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Climate change impact of food distribution: The case of reverse logistics for bread in Sweden

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ABSTRACT

Efficient and purposeful transport of food, from primary production to waste management, is essential to drive the necessary transition towards sustainable production and consumption of food within planetary boundaries. This is particularly the case for bread, one of the most frequently wasted food items in Europe. In Sweden, bread is often sold under a take-back agreement where bakeries are responsible for transportation up to the supermarket shelf and for the collection of unsold products. This provides an opportunity for reverse logistics, but creates a risk of inefficient transport that could reduce the environmental benefits of prevention and valorization of surplus bread. This study assessed the climate change impact of bread transport in Sweden and evaluated the impact of alternative food transport pathways. Life cycle assessment revealed the climate change impact of conventional bread transport, from bakery gate to waste management, to be on average 49.0 g CO_2e per kg bread with 68 % deriving from long-distance transport, 26 % from short-distance delivery, and 6 % from waste transport. Evaluation of alternative bread transport pathways showed the highest climate savings with a collaborative transport approach that also reduced the need for small vehicles and decreased transport distances. The overall contribution of waste transport to the total climate impact of food transport was low for all scenario routes analyzed, suggesting that food waste management facilitating high-value recovery and valorization could be prioritized without increasing the climate impact due to longer transport. It has been claimed that conventional take-back agreements are responsible for most of the climate change impact related to bread transport, but we identified long distances between bakeries and retailers as the main contributor to transport climate impacts.

1. Introduction

Maintaining a stable supply of high-quality food products, without compromising planetary boundaries, is a fundamental cornerstone of sustainable food systems. The current food supply chain often heavily relies on long-distance transport supporting import and export of goods, which requires various means of transportation. Meanwhile, over one-third of the food produced globally is wasted, with recent estimates indicating that 17 % is wasted solely at retail, food service, and household level (UNEP, 2021). This means that considerable amounts of food are produced in vain and also transported unnecessarily. Transport has been shown to account for around 19 % of total greenhouse gas emissions from the food system (Li et al., 2022), so avoiding unnecessary transport could reduce the environmental burden of food and help achieve important sustainability goals. Food waste reduction through prevention, resource recovery and valorization are recognized as critical measures to reduce the climate impact related to food (Bos-Brouwers et al., 2020), but the influence of avoidable food waste transport is rarely considered. There is also a risk that a shift to more circular systems, where food waste is valorized to a larger degree, will require even more transportation. This potential trade-off must be assessed, as whether the benefits of valorization and recovery of surplus food justify the required transportation is still unknown. Thus, in order to achieve sustainable production and consumption of food, the impact of food transport must be quantified.

Bread is one of the most frequently wasted food products in the European Union (EU) (Narisetty et al., 2021), and therefore the environmental impact of the bread supply chain is attracting much scientific attention. In Sweden alone, around 80,000 tons of bread are wasted each year, which correspond to roughly 20 % of total bread produced (Brancoli, 2021). This bread is thus produced and transported without fulfilling its intended purpose: to be sold and consumed as food. Around 90 % of pre-packaged bread distributed in Sweden is sold under a take-back agreement (TBA) which, rooted in the concept of reverse logistics, involves combined delivery and pick-up of bread by the producers. The

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benefits of TBAs are that they allow a clean waste stream and avoid empty backhaul by trucks. However, the prevalent paradigm of delivering as fresh as possible affects the logistics infrastructure and transport distances covered to use shelf space effectively. Moreover, it has been established that take-back practices for surplus food, such as bread, fresh vegetables, and milk, constitute a major risk factor for waste generation at the supplier-retailer interface. When operating under a take-back policy, retailers only pay for the amount sold and producers are required to remove unsold items and refill shelves with fresh produce. For the Swedish bread market, which is dominated by a few large companies with a handful of bakeries with a combined market share of around 86 %, this inevitably requires considerable transportation and logistics to maintain efficiency. Both long- and short-distance transport are required within the Swedish bread system, although the climate burden of this transport is unknown despite the established relation between transport and climate change impact (Kreier, 2022).

To our knowledge, no previous study has performed an in-depth assessment of the transport required to facilitate food waste transport in Sweden. A detailed and comparative assessment of the climate change impact from of transportation on food systems is also lacking. This might be because the agricultural process stages often tend to dominate climate change impact along the supply chain (Notarnicola et al., 2017), and have therefore been the main hotspot for improving the food supply chain. However, this general research gap prevents holistic evaluation of potential benefits and limitations of the food supply chain, especially considering the goal conflicts of food waste reduction and lower transport emissions. The environmental burdens of food transport must be assessed in order to fully achieve sustainable production and consumption of food. Ultimately, this will require identification of potential trade-offs between transportation to facilitate valorization and reduced food waste, on one hand, and high climate impact on the other. The aims of this study were to quantify the climate impact of the TBA system and of alternative bread supply chain scenarios in Sweden, and to identify climate impact hotspots and opportunities to make the bread supply chain more environmentally sustainable.

2. Literature review

Due to its short supply chain lead time, perishability and limited shelf-life, bread has high potential for waste generation (Ghosh and Eriksson, 2019; Ciccullo et al., 2022). Additional factors contributing to bread waste generation at the supplier-retailer interface are quality standards, cost pressure, and consumer demand for variety and freshness (Brancoli et al., 2019; van Herpen and Jaegers, 2022). Overfilling of shelves to attract customers and removal of items from shelves before their expiration date are other identified drivers of waste (Rosenlund et al., 2020; Goryńska-Goldmann et al., 2021; Riesenegger and Hübner, 2022). A few studies have touched upon the supplier-retailer interface of bread in Sweden (Eriksson et al., 2017; Brancoli et al., 2019; Bergström et al., 2020), although without exploring possible re-organization options for alternative pathways.

The food system requires transportation to enable recycling, valorization, and food waste management, especially for food products distributed under reverse logistics agreements and TBAs (Eriksson et al., 2017). Food distributed under such agreements offers unique potential for recovery and valorization of clean waste flows, since it is not mixed with other organic waste. Clean waste flows in turn can enable use of higher valorization or prevention methods, such as food donations (Sundin et al., 2022) or animal feed production instead of anaerobic digestion or incineration commonly used for mixed food waste (Johansson, 2021; UNEP, 2021). Despite these potential benefits, take-back clauses have previously been identified as a potential hotspot for food waste generation (Cicatiello et al., 2017; Rosenlund et al., 2020; Goryńska-Goldmann et al., 2021). In particular, overproduction (with increased returns as a consequence), pre-store waste and excess stock due to lack of supplier-retailer communication, combined with inefficient forecasting and long transport, are known risk factors (Priefer et al., 2016; Bergström et al., 2020). Research on the Swedish bread supply chain has primarily focused on the power relations within the TBA system and bread waste treatment options, but assessments quantifying the transport impact on climate change are increasingly demanded (Kreier, 2022; Li et al., 2022; Pradhan, 2022). When evaluating the bread return process for commercial plant bakeries in South Africa, Muzivi and Sunmola (2021) found similar areas for improvements, in relation to reverse logistics, as for the Swedish bread supply chain. Some of the identified improvement areas were waste generation arising from current return policies, alongside oversight regarding management returns and fresh bread. Bottani et al. (2019) evaluated multiple reverse logistics scenarios for food waste management in Italy, and concluded that there are also important trade-offs to consider between impacts on the environment and the most economically profitable solutions. However, the climate change impact related to logistics and transport inherent to food distributed under TBAs in Sweden, particularly relating to possible re-organization of food distribution in a non-TBA system, has not yet been determined.

