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The power of prevention and valorisation – Environmental impacts of reducing surplus and waste of bakery products at retail

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A R T I C L E I N F O

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A B S T R A C T

The wastage of edible food still remains a major global challenge, despite its well-known consequences. Although bread and bakery products are identified as some of the most frequently wasted foods, the amounts generated and the pathways used to manage this surplus are often unknown. To support sustainable food systems, there is an urgent need to identify how much surplus is generated along the supply chain, including both sweet and savoury products, and to map how this resource is managed. The aim of this study was to quantify the surplus and waste of baked goods in Sweden, alongside mapping the pathways used for managing unsold bread generated at the supplier-retailer interface. Life cycle assessment, considering 16 midpoint indicators and three endpoint indicator, was used to assess the environmental benefits of reducing bakery product surplus. The results reveal that nearly 180 000 tonnes of baked goods are wasted annually in Sweden. Roughly 51% is generated at the supplier-retailer interface, particularly considering bread sold under take-back agreements where 14% of production becomes surplus. Only 2% of this surplus is recirculated to the food system, while the majority is instead used in energy production. Scenario analyses, including nine scenarios designed to capture various innovations to reduce surplus, demonstrated that prevention and valorisation strategies, such as data sharing and price reductions, have the greatest potential for reducing waste and environmental impact. Prevention could result in up to ten times lower climate impact per kg bread. The findings offer valuable insights for future research on sustainable food systems, and can act as practical guidance for industry actors, stakeholders, and policymakers to implement waste-reduction strategies that promote sustainable, resource-efficient food systems.

1. Introduction

An imbalance between production and consumption of food, inevitably leading to surplus, has been identified as a common cause of waste generation at retail level. Despite the known risks attributed to food waste, global wastage of edible food is a major challenge at all stages of the supply chain. Bread is one of the most frequently wasted food products in many parts of the world (Brancoli et al., 2019; Dymchenko et al., 2023; WRAP, 2023), resulting in considerable global issues with environmental, economic, and social consequences (United Nations Environment Programme, 2024). Generation of bread waste is often linked to production of *surplus bread*, i.e., retail bread that remains unsold and is removed from shelves while still perfectly suitable for human consumption. This food resource could in fact be recovered using circular management pathways, such as *prevention* or *valorisation*. Prevention involves measures that reduce generation of food waste at source, while valorisation involves measures to recover or reuse the resource in, for example, new products, animal feed or energy production. These two approaches are usually ranked according to the food waste hierarchy (Papargyropoulou et al., 2014), indicating the priority of action for policy and action against food waste (Giordano et al., 2020).

The benefits of circular food systems have been thoroughly demonstrated in supporting sustainable use of resources and reduce stress on

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planetary boundaries (Rockström et al., 2020; van Zanten et al., 2023). The bread supply chain in Sweden exhibits a degree of circularity, particularly through the implementation of *take-back agreements* (TBA). These agreements operate in a reverse supply chain, holding the supplier financially responsible for unsold products, including collection and disposal (Brancoli et al., 2019). Surplus bread is an abundant, inexpensive and under-utilised resource that could be avoided or recovered via valorisation pathways. However, while TBA can be viewed as a step toward circularity by allowing valorisation of unsold products, this model has also been identified as a risk factor in generating high volumes of bread waste (Eriksson et al., 2017). In Sweden alone, previous research suggests that around 80 000 tonnes of bread are wasted along the supply chain (Brancoli et al., 2020). Wasting surplus bread represents a considerable economic loss for producers, retailers and consumers, but also has a devastating environmental impact through e.g. increased global warming, biodiversity loss, and depletion of natural resources (Crenna et al., 2019; Bergström et al., 2020). Moreover, previous waste quantifications on the Swedish bread system have mainly focused on savoury products, while surpluses of sweet products produced and distributed in parallel have not yet been accounted for. Although prevention and valorisation have attracted increasing scientific and commercial attention in recent years, a substantial research gap still remains regarding the efficacy of different pathways compared with current practice, especially considering resources circulated back to the food system.

The aim of this study was to map the volume of surplus bakery goods generated at the supplier-retailer interface in Sweden and to identify the pathways currently used for managing surplus bread. Using *life cycle assessment* (LCA), the environmental aspect of current and future management of surplus bakery goods was then assessed. The potential benefits of multiple innovations, either within or as a consequence of changes to the current business model, were modeled in scenarios using savoury bread sold under TBA in Sweden as the base case. The goal of this work was to evaluate the outcomes of different prevention and valorisation pathways, in order to support companies in the bakery sector and policymakers in choosing the best-performing options for management of surplus bread.

2. Literature review

The annual wastage of food at retail in high-income countries is estimated to amount to 13 kg per capita, with Swedish retail wasting 9 kg per capita. This translates to roughly 89 000 tonnes at retail, of which 15-30% is estimated to consist of surplus bread (Brancoli et al., 2019; Swedish Environmental Protection Agency, 2024). At retail level, high on-shelf availability and providing a broad selection of products are often prioritised with respect to bread, both due to strong competition and to ensure customer satisfaction (Ghosh and Eriksson, 2019; Riesenegger and Hübner, 2022). However, this have been found to increase overstocking, leading to economic pressures and logistical challenges with unsold products (Cicatiello et al., 2020). Many retailers acknowledge that they are faced with a trade-off situation between providing high availability of products and the environmental, social, and financial burdens related to unsold products. Although on-farm losses and household food waste generally comprise greater quantities, retailers and suppliers have a unique influence on both upstream and downstream food waste generation (Mena et al., 2011).

The generation of surplus bread and bakery products at the supplier-retailer interface has been quantified in several previous studies, though often using different methods, countries of origin, comparison bases, or system boundaries (Goryńska-Goldmann, 2022; Soni et al., 2022). In previous studies in Sweden, Brancoli et al. (2019) combined primary data from 380 stores and a major bakery with national statistics and literature findings to quantify bread waste, while Hildersten et al. (2025) used a qualitative interview approach in collaboration with an industry partner to map their production of pre-packaged rye bread sold under TBA. In their study quantifying surplus bread in Italian small-scale bakeries, Pietrangeli et al. (2023) used a combination of direct measures of surplus bread through daily diaries and calculated values for economic losses at the bakery level. Using individual in-depth interviews with industry experts, Goryńska-Goldmann et al. (2021b) collected qualitative data on average losses for the baking and confectionery industry in Poland, while Riesenegger and Hübner (2022) sourced data for their qualitative study on reducing food waste at retail in Germany by conducting face-to-face interviews with managers of seven case companies.

Various incentives to reduce retail food waste have also been researched, with results highlighting great potential if these actions can be directly influenced by companies and suppliers. Sharing data between retailers and suppliers can allow for more efficient ordering and forecasting (de Moraes et al., 2020), which, in turn, can reduce overproduction and surplus at retail (Canali et al., 2017). Insufficient cooperation and coordination among actors in the supply chain have also been identified as relevant risk factors for bread waste (Cicatiello et al., 2020). Dynamic pricing, which allows retailers to reduce prices depending on external factors such as best-before date or imperfect products, can considerably reduce bread waste generated at retail (Sanders, 2024). In an explorative study on reducing food waste in Germany, Riesenegger and Hübner (2022) showed how better planning of retail operations, such as optimal management of shelving and reduced assortment size, could reduce surpluses. Goryńska-Goldmann et al. (2021a) recommended multiple valorisation pathways for surplus bakery products, including reduced prices, food donations, and animal feed. In a review assessing the effectiveness of the food waste hierarchy in increasing resource use efficiency, Redlingshöfer et al. (2020) concluded that when stakeholders dependent on sales are also responsible for waste management, reuse and recycling methods are often prioritised over prevention. This is likely due to the cost-effectiveness of these methods in relation to potential loss of sales. On the other hand, many benefits of waste reduction have been highlighted (CEC, 2019), including cost savings for stakeholders, reduced environmental impacts, improved food security, and promotion of a circular economy by adding value to resources.

