world average annual yield of sugar from beet is approximately 9.1 t/ha [based upon 16% sugar content (Duraisam et al., 2017) and 57.1 t/ha yield beet (Ritchie

et al., 2021)]. Likewise, sugar from cane might have an annual yield of 10.9 t/ha [based upon 15% sugar content (Duraisam et al., 2017) and a yield of 72.6 t/ha (Ritchie et al., 2021)]. It is estimated that the total production of thaumatin from the West Africa region might be 20 t to 25 t of thaumatin, up from the current 1.5 t market size. This estimate is based upon the exercise conducted previously by the thaumatin producer and extrapolates factors such as growth of Td across the region, and accessibility to the fruit. In effect, it indicates that 20 t thaumatin might replace 10 Mt sugar, and hence spare approximately 0.95 Mha land from sugar production. However, further research into potential upscaling is required, as this approach assumes the same foraging practices can be used at all thaumatin market scales. Alternatively, Td can be cultivated formally or intercropped with rubber or palm (Khairani et al., 2020), but a new LCA would need to be conducted to account for impacts associated with these crops (Wilcove and Koh, 2010) and impacts allocated accordingly. Furthermore, the authors are not aware of any literature with appropriate data for use in an LCA of agriculturally produced thaumatin if such a system were to be adopted. Therefore, a formal LCA of such a cultivation-produced thaumatin production process is outside the scope of this study.

6.5. Limitations and Further research

This study explores the environmental impact of producing purified thaumatin from *T. daniellii* fruit foraged in West Africa. The main limitations to the study relate to the lack of detailed information regarding foraging of Td fruit, cutting and freezing of arils in West Africa and waste disposal. Travel restrictions due to COVID-19 prevented access to the locales. Instead, primary data for the LCA were gathered from a case study thaumatin producer, but, variation in production processes across the region is acknowledged. A study conducted in the local regions and focused on the production of Td fruit (as opposed to the other parts of the plant) would improve accuracy of the LCA data and the richness of the study.

The LCA was cradle-to-gate and does not include the use of thaumatin in food and beverage formulations, which was out of scope for this study but is necessary to better understand environmental impacts across the whole life cycle and, in particular, those relating to consumer health. This is another area for future study.

7. Conclusions

The first environmental life cycle assessment of producing purified thaumatin (a sweetness enhancer) from the fruit of *Thaumatococcus daniellii* which grows in West Africa is presented in this study. Fruit is foraged from fallow land as part of a forest agriculture crop rotation. Results show that environmental impact of a combination of thaumatin and sugar is less than the comparable sweetness of sugar alone.

This study presented the cradle-to-gate results for producing thaumatin, but the whole life cycle needs to be explored in future studies to account for potential health benefits associated with reducing added sugar. Thaumatin represents an interesting opportunity for wider sugar replacement due to the foraged nature of the Td fruit. If managed correctly, there are benefits in forest management that would provide extra income to the rural West African population. However, if a shift in production includes formal cultivation practices, a new LCA would be needed to understand this fundamentally different approach. Diversity in sourcing thaumatin from across the West African region represents an interesting opportunity to explore how upscaling of this product might both reduce environmental impact of sugar use in formulations, and, potentially, improve the livelihoods of those living in the region as well as reducing the risks of non-communicable diseases associated with excess sugar consumption.

CRediT authorship contribution statement

J. Suckling: Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **S. Morse:** Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Writing – review & editing. **R. Murphy:** Conceptualization, Funding acquisition, Investigation, Resources, Supervision, Project administration, Writing – review & editing. **S. Astley:** Conceptualization, Funding acquisition, Writing – review & editing. **C. Boy:** Formal analysis, Investigation, Resources, Writing – review & editing. **J.C.G. Halford:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **J.A. Harrold:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **A. Le-Bail:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **E. Koukouna:** Formal analysis, Writing – review & editing. **H. Musinovic:** Writing – review & editing. **A. Raben:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **M. Roe:** Conceptualization, Funding acquisition, Writing – review & editing. **J. Scholten:** Conceptualization, Funding acquisition, Supervision, Project administration, Writing – review & editing. **C. Scott:** Conceptualization, Funding acquisition, Project administration, Writing – review & editing. **C. Westbroek:** Formal analysis, Writing – review & editing.

Declaration of competing interest

The academic authors declare that they have no conflict of interest, except for A. Raben, who has received honoraria from Unilever and the International Sweeteners Association. The industrial authors produce thaumatin. Their contribution to the study was by way of data on the supply chain and production of thaumatin from *T. daniellii* fruit sourced from West Africa.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2023.137226>.

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