The European Commission (2019) has recognized return policies as a possible point to reduce food waste, while the latest IPCC report (2020) highlighted that reducing food wastage also is a key lever in combating climate change. Food waste reduction is further addressed in United Nations Sustainable Development Goal (SDG) 12 (Sustainable consumption and production), which explicitly identifies the need to halve global food waste per capita at the retail and consumer levels. A study on retail waste management by Mondello et al. (2017) suggested that the transport network organization can also affect the environmental performance of waste management options. Reducing food waste can also improve the energy and resource-efficiency of food systems (Garnett, 2011), lower greenhouse gas emissions along the supply chain (Wunder et al., 2020), reduce the pressure on natural resources, and help to meet increasing demand (FAO, 2019). Efficient food transport can thus also contribute positively to SDG 13 (Climate action) and the climate goal to reduce greenhouse gas emissions within the transport sector by 60 % (compared with 1990) by 2050. A more sustainable transport sector will therefore play an important part in achieving the Paris Agreement (United Nations, 2020), especially considering that transport-related greenhouse gas emissions are projected to increase substantially in the coming years (Liimatainen et al., 2014a). This is especially important given that the transport sector still relies to 65 % on petroleum products (Swedish Energy Agency, 2021) and is responsible for about one-third of Sweden's emissions, of which 90 % derive from road transport (Xylia and Olsson, 2021). Road transport is one of the three largest sources of greenhouse gas emissions in the EU, causing around 72 % of total domestic and international transport emissions (EEA, 2021; IEA, 2021; Aminzadegan et al., 2022). The main factors influencing transport emissions are vehicle type and size, fuel type and consumption, traffic conditions, vehicle load and fuel efficiency, empty trips, and factors such as refrigeration (Liimatainen et al., 2014b; Liang et al., 2016; Stelwagen et al., 2021). With improved infrastructure, fossil free means of transportation and efficient logistic, future transport pathways could facilitate reduced emissions of greenhouse gases on one hand, and reduce food waste by allowing more high-value valorization on the other.

While prevention and valorization of food waste have been shown to reduce the environmental burden of the food supply chain (Brancoli et al., 2020; Despoudi et al., 2021; Do et al., 2021), the environmental impact of transportation required for these measures is often omitted or assessed using a constant value (Notarnicola et al., 2017; Magalhães et al., 2021). Compared with other food chain stages, such as primary production and waste management, the influence from transport is often assumed to have a small contribution to greenhouse gas emissions (Wakeland et al., 2012). However, the dependency on fossil fuels and the frequency of food transport can add considerably to the climate change impact. When considering the entire upstream food supply chain, Li et al. (2022) showed that 19 % of total climate emissions from the food system originate from transport. This corresponds to around 3.0 $GtCO_2e$ per year, a considerably higher value than previously estimated (Pradhan, 2022). When assessing the impact of valorization of surplus bread in Sweden, Brancoli et al. (2020) recognized the inadequacy of using a constant value to account for food transport impact. In later work, Brancoli (2021) emphasized the need for research on this issue. When examining the distribution of food products in Sweden, Tidåker et al. (2021) found a high climate impact from transport, especially for food produced and packaged far from their final destination. When assessing the environmental benefits of reusing bread waste as animal feedstock, Castellani et al. (2017) highlighted collection and redistribution of waste as one of the most critical challenges needed to be overcome. In previous life cycle assessments (LCA) on bread conducted outside the scope of Sweden, transport was not identified as an impact hotspot, contributing to only 5 % of the carbon footprint for bread in a study by Espinoza-Orias et al. (2011). Jensen and Arlbjørn (2014) compared the results of several LCAs and found that transport made up between 2.4 % and 35.4 % of estimated life cycle emissions from bread, excluding waste management and consumption. When applying a constant value for long distance transport and local distribution of food items, Notarnicola et al. (2017) found that around 10 % of the total climate change impact originated from the logistics.

Efficient, low-emissions transport is also a key aspect of sustainable production and consumption of food (Cohen et al., 2021), especially considering the current high dependence on fossil fuels to power logistics in all stages of the food supply chain (Meyer, 2020; Kreier, 2022). A pioneering study by Menna et al. (2019) found that transport of surplus food from generation to waste treatment considerably contributed to the overall climate impact in multiple European countries. They further concluded that efficient transport involving shorter distances, alternative modes of transport with high utility rates, and fossil-free vehicles, is one of the most important factors to maximize the environmental benefits of surplus food valorization. Stelwagen et al. (2021) further concluded that the environmental impact of the last mile in urban food systems (i.e., due to consumer choices) can be considerable, but has been overlooked in most previous studies. A similar conclusion was reached by Croci et al. (2021), who emphasized the benefits of replacing fossil fuels with renewable alternatives in transport vehicles. The importance of addressing the future need for transport and infrastructure, rather than primarily relying on the estimates and demands of today, was also raised by Metson et al. (2022) when addressing the logistical requirements for future food recycling. At present, only a few data on the transport required for Swedish bread have been made public, with somewhat conflicting information stating that bread transport in Sweden is either short (Brödinstitutet, 2016; Sitell, 2020) or that both long- and short-distance transport are required (Polarbröd, 2020). The general order of magnitude for bread transport in Sweden can be exemplified by the distance between bakery and retail. For bread baked in