Previous research suggests that TBA can be a risk factor for surplus generation at retail (Muzivi and Sunmola, 2021), and that this practice may reduce the power and incentives of retailers to develop and implement waste-reducing actions (Eriksson et al., 2017). Similar conclusions were reached in later studies by Brancoli et al. (2019) and Ghosh and Eriksson (2019). However, one of the benefits of TBA is the separate collection of surplus bread, which can be directed toward more high-value valorisation than is possible with mixed waste streams. Identifying how and under what conditions future pathways can contribute to reduced bread waste, with or without TBA in place, is therefore of high scientific relevance. According to Economou et al. (2024), monitoring tools, including LCA, are indispensable for mapping surplus hotspots and tracking the impact of waste-reducing actions. Using LCA, Brancoli et al. (2020) showed that prevention of surplus bread yields the highest environmental benefits, followed by reuse as food, either directly or following conversion, while feed and energy production are less favourable. In later work, Brancoli (2021) concluded that the current return systems for surplus bread in Sweden could serve as a foundation for further sustainability development, e.g., by implementing alternative reuse pathways according to the higher priority levels in the food waste hierarchy. However, current valorisation pathways for food waste, including surplus bread, tend to be directed toward energy production rather than human consumption (Johansson, 2021). These solutions align with the lower-priority levels for managing food waste (Papargyropoulou et al., 2014), such as anaerobic digestion, conversion into biofuels, and incineration. One important benefit with these solutions is their high technological readiness, which facilitates quick implementation.

On evaluating the life cycle of surplus food generated in French retail, Albizzati et al. (2019) concluded that the sector should prioritise redistribution through donations and conversion to animal feed over anaerobic digestion and incineration, due to the environmental benefits and economic gains. This was reiterated by Svanes et al. (2019), who further emphasized the environmental benefits of prevention related to management of surplus bread. Assessing the impact of bread logistics, Weber et al. (2023) found that the long transport distance between suppliers and retailers in Sweden is the main climate hotspot, more so than TBAs as a business model. Many studies have demonstrated the potential to utilize bakery surplus in food production, including food donations (Sundin et al., 2023) and upcycling into breadcrumbs (Samray et al., 2019), fungal food products (Brancoli et al., 2021) or beer (Coelho et al., 2024). Jung et al. (2022) used bread as a feedstock in algae cultivation, while Siddique et al. (2024) mapped the life cycle impact of multiple pathways for valorisation into animal feed. Although previous research has demonstrated the benefits of bread valorisation, Corsini et al. (2023) emphasized the lack of research evaluating the success factors influencing prevention actions at the retail level. A similar conclusion was also presented by Kumar et al. (2023), who pointed out that current literature accounting for environmental impacts of valorisation pathways for bread is very limited. Furthermore, research with a lifecycle perspective of the entire bread supply chain, including baking, distribution, retail, and management of surplus products, is urgently required to identify how, and under what conditions, different prevention and valorisation pathways should be used. Siddique et al. (2024) suggested that a broad selection of impact categories should be included in LCA studies, along with the benefit of any avoided emissions due to prevention or valorisation. Despite the acknowledged limitations of ecosystem coverage in LCA, Crenna et al. (2019) showed the importance of also accounting for ecosystem impact in future food system research. Goryńska-Goldmann (2022) further concluded that there is an urgent need for joint actions by suppliers and retailers to mitigate waste generation, preferably through prevention and high-value valorisation.

3. Material and method

3.1. Mapping of Swedish bakery products

To distinguish the different main types of bread and baked products sold in Sweden, the definitions used by the Swedish Board of Agriculture (2022) were applied in this study. Bread, as a product, was considered to be the baked result of a simple dough containing flour (wheat and rye), water, salt and rising agent. Similar ingredients, but in different quantities, are often used to produce sweet products, with the addition of sugar. Two main categories of soft bread are sold at Swedish retail: *pre-packed* soft bread products, which are produced by bakeries and transported to retail where they are sold in plastic bags; and *non-packaged* or *bake-off* products that are delivered as industrially produced doughs or semi-baked products, which are baked after delivery, and sold individually at retail or convenience stores. One of the major differences between these products is the distribution system, where a large proportion of pre-packed products, but not bake-off products, are distributed under TBA. Within the sub-category of pre-packaged goods, retailers also produce their own *private label products* or import from other countries, which are distributed without TBA. Furthermore, the pre-packed category includes sweet and savoury baked goods that have been exposed to air or heat to become hardened, such as crispbread and cookies. The convenience market in Sweden is dominated by a handful of companies, some operated by retail companies primarily selling private label products. Only about 2% of the bread market in Sweden consists of home baking (Iakovlieva, 2021).

3.2. Quantification of the Swedish bakery supply chain

Two rounds of *stakeholder dialogues* (Sjölund et al., 2022; Mesiranta et al., 2023) were conducted with five industry actors operating within the Swedish TBA system, including two industrial bakeries, retailers, and logistic companies. The information shared enabled identification of current challenges and future potential within the bread supply chain, findings which were later used to quantify the surplus of bakery products sold under TBA and to develop scenarios representing a shift to alternative surplus pathways. Data disclosed by industry actors on surplus bakery products generated at bakery and retail level were aggregated, and the extrapolation variable used was market share based on sold products per year. The quantification of private-label bakery products included the same five major retailers as used in national statistics (Statistics Sweden, 2022) and values were extrapolated based on market share. Information on waste rates, sales, and annual production of private-label and bake-off bakery products was sourced via correspondence with bakeries and private actors, and supported with national data.

Through the stakeholder dialogues, along with literature, previous research, public company reports, and data shared via correspondence with industry actors and charity organizations, the volumes of surplus arising at the supplier-retailer interface were quantified. Alongside, the amount of surplus bread sold under TBA following different pathways was mapped. Loss rate records for bread and bakery products, monthly point-of-sale data, and surplus management data disclosed via correspondence with industry actors were used in waste quantification in this study. Additional data were collected from public reports (Polarbröd, 2020; Pågen, 2020; Fazer, 2022), previous research (Brancoli, 2021; Sjölund et al., 2023; Hildersten et al., 2025), and national statistics (Swedish Board of Agriculture, 2022). Based on annual consumption data, and accounting for waste occurring at different stages of the supply chain, *material flow analysis* (MFA) was used to map the level of production needed to support Swedish bakery goods consumption. Additional information on quantities is available via *Supplementary material* (Tables S1-S3). A second round of stakeholder dialogues was then conducted with relevant industry actors to verify the quantification and adjust the scenarios using their input.

Prevention pathways were defined in this study as measures that involve direct source reduction, while valorisation pathways were divided into high-value and low-value categories. High-value valorisation comprises measures for food redistribution, ultimately allowing surplus to be circulated back to the food system, such as food donations or price reductions. Low-value valorisation includes measures that repurpose the resource into other products, such as animal feed or ethanol used as fuel. Anaerobic digestion and incineration were considered in this study as pathways directed toward energy recovery.

3.3. Scenario development

The most promising pathways for reducing surplus and lowering environmental impacts that emerged during the stakeholder dialogues were used to formulate a total of nine tangible scenarios for bread management. The conventional *Base case* scenario was modeled to capture the current bread management pathways in Sweden. The results from the mapping of bakery supply chain in Sweden were used as input to design the pathways for surplus and waste in this scenario. Six alternative pathways were modeled as conceptual scenarios to simulate the impact of improvements applied either within the current system or without TBA in place, while the final two scenarios were developed to simulate optimal management. Fig. 1 presents an overview of all developed scenarios. To enable scenario analysis for each innovation separately, all scenarios were deliberately designed with minimal changes in parameters at a time.