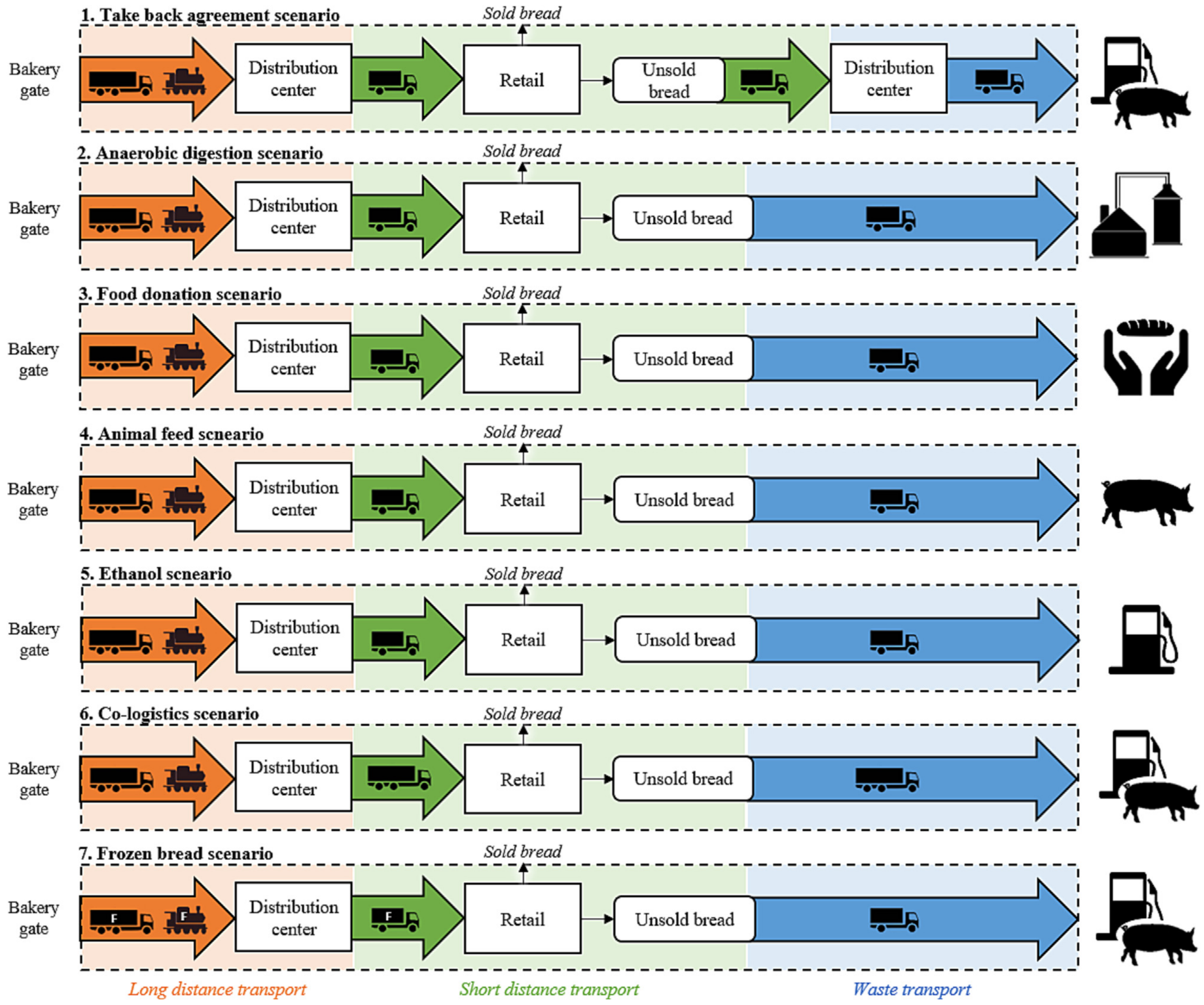

Fig. 1. Illustration of transport requirements in the Swedish bread supply chain, from bakery gate to waste treatment facility, for the current take-back agreement system and for the six alternative systems. The dashed line represents the system boundary.

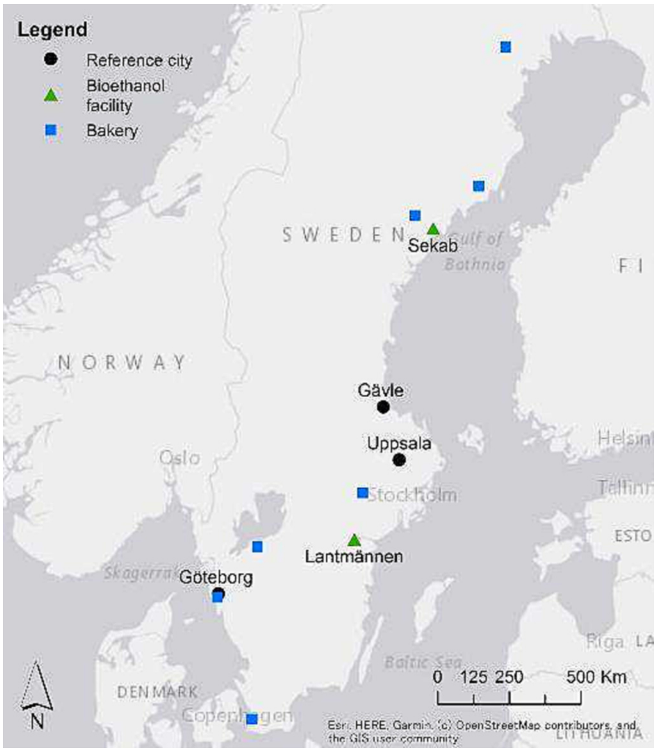

Fig. 2. Map showing important locations in the bread supply chain and surplus bread transport in Sweden.

southern Sweden (Malmö) and sold in the northernmost supermarket in Sweden (ICA Nära Riksgränsen, 2022), the required transport distance is 1973 km for the quickest freight route. Although most bread is transported between more densely populated areas (southern and central) in Sweden, this example shows that long-distance transportation is needed. Given the established connection between climate change impact and supply chain logistics, the importance of adequately accounting for the environmental impact of food transport in Sweden is evident. The outcome of this study therefore aim to fill this research gap, by modeling and assessing multiple transport pathways for bread. By identifying key hotspots for impact, this study further aims to evaluate potential trade-offs between climate change impact driven by transport and food waste management.

3. Material and method

3.1. Goal and scope

A systematic life cycle assessment following the ISO (2006a, 2006b) standards was used to quantify and identify the climate change impact of bread waste transport. The functional unit (FU) of 1 kg bread leaving the bakery gate was selected to capture the main function of the system, with the system boundary including all transport necessary from the bakery gate to delivery at the waste management facility. The return trip, when applicable, was accounted for in the waste transport stage. All bread was assumed to be edible when discarded at the retail level, as assumed by Ghosh and Eriksson (2019). Additional energy use and emissions related to construction, maintenance, and disposal of infrastructure were excluded from the analysis. Primary data were obtained from an ongoing internal data collection drive via e-mail conversations and semi-structured interviews with retailers, bakeries, and other relevant industry stakeholders. These data were combined with data from publicly available company information and reports, documents of public authorities, and scientific articles. Data on electricity and vehicles were used from Ecoinvent 3.8 and DEFRA (2021).

3.2. Description of scenarios

The current TBA system for bread in Sweden was assessed as a base scenario, to which alternative transport pathways were applied to enable the evaluation of six alternative scenarios based on either TBA or non-TBA systems (Fig. 1).

The three largest bakery companies producing pre-packaged bread in Sweden were included in the analysis, as approximately 90 % of the pre-packaged bread sold in Sweden is sold under TBA (Eriksson et al., 2017) and the three largest companies together account for 85 % of the market share (Brancoli, 2021). A route from each bakery to each of three selected reference cities (Uppsala, Gävle, Gothenburg) was modeled (Fig. 2) and emissions calculated with regard to their market share. An average emissions result for each bakery was then determined and the values for all bakeries were combined. A default route for local delivery to retail was modeled based on available data and information. The waste transport was calculated for each scenario assuming an optimal transport route based on the shortest distance, available infrastructure, or company-specific information. In all scenarios, a return rate of 7.7 % at the retail level was assumed, representing the average return rate for bread in Sweden (Brancoli, 2021). The distance of transport routes required from the bakery gate, via distribution hubs and retail, to the waste treatment facility, was quantified and mapped for the Swedish bread supply system, and the value was used as input to design a transportation model. A total of seven scenarios were modeled (Table 1), to assess the impact of transport on bread waste management for the three Swedish reference cities.

The first two scenarios were designed to on one hand capture the conventional TBA system for bread in Sweden with bread waste directed to either bioethanol or animal feed, and on the other hand to capture a conceptual scenario in which bread is delivered without a TBA. Without the TBA in place it can be assumed that more bread waste will be treated via anaerobic digestion, as is done for the majority of food waste in Sweden (Johansson, 2021). Transport distances and vehicles used to model these scenarios are presented in Table 2. Calculations

Table 1
Summary of the seven scenarios assessed, with specific characterizations and modeled waste treatment practice. U = Uppsala, Gä = Gävle, Go = Gothenburg, TBA = take-back agreement.

No	Scenario name	TBA	Key characteristics	Waste treatment
1	Take back agreement	Yes	Conventional system, representing the current transport and logistics used for pre-packaged bread in Sweden.	Ethanol (U) Animal feed (Gä/Go)
2	Anaerobic digestion	No	Conceptual scenario in which retailers handle surplus bread, using different waste transport distance compared with scenario 1.	Anaerobic digestion
3	Food donation	Yes	Same as scenario 1, but using different waste transport distance.	Donation
4	Animal feed	Yes	Same as scenario 1, but using different waste transport distance.	Animal feed
5	Ethanol	Yes	Same as scenario 1, but using different waste transport distance for Gävle and Gothenburg.	Ethanol
6	Co-logistics	Yes	Same as scenario 1, with larger vehicle size representing an integrated logistics system.	Ethanol (U) Animal feed (Gä / Go)
7	Frozen bread	Yes	Same as scenario 1, but with all bread delivered frozen, requiring freezer vehicles for all transport except waste transport.	Ethanol (U) Animal feed (Gä / Go)

Table 2
Transport distances and vehicles assumed for the conventional take-back agreement system (scenario 1) and a conceptual Anaerobic digestion system (scenario 2), expressed per 1 kg bread leaving the bakery gate.

1: Take back agreement scenario	Long distance (km)	Short distance (km)	Waste transport (km)
Uppsala	Train (180.1 km) Freight (341.1 km) Train$_{\text{Frozen}}$ (132.0 km) Freight$_{\text{Frozen}}$ (2.5 km)	Truck (25.6 km)	Truck (225 km)
Gothenburg	Train (214.0 km) Freight (77.0 km) Train$_{\text{Frozen}}$ (216.0 km) Freight$_{\text{Frozen}}$ (3.0 km)	Truck (31 km)	Truck (133.5 + 26 km)
Gävle	Train (137.0 km) Freight (341 km) Train$_{\text{Frozen}}$ (112 km) Freight$_{\text{Frozen}}$ (2 km)	Truck (18 km)	Truck (418.8 + 55 km)
2: Anaerobic digestion scenario	Long distance (km)	Short distance (km)	Waste transport (km)
Uppsala	Train (180.1 km) Freight (341.1 km) Train$_{\text{Frozen}}$ (132 km) Freight$_{\text{Frozen}}$ (2.5 km)	Truck (25.6 km)	Truck (4.3 km)
Gothenburg	Train (214 km) Freight (77 km) Train$_{\text{Frozen}}$ (216 km) Freight$_{\text{Frozen}}$ (3 km)	Truck (31 km)	Truck (13.5 km)
Gävle	Train (137 km) Freight (341 km) Train$_{\text{Frozen}}$ (112 km) Freight$_{\text{Frozen}}$ (2 km)	Truck (18 km)	Truck (20.2 km)

of all transport stages, including a detailed version for long-distance delivery, are provided in *Supplementary Material*.

Other scenarios were designed to account for other common food waste management strategies applied for surplus bread in Sweden, namely food donation, reuse as animal feed, and ethanol production (Johansson, 2021). These are in line with the priority levels suggested by the food waste hierarchy (Papargyropoulou et al., 2014). Moreover, a collaborative logistics (co-logistics) scenario was developed to simulate an integration of a multiple-actor approach to bread waste treatment (Liang et al., 2016). Long-distance and short-distance transport were assumed to be the same as for the TBA scenario, with changes to waste transport in the alternative scenarios shown in Table 3.

The final scenario considered the option of delivering all bread in frozen form (Table 4), as a way to adapt and adjust shelf volumes by storing bread frozen (van Herpen and Jaegers, 2022). In theory, this could also be an option for a non-TBA scenario, and could reduce bread waste generation at retail.

3.3. Sensitivity analysis

To increase the robustness of the results, several sensitivity analyses were performed (Table 5). Transport distances in all three transport stages considered (long, short, waste) were identified as influential parameters in this study and were therefore adjusted in several separate analyses. For the short-distance (delivery to retail) stage, the distance was adjusted to facilitate detailed analysis of the influence of short-distance on the final results. A similar sensitivity was tested for the waste transport stage in the anaerobic digestion scenario, allowing for closer analysis of the limitations of local waste treatment. For both mentioned sensitivity analyses an increase and decrease in distance was assumed to 20 % and 50 %, which aimed to capture the influence of local transport variations and delivery to more rural areas in Sweden. The waste transport distance for the donation scenario was increased to 25 km, to test whether its benefit is lost in the case of limited local availability for bread donations. To adjust long-distance delivery transport distance, it was assumed that all bread is baked centralized, taking Eskilstuna as a reference point. This allowed to test the influence of the long-distance delivery stage, by simulating baking closer to the consumer. Bread return rate, i.e., bread waste rate, was also identified as an influential parameter as it affects the weight of bread transported per functional unit. The sensitivity to changes in this parameter was assessed by increasing the waste rate to 10 % and decreasing it to 2 %, to simulate the highest and lowest waste rates previously reported (Brancoli, 2021). Moreover, the presence of a threshold transport distance beyond which the animal feed scenario outperformed the anaerobic digestion scenario was evaluated.

Table 4
Transport distance and vehicles needed for frozen bread transport (scenario 7), expressed per 1 kg bread.