The first scenario was identified through the stakeholder dialogues as an innovation applicable within the current TBA system that could reduce surplus bread, namely sharing data. In the absence of previous research on data-sharing specifically related to bread supplied under TBA, the reduction potential at retail and bakeries was calculated using

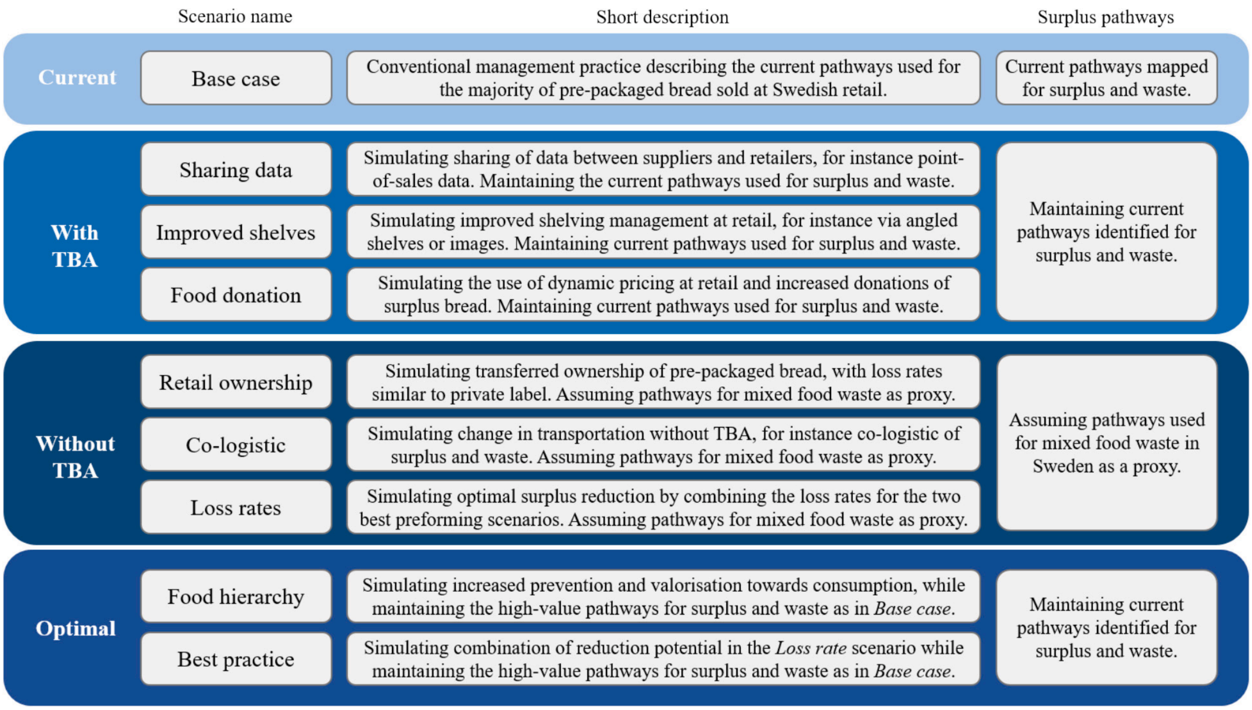

Fig. 1. Graphical illustration of the developed scenarios, specifying scenario name, short description, and surplus pathways. Included is the current management practice, six conceptual scenarios applied either within the current system or without a take-back agreement (TBA) in place, alongside two scenarios simulating optimal management.

data for milk. Nikolicic et al. (2021) found that 38% and 29% of waste was avoided for suppliers and retailers, respectively, when the TBA system was removed. These reduction factors were applied in the *Sharing data* scenario. Moreover, sub-optimal management of shelving together with a large product assortment was another risk factor for surplus bread generation at retail identified through the stakeholder dialogues. Previous studies have shown that by using angled shelves and images of bread, the feeling of abundance desired by consumers can be maintained while less bread needs to be placed on the shelves. A 50% reduction in surplus bread can be achieved at retail when incorporating images of bread in shelving units (Alm, 2021), while a 10-15% surplus can be avoided when using angled shelves (Easyfill, 2019). An average 31% reduction in the surplus generated at retail formed the modeling basis for the *Improved shelves* scenario. The final innovation applied within the TBA system was increased donations, since pre-packaged bread has a high potential to be redirected toward human consumption. Decentralised food donations were suggested as a pathway during the stakeholder dialogues, and the Swedish charity Sveriges stadsmissioner (2023) recently reported a 67% increase in demand for donated and price-reduced food. This scenario assumed that dynamic pricing could reduce surplus at retail by 21% (Sanders, 2024), favouring valorisation via food donations. The *Food donations* scenario assumed that all bread available via dynamic pricing was redirected toward human consumption via price reductions and donations.

A previously identified limitation of the TBA system is the low incentive for retailers to actively work toward reducing bread waste generated at their stores, since this bread is currently owned by the bakeries. If retailers were to take ownership of bread distributed under TBA, it is reasonable to assume that the loss rate would be similar to that of private-label bread already owned by retailers. A *Retail ownership* scenario was designed to simulate this shift, for which an average loss rate of 4.5% was calculated using data supplied by industry actors on waste rates for private-label bread. Waste transport distances required when removing TBA were used according to Weber et al. (2023) and the majority of the surplus was assumed to be directed toward anaerobic digestion and incineration (Johansson, 2021), since the lack of separate collection of bread would block pathways toward animal feed and ethanol production. The same surplus pathways, but applying the co-logistics distances suggested by Weber et al. (2023), were assumed in a *Co-logistics* scenario, which was requested by stakeholders and developed to simulate more streamlined transportation of bread as a way to reduce its climate impact. An optimal *Loss rate* scenario was developed to simulate the benefits of joint innovations at both bakery and retail level, by combining the loss rates used in *Sharing data* and *Retail ownership* scenario.

The final two scenarios were developed to simulate a theoretical optimal surplus management of bread, where the benefits of separate waste collection enabled via TBA are maintained but favouring more high-value pathways. A *Food hierarchy* scenario simulated the benefits of keeping TBA, but directing the surplus to human consumption via food donations and price reductions to a higher extent. A *Best practice* scenario also assumed that the TBA system was maintained, but applying the lowest waste rates at bakery and retail level. This scenario thus captured the benefits of reducing surplus while retaining the high-value pathways toward animal feed and ethanol production, which are otherwise often limited for mixed food waste.

3.4. Life cycle assessment

The environmental impacts of shifting from the conventional *Base case* scenario for surplus bread in Sweden to a conceptual scenario with or without TBA in place, was assessed using life cycle assessment following the ISO standards (ISO, 2006). A functional unit of *1 kg bread* sold to consumer at retail was selected to capture the scope of the study, following a cradle-to-gate approach. The system boundary accounted for inputs and outputs from ingredients, up to and including retail, alongside inputs needed for managing surplus following different pathways (Fig. 2). The software SimaPro 9.2 was used to model the scenarios, with datasets from Ecoinvent 3.8 and Agri-footprint 4.0. Although a shift from current to future scenarios is often described using consequential datasets, this study used cut-off datasets to ensure compatibility between the databases, since Agri-footprint implements Ecoinvent cut-off