7: Frozen bread scenario	Long distance (km)	Short distance (km)	Waste transport (km)
Uppsala	Train$_{\text{Frozen}}$ (312.5 km) Freight$_{\text{Frozen}}$ (343.6 km)	Freezer truck (25.6 km)	Truck (225 km)
Gothenburg	Train$_{\text{Frozen}}$ (430 km) Freight$_{\text{Frozen}}$ (80 km)	Freezer truck (31 km)	Truck (133.5 + 26 km)
Gävle	Train$_{\text{Frozen}}$ (249 km) Freight$_{\text{Frozen}}$ (344 km)	Freezer truck (18 km)	Truck (418.8 + 55 km)

4. Results

The conventional take-back agreement transport system for bread in Sweden was found to emit on average 49.0 gCO_2e per kg bread leaving the bakery gate, of which 68 % occurred during long-distance transport, 26 % during short-distance delivery, and only 6 % during waste transport (Fig. 3). In all scenarios assessed, Uppsala was found to have a higher climate impact than the other reference cities, with a net difference of 14 g CO_2e per kg bread compared with Gothenburg, with city with the lowest climate impact. The lowest emissions in all three cities were found for the co-logistics scenario, which gave an average reduction of 13 % for Uppsala, 10 % for Gävle, and 16 % for Gothenburg.

For all three cities assessed, the food donation scenario gave on average a 7 % emissions reduction compared with the current TBA transport pathways, while the animal feed and ethanol scenarios showed negligible reduction potential. Directly comparing the TBA and anaerobic digestion scenario revealed on average 5 % lower climate impact when considering all cities, but with higher climate impact mitigation potential for Gävle and Uppsala than for Gothenburg. The frozen bread

Table 3
Transport distance and vehicles used in the alternative transport scenarios for bread waste (scenarios 3–6), expressed per 1 kg bread.

	3: Food donation scenario Waste transport (km)	4: Animal feed scenario Waste transport (km)	5: Ethanol scenario Waste transport (km)	6: Co-logistics scenario Waste transport (km)
Uppsala	Truck (6.2 km)	Truck (413.9 + 9 km)	Truck (225 km)	Truck (6.2 km)
Gothenburg	Truck (3.9 km)	Truck (133.5 + 26 km)	Truck (319 km)	Truck (3.9 km)
Gävle	Truck (3.3 km)	Truck (418.8 + 55 km)	Truck (330 km)	Truck (3.3 km)

Table 5
Sensitivity tests performed, showing parameter values changed for the respective scenarios (1–7).

No.	Scenario	Parameter changed	Value of parameter change
1–7	All	Short-distance	Distance changed ±20 % and ± 50 %
2	Anaerobic digestion	Waste transport	Distance changed ±20 % and ± 50 %
3	Food donation	Waste transport	Increased distance to 25 km
1–7	All	Bread waste rate	Decreased to 2 % and increased to 10 %
1–7	All	Long-distance	Bakery location changed, centralized in Eskilstuna

scenario was found to give the highest emissions of all scenarios, 40 % higher than average. The conventional TBA, animal feed and ethanol scenarios had considerably lower emissions than the frozen bread scenario and performed similarly in the case of Uppsala and Gävle, but gave notably lower emissions for Gothenburg.

4.1. Sensitivity results

Changing the default bakery location to Eskilstuna lowered the average long-distance delivery emissions per scenario by 17 % (Fig. 4). For Uppsala the climate impact was reduced by more than half and for Gävle it was reduced by almost 40 %, while for Gothenburg the climate impact increased by 40 % (see *Supplementary Material*). Since a bakery was located in Gothenburg in the baseline scenario, changing location to Eskilstuna was not beneficial. Long-distance delivery proved to be the most sensitive stage in all sensitivity analyses, which is logical considering the large fraction of total emissions caused by long-distance transport. However, the Eskilstuna baking location gave a similar ranking of the scenarios in terms of emissions reduction potential (co-logistics, food donation, anaerobic digestion, animal feed, conventional TBA system, ethanol, frozen bread).

Emissions in the waste transport stage were found to increase or decrease proportionally with the change in waste rate, with a 1.7 % increase in emissions for 10 % waste rate and a 6 % decrease for 2 % waste rate. On adjusting the transport distance in the waste transport stage of the donation scenario to 25 km, the climate impact of this stage increased by 3 % on average, making the donation scenario third lowest in terms of climate impact (changing position with the anaerobic digestion scenario in the order of results). Adjustments to the local delivery distance caused smaller changes in climate impact, e.g., a 20 % distance increase led to a 5 % emissions increase and a 50 % distance increase caused a 14 % emissions increase, while a 20 % and 50 % distance decrease led to a 5 % and 14 % emissions decrease, respectively. This is primarily attributable to the fact that this stage only made up a small proportion of total emissions. The ranking of scenarios and cities remained the same, so despite the medium strong sensitivity of this transport stage, changes in distance did not affect the favorability of the scenarios. Despite the different transport pathways simulated, the non-TBA anaerobic digestion scenario always outperformed the animal feed scenario. Therefore, the threshold value was 0 km, for all assessed cities.

Adjustments in the distance for local delivery in the anaerobic digestion scenario had a negligible and under-proportional effect on the total sum of emissions. An increase/decrease of 20 % led to less than 1 % change in emissions, while for an increase/decrease of 50 % the change was only ~1 %. This indicates that the results were not very sensitive to changes in this part of the transport system, for the anaerobic digestion treatment option, but once again this must be viewed in light of the low contribution to total emissions of this transport stage. These results must be considered within the context of waste treatment and emission savings potential, which was outside the system boundary of this study.

5. Discussion

One important outcome of this study was the quantification of potential climate change impacts from transportation of food waste, using pathways within the Swedish bread supply chain as a realistic example. Previous studies on bread waste and bread waste management in Sweden have not assessed the logistics system and distribution alternatives of its supply chain in detail, so the novel findings in this study improve knowledge of the actual climate impact and relevant hotspots in future logistics options for the bread supply chain. Although exemplified specifically for the bread supply chain, the results illustrate the