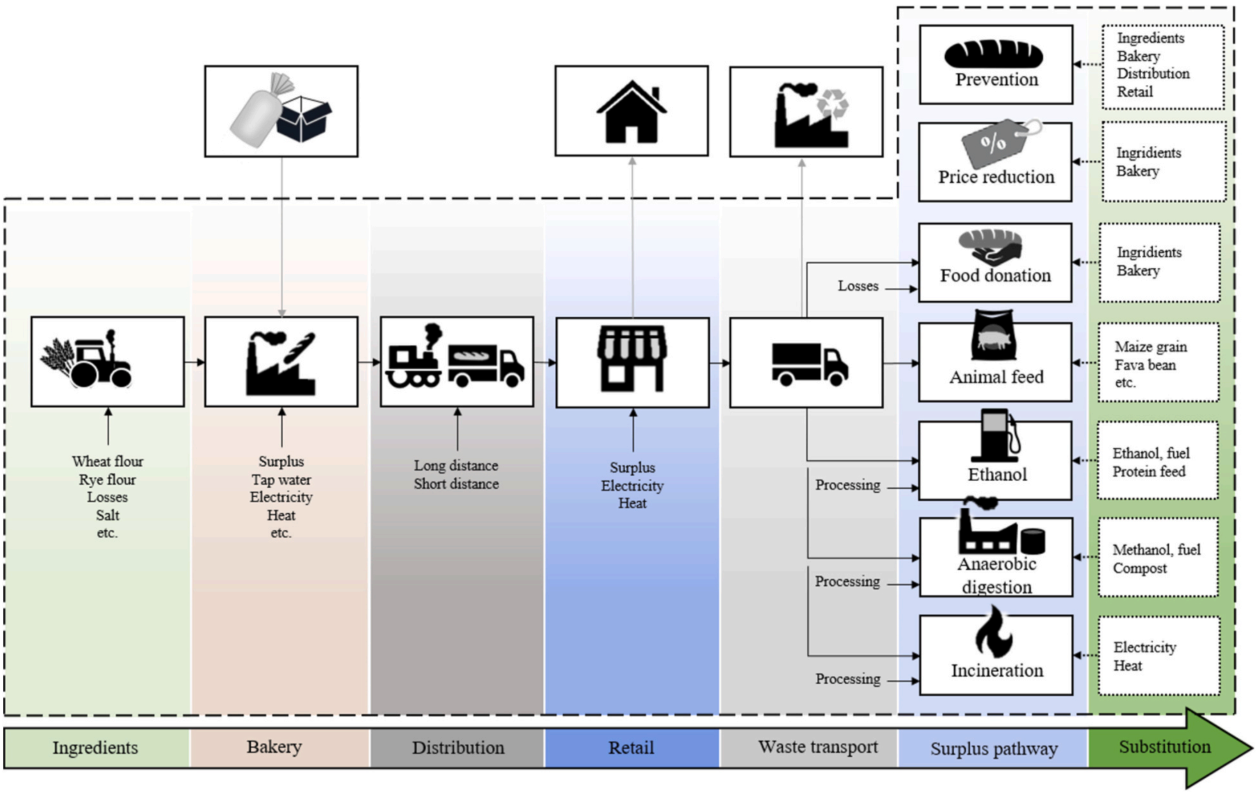

Fig. 2. Illustration of the modeled bread system in Sweden, indicating inputs and outputs accounted for along the value chain. The dashed line represents the system boundary, while the dotted line show the substitution included via system expansion. Outside the system boundary are production and recycling of packaging, alongside consumption and management of bread at households.

datasets for energy and fuel as background data (Blonk et al., 2022). Substitution via system expansion was used to account for avoided impact due to prevention and valorisation pathways for surplus bread. The impact of shifting from one scenario to another was calculated as the net difference between the two scenarios. The method Product Environmental Footprint (PEF) was used to assess environmental impact for 16 midpoint indicators, while the ReCiPe Endpoint (H) method was used to aggregate impact at midpoint to obtain a weighted result for three endpoint indicators. Supporting modeling inputs are available in Supplementary material (Tables S4-S12).

4. Results

4.1. Quantification of surplus bakery products

Based on the latest estimates of average consumption of baked goods (74.5 kg per person per year), annual consumption of bakery products in Sweden amounts to roughly 784 800 tonnes. Of this, industry-baked goods sold at retail level account for 79%, while roughly 11% originates from imports, 4% from small-scale production, including local bakeries and home baking, and 6% from the service sector, such as restaurants and schools. Of the baked goods sold at retail, 81% are pre-packaged products (Table 1). Our mapping also showed that 76% of all savoury bread is produced by industrial bakeries and sold under TBA, while the majority of sweet products (65%) are sold pre-packaged but distributed without TBA. Hardened products, both savoury and sweet, constitute 13% of retail products, while an additional 11% are non-packaged products.

At the national level, the quantification results showed that nearly 180 000 tonnes of baked goods (translating to roughly 17 kg per person) are wasted every year, with 51% of this waste originating from the supplier-retailer interface. Bakery products, both savoury and sweet, sold under TBA were found to be the largest surplus category at both the bakery and retail stages, while also being among the most wasted bakery products in households (Fig. 3).

Table 1
Quantity of different bakery products available at retail level in Sweden, expressed in tonnes annually.

Take-back agreement	Product category	Savoury	Sweet
Yes	Pre-packaged, soft	3.0×10^5	6.1×10^4
	Pre-packaged, hard	1.1×10^4	2.2×10^4
	Total	3.1×10^5	8.3×10^4
No	Pre-packaged, soft	1.6×10^4	1.6×10^5
	Pre-packaged, hard	2.3×10^4	4.8×10^4
	Total	3.9×10^4	2.1×10^5
No	Non-packaged, bake-off	4.7×10^4	1.6×10^4
	Non-packaged, convenience	1.4×10^4	1.4×10^4
	Total	6.1×10^4	3.0×10^4
	Total, retail level	**7.3×10^5**	

4.2. Management pathways for surplus bread

Mapping of surplus pathways for bread sold under TBA along the supplier-retailer interface revealed that 86% of all bread produced is sold to consumers via retail (Fig. 4). The remaining 14% constitutes surplus bread not sold at retail (approximately 27 000 tonnes), with average loss rates of 6% at the bakery and 9% at retail levels. Less than 2% of the total surplus is currently redirected toward human consumption via reduced prices or food donations, while the majority is instead directed toward energy recovery (59%), ethanol production (22%), and animal feed (17%).

All alternative scenarios applied to the Swedish bread system, with or without TBA in place, resulted in an overall reduction in surplus bread. The change in waste rates when shifting from the conventional

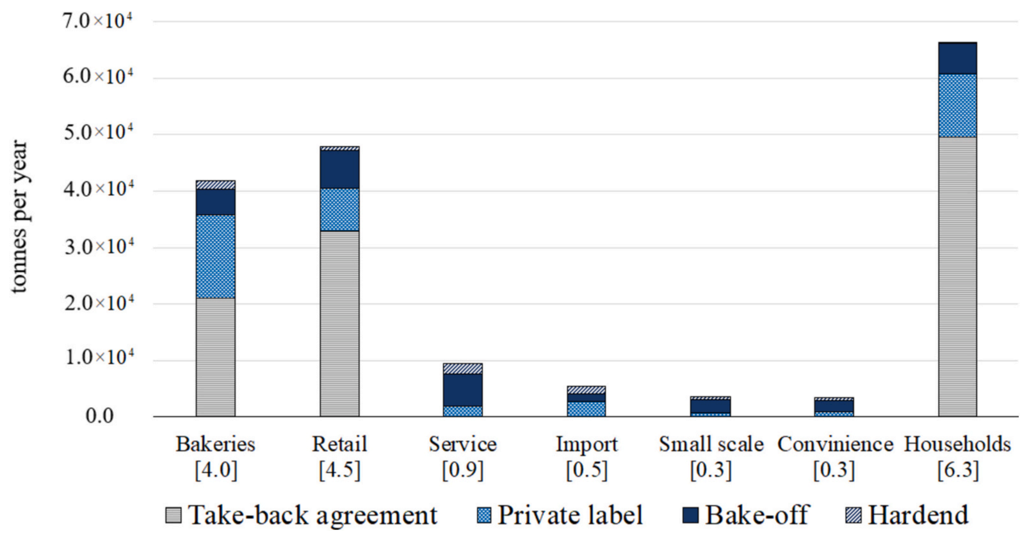

Fig. 3. Quantification of surplus bakery products generated annually along the value chain, including both savoury and sweet products. Numbers in brackets represent the amount of surplus in kg per person and year.