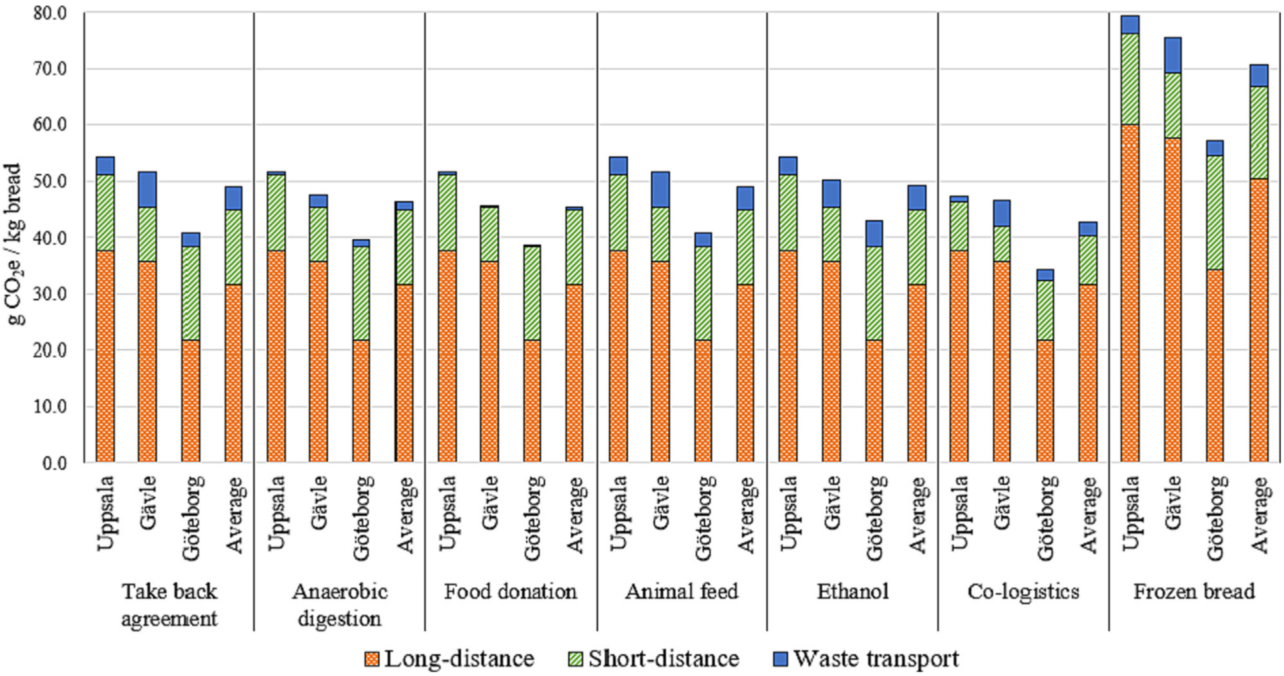

Fig. 3. Climate impact results for all scenarios and reference cities. The contribution of each process to total impact is indicated.

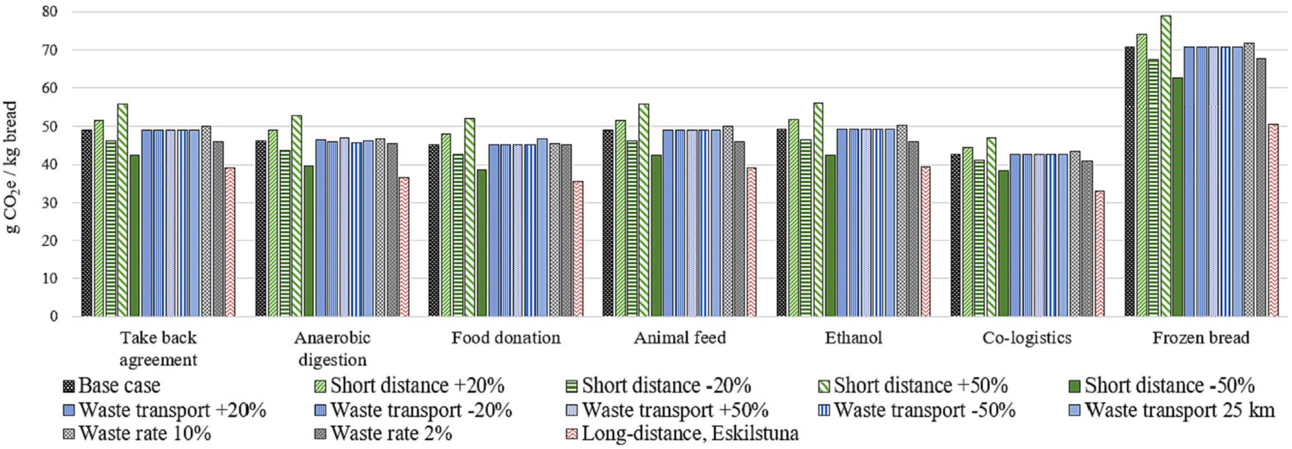

Fig. 4. Climate change impact results for the average Swedish city, with respect to all assessed sensitivity analyses. The magnitude of impact from each scenario is indicated to enable comparison between the different sensitivity results.

importance of adequately accounting for waste transport, especially long-distance transport, within the food system.

5.1. Environmental impact of bread waste transport

The primary climate impact hotspot within bread waste transport was found to be long-distance transport, generating 68 % of total transport emissions, which is in line with previous findings (Tidåker et al., 2021). However, it is important to note that the modeled transport system in this study assumed a constant share of long-distance transport in all scenarios. Part of the long-distance delivery in this study (long-distance transport below 350 km) was assumed to be fully via truck, thus offering future emissions reduction potential through increased rail freight. Liang et al. (2016) found that multi-modal approaches including rail transport can improve transport energy efficiency. However, to make this feasible, cost-benefit and time aspects must also be assessed, to determine whether they might outweigh environmental benefits.

Comparing each city, it was evident that hosting a bakery (in this study Gothenburg) gave the lowest climate impact (Fig. 3). This suggests a benefit in producing close to the consumer. In the calculations, hosting a bakery avoided a full route that would otherwise increase the average distance. It is important to note that this study excluded raw material sourcing and a considerable associated transportation effort, which could lead to different conclusions. Furthermore, trade-offs across value chain stages are possible. Sensitivity testing showed that the climate impact could be reduced by 17 % by reducing long-distance transport distance. Thus, an argument can be made for moving large-scale bread production closer to more densely populated regions, in order to reduce transport emissions and thereby also lower the total climate impact of the food supply chain. When evaluating future development strategies for low-emissions transport of food, this fact should be considered.

Local delivery to retail also had a high climate impact (Fig. 3), which can be explained by the location of redistribution centers quite far outside the assessed cities. As voiced by Stelwagen et al. (2021), this underlines the importance of the last mile covered in delivering goods which commonly involves smaller trucks with higher emissions per kg load, as reported previously. Moreover, sensitivity analysis evaluating increased transport distance for delivery to retail showed an under-proportional increase in emissions, and therefore short distance transport was found not to be sensitive to assumptions made in this study. This stage could benefit from electrification of vehicles, which could reduce air pollution, traffic congestion, noise, and accident risks, although electric vehicles still lack sufficient range to transport heavy goods over considerable distances (Liimatainen et al., 2014a, 2014b).

Average transport emissions were found to be 49 g CO_2e per functional unit, which is broadly in line with findings in previous LCA studies on bread supply of 70 g CO_2e (Jensen and Arlbjørn, 2014) and on the transport stages in bread supply of 29 g CO_2e (Espinoza-Orias et al., 2011). The difference in results could be due to several reasons. For example, Jensen and Arlbjørn (2014) assumed a distance of 175 km from depot to retail, much higher than the 18–31 km assumed in this study, likely increasing the emissions as this transport stage typically involves use of small vehicles, and Espinoza-Orias et al. (2011) assumed a distance of 50 km from bakery to retail, which is much lower than the distance modeled here. In general, the results in this study can be considered to support previous findings as they are within the same order of magnitude and highlight similar climate impact hotspots. A study by Angervall (2011) found transport to be, on average, the second highest contributor to the climate impact of industrialized baked bread in Sweden. They considered the whole life cycle, showing that the carbon footprint of bread was around 700 gCO_2e per kg of bread. Combined with average climate impact of transport assessed in this study, this translates to roughly 7 % impact origin from transport. This is in line with previous findings (Espinoza-Orias et al., 2011; Jensen and Arlbjørn, 2014). The findings from Angervall (2011) on climate change impact from transport indicates a wide variation (~40 to ~300 gCO_2e per kg bread). This variation could be explained by the fact that did not use average values based on market share, as done in this study. Instead they performed calculations separately for four bakeries located at different sites throughout Sweden and using different transport systems (e.g. with or without freezer units and/or using only trucks or using both trucks and trains for the long-distance transports). Their analysis also included inbound transport of raw and packaged materials to the bakeries, which was outside the system boundaries of the present study, and they did not explicitly describe how waste transport was accounted for.

The climate impact from waste transport was found to account for on average only 6 % of the total transport required. On the one hand this low number is connected to the small amount of bread transported, amounting to only ~0.079 kg, on the other hand this percentage is notably an average value which takes into account both larger distances, for instance to ethanol production or in the case of the TBA, but also short waste transport distances of around 5 km. Nevertheless, waste transport was still highly dependent on the waste treatment pathway. The climate impact of transport to waste treatment facility was found to be lowest for the food donation scenario (1 % of total impact) and highest for the ethanol scenario (8 % of total impact). The anaerobic digestion scenario performed slightly better than the scenarios involving changes to the conventional TBA transport system for bread, but did not reduce the climate impact considerably. This again indicates that the conventional TBA system itself might not be the primary cause of transport-related impact, but rather the transport and waste treatment options used and their locations. In transport for the food donation scenario and the anaerobic digestion scenario, a benefit of local waste treatment was found. Compared with the ethanol scenario, where the waste was assumed to be transported farther away from cities, the local transport alternatives performed on average 7 % better in terms of emissions per kg bread (Fig. 3), regardless of whether smaller or larger vehicles were used. This indicates a clear benefit of short-distance waste transport, but the advantages of short-distance waste transport were also affected by the location of the waste treatment plant, as shown by the slightly higher emissions for anaerobic digestion waste transport in Gävle. This should be taken under consideration when assessing different waste treatment options in more rural areas.

Overall, the waste transport stage was strongly limited by the current TBA, but was not identified as a primary impact hotspot. However, the difference in emissions from the waste transport stage between the TBA scenario and non-TBA scenario was on average 66 % for all three cities assessed, indicating an important leverage point for future improvements towards more sustainable transport of food. In the TBA scenario, waste transport resulted in the second largest emissions of all scenarios. This underlines the disadvantage of transporting bread back to the bakery, even when using a large vehicle, for a treatment option that is likely available locally. Interestingly, the frequently recommended option of using the clean stream of TBA bread for ethanol production (Hirschnitz-Garbers and Gosens, 2015; Brancoli et al., 2020), to achieve considerable emissions reductions while obtaining an economic return for the waste, had a less positive ranking in this study, giving the second highest transport emissions (Fig. 3). Thus it can be questioned whether its benefits might be outweighed by the transport emissions. Many of these transport emissions are connected to the current limited infrastructure for ethanol production, with only two bioethanol plants currently operating in Sweden. This indicates a need for further plants, but also shows the benefit of local waste treatment. The results for the ethanol scenario make it clear why some bakeries decide to direct bread from the Uppsala and Stockholm regions to ethanol production, but bakeries in other parts of Sweden choose not to do so. Overall, the results show that transport network organization can affect the environmental performance of waste management and that distance is particularly critical for ethanol production, which is in line with previous findings (Mondello et al., 2017; Brancoli, 2021).

5.2. Limitations and scenario analysis

Although offering a clean waste flow for surplus bread, which in turn allows for valorization and prevention according to higher prioritization levels, the current TBA system for bread limits additional climate savings by not allowing incorporation of alternative transport pathways such as co-logistics. The results obtained in this study indicated the following preferred ranking of the fresh bread scenarios, from lowest to highest climate impact per kg bread: co-logistics, food donation, anaerobic digestion, animal feed, conventional TBA system, and ethanol. However, indirect effects of the TBA system on the long-distance delivery stage are possible and it could be speculated that delivery frequency would increase with a non-TBA system, with more frequent deliveries of smaller volumes to maintain the standard of freshness and a wide product range on supermarket shelves, without requiring removal of older bread. Higher delivery frequency with smaller volumes could result in greater usage of smaller trucks, thus increasing emissions. Incorporating weekly or monthly delivery volumes into the model in future analyses would enable assessment of delivery frequency and bread removal and refill rates in different bread supply chain scenarios. This would allow for an in-depth investigation of the effect of the TBA system on long-distance transport and possible rebound effects. An assessment of the impact of prospective solutions, such as the non-TBA scenarios in this study, is always associated with limitations, as LCA cannot account for the influence of future developments. The differences between a TBA and non-TBA system, particularly at the delivery stages, can be evaluated for different vehicle load utilization rates, depending on whether unsold bread is picked up during the delivery trip or not. However, the change in load was minimal in the present model, and the datasets used did not allow modeling of small percentage changes in load.

Delivery to retail made a relatively small contribution to total impact, but emissions in this transport stage are primarily connected to the use of small vehicles and can further increase due to urban traffic conditions, a factor not accounted for in this study. Importantly, future assessments should take both urban and rural areas into account, which will likely result in higher climate impact for the latter, as more transport efforts are needed to maintain a stable distribution of bread. Additionally, this study assumed conventional diesel fuel use in transport, a simplification that could cause overestimation of climate impact values since use of biodiesel in Sweden has increased to roughly 20 % of the total energy use within the transport sector. Therefore, use of alternative fuels such as biodiesel and electricity should be accounted for in future studies. Notably, the relative benefit of biofuels over fossil diesel decreases when taking its impact on land-use change into account. In this study, including a single impact category allowed for a detailed investigation of the different scenarios, but could also have increased the risk of burden-shifting, as stressed by Jensen and Arlbjørn (2014). This underlines that greenhouse gas emissions alone are not a reliable indicator of the environmental impact of transportation. Thus, future research would benefit from employing an even more holistic approach, by assessing the food transport impact including multiple impact categories such as smog, land use, or acidification potential.