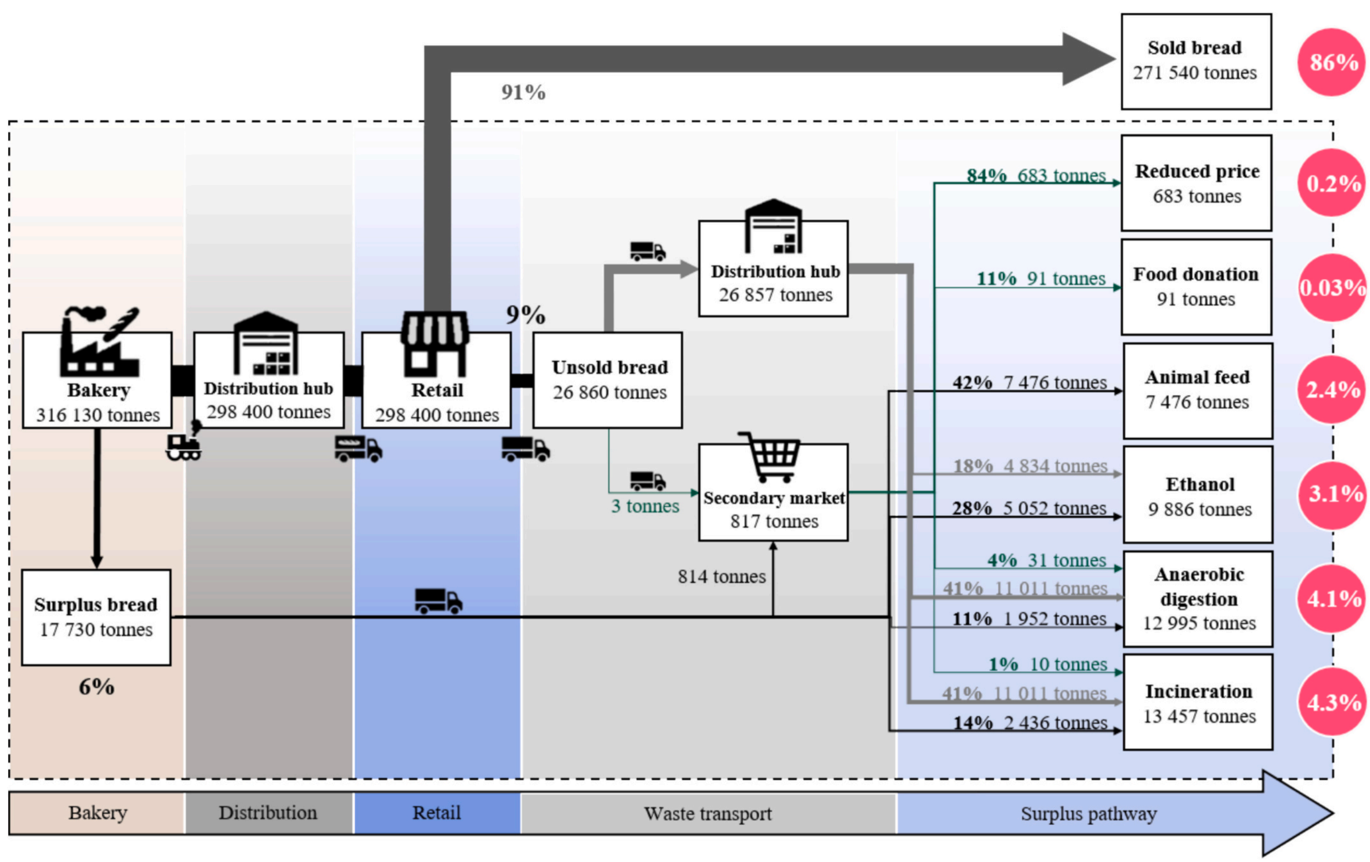

Fig. 4. Mapping of the current *Base case* scenario, indicating loss rates and management pathways, for surplus and waste generated at different stages of the supplier-retailer interface. The distribution of pathways (%) is shown per kg of produced bread.

Base case scenario is shown in Table 2, along with the corresponding waste reduction potential and alternative pathways for surplus products at the bakery and retail levels. The highest waste prevention potential was found for the *Sharing data* and *Retail ownership* scenarios, and the scenarios assuming their loss rates. Both the *Best practice* and the *Loss rates* scenario resulted in 20 000 tonnes less bread wasted at the supplier-retailer interface, while the *Food donation* and *Food hierarchy* scenarios yielded the highest share of valorisation toward human consumption.

4.3. Environmental impacts of bread scenarios

In terms of climate impact and damage to ecosystems, the conventional *Base case* scenario was found to result in 1.0 kg CO_2eq and loss of 3.9×10^{-8} species.year per kg bread. The results further show that the impact at midpoint and damage at endpoint decreased for the majority

Table 2
Loss rate and surplus quantities not sold via the intended pathway, in relation to amount produced, for each of the nine scenarios assessed.

	Base case	Sharing data	Improved shelves	Food donation	Retail ownership	Co-logistics	Loss rates	Food hierarchy	Best practice
Loss rate (%)									
Bakery	6.0%	3.4%	6.0%	6.0%	6.0%	6.0%	3.4%	6.0%	3.4%
Retail	9.0%	6.4%	6.2%	7.1%	4.5%	9.0%	4.5%	9.0%	4.5%
Surplus (tonnes)									
Bakery	1.8×10^{4}	1.1×10^{4}	1.8×10^{4}	1.8×10^{4}	1.8×10^{4}	1.8×10^{4}	1.1×10^{4}	1.8×10^{4}	1.1×10^{4}
Retail	2.7×10^{4}	1.9×10^{4}	1.9×10^{4}	2.1×10^{4}	1.3×10^{4}	2.7×10^{4}	1.3×10^{4}	2.7×10^{4}	1.3×10^{4}
Pathway (tonnes)									
Prevention	0	1.4×10^{4}	8.3×10^{3}	0	1.3×10^{4}	0	2.0×10^{4}	0	2.0×10^{4}
Reduced price	6.8×10^{2}	4.5×10^{2}	5.6×10^{2}	5.6×10^{3}	8.8×10^{2}	1.3×10^{3}	7.0×10^{2}	1.3×10^{4}	3.8×10^{2}
Donations	9.1×10^{1}	7.0×10^{1}	7.4×10^{1}	1.5×10^{3}	2.9×10^{2}	4.2×10^{4}	2.3×10^{2}	1.3×10^{4}	5.1×10^{1}
Animal feed	7.5×10^{3}	4.8×10^{3}	6.1×10^{3}	6.5×10^{3}	0	0	4.2×10^{3}	8.9×10^{3}	4.2×10^{3}
Ethanol	9.9×10^{3}	6.7×10^{3}	8.0×10^{3}	6.2×10^{3}	0	0	2.8×10^{3}	4.5×10^{3}	5.5×10^{3}
Anaerobic digestion	1.3×10^{4}	9.2×10^{3}	1.1×10^{4}	9.4×10^{3}	1.0×10^{4}	1.3×10^{4}	6.7×10^{3}	2.2×10^{3}	7.2×10^{3}
Incineration	1.3×10^{4}	9.5×10^{3}	1.1×10^{4}	1.1×10^{4}	2.0×10^{4}	3.0×10^{4}	1.0×10^{4}	2.2×10^{3}	7.5×10^{3}

of alternative scenarios when simulating a shift from the current system (Table 3). Shifting from the *Base case* scenario to any of the alternative scenarios was found to reduce the climate impact. In general, the *Food hierarchy* and *Best practice* scenario returned the highest environmental savings per kg bread at both midpoint and endpoint level, while shifting to the *Co-logistics* scenario resulted in an increased impact for 12 of the 16 midpoint categories and two of three endpoint categories.

With respect to climate, the annual impact for the current *Base case* scenario was translated to roughly 46 000 tonnes CO_2eq (Fig. 5). The primary impact hotspot for all scenarios was production of ingredients, primarily wheat and rye cultivation (see Fig. S14 in *Supplementary material*), while retail operations and bakery processing contributed very little to impact at midpoint level. Substitution, constituting prevention and valorisation pathways, accounted for via system expansion was also found to greatly influence the overall result for most scenarios.

The results further show that scenarios with a high use of prevention and high-value valorisation resulted in larger environmental savings, while anaerobic digestion and incineration resulted in five-fold and 10-fold lower climate benefits, respectively (Table 4). Environmental impact for all assessed midpoint and endpoint categories are available in *Supplementary material* (Table S15).

5. Discussion

Mapping the Swedish bakery sector, accounting for surpluses and losses of both savoury and sweet products along the supply chain, is one of the key outcomes of this study. We found that roughly 784 800 tonnes of bakery products are consumed annually in Sweden, of which 51% are sold and distributed under TBA. Approximately 14% of the savoury bread distributed under TBA is never sold at retail, due to the surplus generated along the supplier-retailer interface. This is in line with the loss rates for bread of 10-13% of production volume estimated by

Table 3
Environmental impacts per kg bread from the *Base case* scenario, alongside the impact per functional unit of shifting from the current *Base case* scenario for each alternative scenario. Green: reduced impact. Gray: increased impact.

Midpoint level	Base case	Sharing data	Improved shelves	Food donation	Retail ownership	Co-logistics	Loss rates	Food hierarchy	Best practice
Climate change	1.0×10^{0}	-6.4×10^{-2}	-2.8×10^{-2}	-1.3×10^{-2}	-5.7×10^{-2}	-1.8×10^{-2}	-7.7×10^{-2}	-7.4×10^{-2}	-9.0×10^{-2}
Ozone depletion	1.2×10^{-7}	-9.9×10^{-9}	-4.9×10^{-9}	-2.4×10^{-9}	-1.1×10^{-8}	-4.8×10^{-9}	-1.3×10^{-8}	-1.4×10^{-8}	-1.6×10^{-8}
Ionising radiation	3.5×10^{-1}	-1.1×10^{-2}	-2.8×10^{-3}	-2.3×10^{-3}	-1.8×10^{-2}	-2.2×10^{-2}	-2.4×10^{-2}	-4.0×10^{-3}	-1.2×10^{-2}
Ozone formation	5.9×10^{-2}	-2.7×10^{-3}	4.4×10^{-5}	-5.3×10^{-6}	1.3×10^{-3}	3.9×10^{-3}	-1.6×10^{-4}	-3.3×10^{-3}	-3.0×10^{-3}
Particulate matter	1.9×10^{-7}	-1.1×10^{-8}	-2.9×10^{-9}	-1.7×10^{-9}	-4.0×10^{-9}	3.8×10^{-9}	-8.3×10^{-9}	-1.4×10^{-8}	-1.4×10^{-8}
Human toxic $_{non\text{-}cancer}$	4.5×10^{-8}	-2.8×10^{-9}	-1.2×10^{-9}	-7.5×10^{-10}	-1.5×10^{-9}	4.3×10^{-10}	-2.5×10^{-9}	-3.8×10^{-9}	-3.0×10^{-9}
Human toxic $_{cancer}$	1.4×10^{-9}	-8.4×10^{-11}	-3.6×10^{-11}	-2.1×10^{-11}	-3.6×10^{-11}	2.9×10^{-11}	-6.7×10^{-11}	-1.1×10^{-10}	-9.3×10^{-11}
Acidification	5.3×10^{-2}	-2.6×10^{-3}	-2.0×10^{-4}	-1.6×10^{-4}	7.3×10^{-4}	3.0×10^{-3}	-5.8×10^{-4}	-3.2×10^{-3}	-2.8×10^{-3}
Eutrophication $_{fresh}$	4.2×10^{-4}	-2.6×10^{-5}	-1.0×10^{-5}	-6.7×10^{-6}	-1.4×10^{-5}	2.4×10^{-6}	-2.4×10^{-5}	-3.3×10^{-5}	-2.7×10^{-5}
Eutrophication $_{marine}$	3.0×10^{-2}	-1.5×10^{-3}	-1.8×10^{-4}	-1.4×10^{-4}	3.0×10^{-4}	1.6×10^{-3}	-4.6×10^{-4}	-1.9×10^{-3}	-1.6×10^{-3}
Eutrophication $_{terrestrial}$	2.8×10^{-1}	-1.3×10^{-2}	-6.0×10^{-4}	-5.9×10^{-4}	5.0×10^{-3}	1.7×10^{-2}	-2.2×10^{-3}	-1.7×10^{-2}	-1.4×10^{-2}
Ecotoxicity $_{freshwater}$	8.2×10^{1}	-4.9×10^{0}	-1.9×10^{0}	-1.2×10^{0}	-2.1×10^{0}	1.3×10^{0}	-4.0×10^{0}	-6.7×10^{0}	-5.3×10^{0}
Land use	1.1×10^{2}	-7.2×10^{0}	-3.1×10^{0}	-2.1×10^{0}	-4.4×10^{0}	2.8×10^{-1}	-7.1×10^{0}	-9.9×10^{0}	-7.6×10^{0}
Water use	6.1×10^{0}	-3.8×10^{-1}	-1.8×10^{-1}	-1.2×10^{-1}	-2.1×10^{-1}	4.1×10^{-1}	-3.6×10^{-1}	-5.6×10^{-1}	-4.0×10^{-1}
Resource use $_{fossils}$	1.4×10^{1}	-8.9×10^{-1}	-3.8×10^{-1}	-2.0×10^{-1}	-9.4×10^{-1}	-5.1×10^{-1}	-1.2×10^{0}	-1.1×10^{0}	-1.3×10^{0}
Resource use $_{mineral}$	9.1×10^{-6}	-4.5×10^{-7}	-1.3×10^{-7}	-5.9×10^{-8}	-9.1×10^{-8}	2.6×10^{-7}	-2.9×10^{-7}	-4.6×10^{-7}	-5.1×10^{-7}
Endpoint level									
Human health	6.7×10^{-6}	-3.5×10^{-7}	-6.5×10^{-8}	-3.8×10^{-8}	-1.8×10^{-8}	2.7×10^{-7}	-1.2×10^{-7}	-1.2×10^{-7}	-4.1×10^{-7}
Ecosystems	3.9×10^{-8}	-2.3×10^{-9}	-7.2×10^{-10}	-4.8×10^{-10}	-7.9×10^{-10}	8.4×10^{-10}	-7.5×10^{-10}	-7.5×10^{-10}	-2.4×10^{-9}
Resources	8.8×10^{-2}	-7.1×10^{-3}	-3.4×10^{-3}	-1.7×10^{-3}	-7.2×10^{-3}	-2.8×10^{-3}	-3.5×10^{-3}	-3.5×10^{-3}	-1.1×10^{-2}

Climate change: kg CO_2eq, ozone depletion: kg CFC_{11}eq, ionising radiation: kBq U-235eq, ozone formation: kg NMVOCeq, particulate matter: disease inc., human toxic: CTUh, acidification: mol H^+eq, $\text{Eutrophication}_{fresh}$: kg Peq, $\text{Eutrophication}_{marine}$: kg Neq, $\text{Eutrophication}_{terrestrial}$: mol Neq, $\text{Ecotoxicity}_{freshwater}$: CTUe, land use: Pt, water use: m^3 depriv., $\text{Resource use}_{fossils}$: MJ, $\text{Resource use}_{mineral}$: kg Sbeq. Human health: DALY, ecosystems: species·year, resources: USD2013.