The assumptions made regarding bread waste rates affected the transported mass and thereby transport emissions, but also revealed the most feasible waste treatment option. The return rate modeled in this study influenced the amount of waste requiring transportation to waste management and the amount of bread that needed to be transported in order to have 1 kg available at retail. In the non-TBA scenario, this might have caused less waste, and consequently less bread would need to be transport to maintain the same amount of bread on retail shelves, but this was not considered in modeling because of the functional unit chosen. Moreover, although LCA is an established research method for environmental impact assessment, the results must be viewed with caution as they primarily provide an indication of environmental impact, and not an exact prediction of total impact (Klöpffer and Grahl, 2014). In this study we primarily used secondary data, average transport distances, and median dataset values to model bread supply chain transport, which may have influenced the reliability of the results. Additional simplifications were also necessary, such as only accounting for the three largest bakeries based on their market share in Sweden. Moreover, some methodological choices might have influenced the results, e.g., the same operations were assumed in all scenarios. A focus on modeling the differences in waste transport as a less static factor compared with the bakery locations was considered reasonable.

Even though bread donations also provide a social benefit and in theory can be recovered locally, the amount of bread wasted currently exceeds the amounts accepted by donation organizations. If the future demand for donated bread in Sweden is low (Ungerth, 2021), the surplus would need to be sent to either anaerobic digestion or incineration. Similarly, the animal feed scenario has geographical limitations since the majority of animal feed production, and animal farms, are located in southern Sweden. Therefore, considerable amounts of surplus bread generated at bakeries or retailers would have to be transported over long distances if reuse in animal feed were the sole waste treatment option. Our results (Fig. 3) suggest that a more favorable approach would be to combine different solutions, e.g., directing waste bread to animal feed would be more beneficial for bakeries located in southern Sweden, while other treatment options should be considered in areas further north. Moreover, in the scenario for animal feed considered here there was only one change (waste transport distance) compared with the conventional TBA scenario, while bread waste from all bakeries was assumed to be sent to pig farms in both cases. For the case of Uppsala this resulted in a similar climate impact as for the ethanol scenario, as that city is relatively close to an ethanol production plant (Fig. 2), i.e., there was no extra benefit from directing the bread waste to animal farms instead of ethanol production. The co-logistics scenario demonstrated the climate benefit of using larger and fewer vehicles, with average emissions reduced by up to 40 % for short distance and waste transport compared with the TBA system. The environmental benefit of collaborative logistics, which also results in efficiency improvements, has been highlighted in previous studies (Eriksson et al., 2017; Bergström et al., 2020; Croci et al., 2021). However, considering the current market share of the three largest bread suppliers in Sweden (86 %), a further increase in logistics cooperation might not be entirely realistic, especially considering its limited acceptability by industry stakeholders and the feasibility of integrating complex logistics operations with established logistics chains. Innovations of a collaborative nature must also consider a company's priorities, as optimizing cost, time, and sustainability of transport could come with trade-offs. The large climate benefit achieved with this scenario also points to improvement potential for the long-distance delivery stage, but it is more static due to the fixed position of bakeries, so integration would likely be more difficult and would require strong joint commitment of all players. Choosing the option to freeze bread after baking and defrost it on the way to the retail store could reduce food waste at retail level and also enable more high-value recovery, as bread quality could be maintained for longer. However, the impact of vehicles with a freezer unit should not be under-estimated, as a 60 % increase in climate impact was obtained for long-distance transport of frozen bread compared with the current TBA system. The results also indicated that the increasing transport distance from the bakery, frozen transport becomes worse from a climate impact perspective. This highlights the potential for trade-offs between economic and environmental aspects, since the environmental benefits from valorization pathways might outperform the environmental impacts of longer transportation to a certain degree. Similarly, although transportation of raw materials was outside the scope of this study, moving the bakeries to Eskilstuna would probably increase the need for transport of raw materials while reducing the transport of baked bread. This could also be a relevant trade-off to consider, and would benefit from being further assessed in future studies. It should also be noted that conclusions and recommendations regarding bakery location must consider variations in electricity prices depending on location, as these would influence profit margins, production aspects, and other possible trade-offs in supply chain organization, transport impacts, and food wastage. However, this sensitivity analysis allowed evaluation of the potential future impact related transport and infrastructure. As emphasized by Metson et al. (2022), this is an important aspect when addressing the logistical requirements of future food systems.

5.3. Future outlook

Transport is a necessary step in the value chain of almost all food products, so any comprehensive evaluation of the climate impact of bread wastage must address transport emissions. Excluding previously identified climate impact hotspots for bread, namely production of raw materials, processing, consumption stages, and the waste treatment itself, often offering considerable emission savings potential, the present study allowed for in-depth evaluation of the transport contribution to climate impact. Using all food produced at its highest value possible, and with optimal transportation, is especially important to maintain the potential benefits of recovering resources via valorization. Modifications to bread transport in Sweden could facilitate more high-value recovery pathways than in current practice. The high contribution of long-distance delivery in terms of total emissions raises questions about whether the polarized debate on the TBA system is reasonable and whether food transport chains need general reform to acknowledge the importance of local food production and, from a consumer perspective, choosing food according to local seasonality. As voiced by Bartek et al. (2022) multiple simultaneously adapted solutions are needed to drive the necessary transition towards sustainable food systems. Nevertheless, the results in this study indicate that long- and short distance deliveries, together or separately, have the highest potential for adjustments in their logistics to reduce climate impact. This result can be used in practical implications when designing transport pathways or when promoting valorization of surplus food, which in turn further can drive the transition towards lower transport emissions. Moreover, the results show that waste transport has the lowest climate impact of all transport stages, regardless of the route required for each waste treatment option. This indicates that waste management according to the higher waste priority levels can likely be prioritized without jeopardizing the climate benefits of high-value food waste recovery. These results can be used to support holistic assessment of food systems and can serve as a foundation for company development to maintain future efficiency, sustainability, and profitability.

6. Conclusions

This study showed that the current transport pathway for bread in Sweden has great potential to contribute to increased environmental sustainability within the food supply chain. An important finding was that the TBA system per se is not the primary cause of transport-related impacts, but rather the distance between bakeries, consumers, and waste treatment facilities. Compared with the conventional TBA system, alternative transport pathways such as co-logistics and valorization via food donations, were found to reduce the climate change impact by up to 13 % per kg pre-packed bread leaving the bakery gate. Long-distance transport was identified as a key climate impact hotspot, while waste transport represented an important leverage point to exploit the considerable benefit of producing close to consumers. Waste transport made the lowest contribution to the transport impact of bread, indicating that high-value waste management, including prevention and valorization, could be prioritized without being compromised by the alternative transport routes. This study thereby provided an important insight to the potential trade-offs between environmental impacts driven by transport and food management. Practical implementation of alternative food transport pathways will require acceptance by companies and consumers, along with feasible infrastructure.

Declaration of competing interest

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

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Appendix A. Supplementary data

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