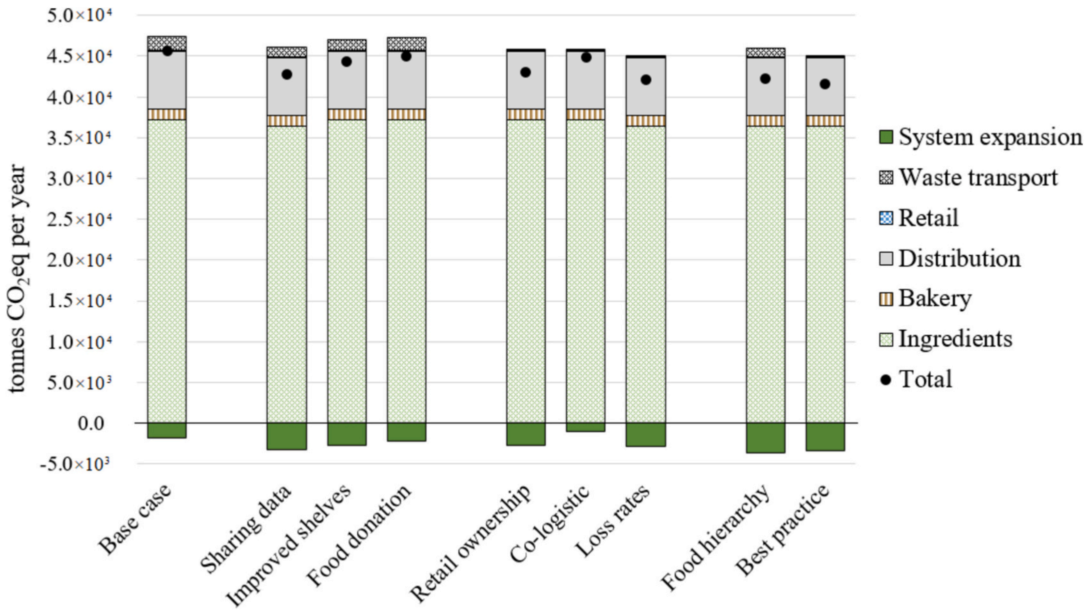

Fig. 5. Climate impact of bread on a national level, indicating each process contribution to total impact for all nine scenarios. Negative values indicate avoided impact due to system expansion via substitution of products from surplus bread pathways.

Table 4
Climate impact and ecosystem damage per kg of bread following each surplus pathway.

	Prevention	Reduced price	Donation	Animal feed	Ethanol	Anaerobic digestion	Incineration
kg CO_2eq	-1.0×10^{0}	-8.4×10^{-1}	-5.2×10^{-1}	-4.8×10^{-1}	-4.3×10^{-1}	-1.8×10^{-1}	-1.0×10^{-1}
Species.year	-3.8×10^{-8}	-3.8×10^{-8}	-2.4×10^{-8}	-9.2×10^{-9}	-2.9×10^{-8}	-4.1×10^{-10}	-7.7×10^{-10}

Goryńska-Goldmann et al. (2021b) and the bread return rates of 4-17% in Germany reported by Ritter et al. (2015). However, it is considerably higher than the 5% rate of surplus bread generation reported for small-scale bakeries in an Italian study (Pietrangeli et al., 2023).

The Swedish loss rate translates to annual wastage of around 27 000 tonnes of still edible bread sold under TBA, making it the single largest category of bakery surplus (54%) generated at retail (Fig. 3). Brancoli et al. (2019) also identified TBA bread as the largest waste category at retail (55%), but estimated a slightly lower quantity of 15 500 tonnes wasted bread. A plausible explanation for the similar waste fraction but higher quantities found in this study is the increased consumption of bread over the years, while the TBA system has remained unchanged. Using the price of a "*Lingongrova*" loaf (25 SEK per 500 g), marketed as "*Sweden's most purchased bread*" (Pågen, 2024), this corresponds to an economic loss of around 1.4 billion SEK every year only at retail. Applying the same price per 500 g to estimate the economic value of all bakery products wasted, roughly 9 billion SEK (780 million EUR) are lost via surplus each year. Despite the relatively low price of bread in Sweden, the vast quantities of surplus add up to a considerable amount of economic losses, in addition to the social and environmental consequences of under-utilising food resources.

Although surplus bread is often of good quality and suitable for high-value valorisation, our results show that the largest surplus pathway is currently anaerobic digestion, followed by incineration, and ethanol production (Table 2). This supports previous findings on food waste pathways in Sweden by Johansson (2021). Only 2% of surplus bread sold under TBA is directed toward human consumption via reduced prices or food donations (Fig. 3), likely since this pathway currently requires incentives in terms of time and money to facilitate. Of the bread directed toward human consumption, our mapping showed that 5% is currently diverted to anaerobic digestion or incineration. This is in line with findings for food donations by Sundin et al. (2023), and emphasises an important limitation related to efficiency and management in current high-value valorisation pathways for surplus food. These results confirm that the existing TBA system can indeed be considered a cause of bread waste at both supplier and retail level. More importantly, the current TBA system tends to limit use of high-value pathways for unsold products, since energy production is favoured over human consumption. Therefore, one could argue that the bread system would greatly benefit from innovations that promotes pathways for prevention and valorisation.

The potential benefits of shifting from the current system, or applying changes to it, were assessed using different scenarios. *Sharing data* between suppliers and retailers operating within the conventional TBA system, or implementing *Retail ownership* of all bread sold at retail without TBA in place, reduced surplus by 30% (Table 2). At national level, this represents a reduction in surplus of over 13 000 tonnes annually. The threshold to share data should arguably be quite low, since much of the data are already being collected, but sharing agreements between supplier and retailer will need to be put in place for this solution to become reality. However, since businesses often prioritise economic aspects rather than the environmental impacts of their operations, there can be considerable barriers or conflicts of interest preventing them from actually sharing data, as also noted by Winkler et al. (2023). If the TBA system were instead to be completely removed and replaced with *Retail ownership*, emulating the current system for private-label bread, less surplus would be generated at retail. The transfer of ownership to retail would not necessarily affect the pathways used for any bread waste generated, but would rather support further prevention measures, like coordination of promotions in the store and discounts at the end of shelf life. Although this assumption is plausible, it is also important to highlight the potential burden shifting related to actions targeted at reducing waste at retail. For instance, reducing prices at retail might lead to increased bread waste at households when consumers are enticed to buy more than will be consumed. This is especially relevant to consider for price reduction pathways, alongside, for instance, bake-off products with a shorter shelf life compared to pre-packaged bread. However, allowing retailers to influence the management of bread sold in their stores would likely reduce surplus generation via prevention.

Even though the *Sharing data* and *Retail ownership* scenarios involved similar loss rates, the former focused more on waste prevention actions, while the later both directed more toward human consumption while also impeding pathways toward animal feed and ethanol production. The *Best practice scenario* showed that there are considerable climate and ecosystem benefits of keeping the current surplus pathways enabled via TBA, but at the same time allowing retailers to influence the management of bread. When considering all impact categories at midpoint, shifting to the *Food hierarchy* scenario and ultimately using food resources according to their highest value enabled the highest environmental benefits. Although the climate impact was reduced when simulating a shift to *Co-logistics* scenario, the shift also inferred increased impact for a majority of other categories, including acidification, eutrophication, land use, and ecosystem damage (Table 3). This emphasizes the importance of including a broad range of impact categories, as crucial aspects might otherwise be overlooked.

Furthermore, it is important to note that there are other potential trade-offs between the scenarios. For instance, if the pathways for prevention, price reduction, and food donations are opened up, then less fossil fuel can be substituted, as less ethanol and biogas would be produced. Increased donations are both required and feasible within the current *Base case* scenario, but would require adaptation and agreements for distributing the bread to people in need. The resource requirements of food aid organisations, which often operate on a non-profit basis, are also a significant factor for the feasibility of these scenarios (Mesiranta et al., 2022). Favouring decentralised donations, for example, by allowing people to pick up bread directly at retail, could reduce the need for additional management outside the retail stage.

Modeling the innovations as separate scenarios allowed evaluation of the individual actions, but many of the innovations assessed via scenarios can, and arguably should, be combined with other non-overlapping actions to enhance the positive effects. For instance, *Food donation* could be combined with *Sharing data*, *Retail ownership* or *Improved shelves* to enhance the positive effects of prevention and circulating bread back to the food system. A similar rationale applies to the *Co-logistics* scenario, which in itself did not contribute to reduced surplus, but rather focused on optimising transport and management, which can be a limitation for other scenarios. The *Co-logistics* scenario could in theory be combined with any other scenario assessed, and would benefit pathways that would otherwise require increased transportation, such as the *Food donation* scenario. The power of prevention and valorisation pathways was even more evident when each pathway was analysed separately (Table 4), where prevention gave five-fold and 10-fold higher climate savings than anaerobic digestion and incineration, respectively. These benefits will likely be maintained when prevention is favoured, as illustrated by the *Food hierarchy* scenario.

5.1. Environmental benefits of prevention and valorisation

The conventional *Base case* scenario was found to contribute an annual climate impact of nearly 46 000 tonnes CO_2eq and an ecosystem damage of close to 2 species per year at national level (Table 3). Keeping in mind that factors such as type of bread, energy use, and LCA methodology heavily influence the environmental performance of bread, the climate impact of 1.0 kg CO_2eq per kg bread sold under TBA found in this study follows the same order of magnitude as reported in previous studies. When assessing the impact of rye bread produced in Sweden, Hildersten et al. (2025) found that 1 kg of bread resulted in 0.81 kg CO_2eq. This is in line with the present results, although their study also included packaging, which was omitted in this study. When assessing the carbon footprint of bread in the United Kingdom, Espinoza-Orias et al. (2011) found a climate impact ranging from 1.2 to 1.5 kg CO_2eq per kg of bread, which was similar to the range reported by Kulak et al. (2015) of 0.6 to 1.7 kg CO_2eq per kg of bread. The differences in climate impact per kg bread could be a consequence of different methodological choices, including system boundaries and how the studies dealt with multifunctionality. When accounting for the climate benefits of prevention and valorisation of surplus bread at the supplier-retailer level in Norway, Svanes et al. (2019) found a climate impact of 1 kg CO_2eq per kg bread. However, although the impact per functional unit was similar to that in our study, their study included, for example, more transportation of ingredients and omitted valorisation pathways toward human consumption. Important to note is the considerable range in climate impact of bread reported in previous research, also highlighted by Notarnicola et al. (2017) and later by Rayichuk et al. (2023). Accounting for the avoided environmental impacts of substituted ingredients in LCA studies could aid in determining the valorisation pathway with the best environmental outcome, a conclusion also reached by Thorsen et al. (2024). The result per kg bread following a prevention or valorisation pathway in this study (Table 4) is consistent with previous findings by Brancoli et al. (2020) using a similar modeling approach. However, in the present study, we incorporated updated values from Ecoinvent, literature and input obtained via stakeholder dialogues, which explains the slight difference in numerical values. Another important aspect is that the present study combined data from both Ecoinvent and Agri-footprint, as this enabled a better description of the inputs used. To ensure compatibility between the databases, this also inferred that the study used cut-off as allocation principle for the inputs and outputs. Since LCA methodology heavily influence the results, this should be accounted for when evaluating the result.

Production of ingredients and distribution of bread from bakery to retail were found to be the primary hotspots with respect to climate impact, as expected due to the high dependency on fossil fuels during production and transport. This is in line with previous findings on the climate impact of bread (Svanes et al., 2019; Nadi et al., 2022; Weber et al., 2023). It should also be highlighted that our results show that prevention and valorisation to human consumption provide the greatest climate and ecosystem benefits, since these pathways reduce the demand for new materials. Although ecosystem damage has been identified as an increasingly important aspect to consider, especially regarding food systems, this method is rarely adequately included in LCA research (Gabel et al., 2016). To our knowledge, no previous study has accounted for the ecosystem damage related to the bread system, making the outcome from this study unique. The results can be used as a foundation for future comparison and validation, while the numerical value for ecosystem damage should primarily serve as an indicator for damage hotspots.

5.2. Market power for reduced bread waste

The use of TBA has often been attributed to the high market power of Swedish retailers, but similar agreements are used in multiple countries (Brancoli et al., 2019). The system ensures that bread waste is collected separately from other food waste fractions, opening up for alternative pathways for waste management and valorisation of unsold bread. Ideally, all bread produced should be eaten, either directly or following conversion into new food products. Incorporating environmental aspects into business management has been shown to positively influence consumer attitudes, benefit retailer branding, and support further implementation of high-value food recovery. As the success and efficiency of food retailers are also linked to corporate social responsibility (Kulikovskaja and Aschemann-Witzel, 2017), food retailers can reap multiple benefits from actions to reduce food waste without compromising customer satisfaction or marketability.

Considering that the Swedish bread supply chain is dominated by three industry bakeries, it is nonetheless important to question the potential to further reduce the surplus generated at the supplier-retailer interface. The Swedish bread system may already be quite optimized, as we observed only a 14% loss from production to retail for TBA bread. Further prevention measures might not be economically feasible for bakeries or retailers, which is another aspect that should be evaluated. Although some pathways favoured for redirecting surplus bakery products may not result in less overall surplus being generated, they can still contribute to higher value recovery of available resources. The lowest waste rates were found for hardened bakery products, both savoury and sweet, due to their considerably longer shelf-life. Therefore, a higher consumption share of hard bread would likely reduce overall bread waste. Consuming more products from these categories could also become an important aspect of food preparedness and self-sufficiency. Hard savoury bread can often be considered healthier than soft bread, containing more whole grains and fibre. Thus, shifting to a higher share of hard bread for the purposes of waste reduction could also bring health benefits (Edgar et al., 2022). Introducing more bread of any kind into the human diet, preferably at the expense of animal-based foods, could also reduce environmental burdens related to a nutritionally balanced diet (Kramer et al., 2018).

While the TBA as a business model requires separate collection of bread, it has also been identified as a risk factor for bread waste generation (Eriksson et al., 2017). The positive correlation between TBA and high levels of waste can be explained by the constant battle between suppliers and retailers, and among suppliers themselves, over the service level on the shelves. Thus, while TBA contributes to the circularity of the bread supply chain, it also has the potential to increase waste generation, presenting a complex challenge for sustainability in the industry. In April 2019, EU Directive 2019/633 categorized TBA as potentially unfair trading practice, which has made this business model less frequent in other countries (Pietrangeli et al., 2023). The TBA model is not enforced by any policy or regulation, and bakeries are in theory free to use any business model they choose. However, as shown by Ghosh and Eriksson (2019), the TBA has become the trade standard in Sweden, and bakeries therefore often feel pressured to adopt this business model. The results from this study show that the current TBA model generates most surplus and performs worst with respect to almost all midpoint and endpoint categories assessed, while considerable savings in both waste generation and environmental impact were found for all alternative scenarios. Since many of these scenarios could be implemented into the current bread supply chain, either directly or following minor modifications, it should be emphasized that taking any action toward prevention and valorisation of surplus bread is more important than optimizing the actions taken. Given that the current TBA system is already in place and works well in many aspects, it can be argued that innovations to improve this system should be prioritized initially. Identifying the benefits and favouring pathways that allow high-value recovery of surplus bakery products can enable a more purposeful use of resources, ensuring that the food we produce is consumed by humans rather then used feed the energy sector. In turn, this supports efficient food systems that will benefit the environment, society, and the economy.

5.3. Limitations and future outlook

Although quantification via self-assessment tends to yield underestimates, this method engaged stakeholders and provided important insights into bread pathways. Direct measures of surplus or waste were not possible in this study, as most production data are currently not openly shared by bakeries or retailers. In waste quantification, we instead used inputs from literature, previous research, and information shared in stakeholder dialogues, alongside data provided by industry actors. We attempted to validate the production quantities, loss rates, and surplus pathways for bread with multiple industry actors, and the results were accepted by two independent actors operating within the Swedish bakery system. The in-depth mapping mainly focused on savoury bread distributed under TBA, while the quantification of the remaining bakery products was only addressed at national level. To capture the environmental impact of the entire bakery sector, the life cycle of sweet and hardened products should also be assessed. Future studies would also benefit from including multiple impact categories to allow in-depth analysis of environmental impact, which is especially important when evaluating the performance of food systems.

Alongside Agenda 2030 and SDGs, the Swedish government has set a goal to reduce food waste by 20% until 2025, and to increase the amount of food entering the retail and consumer level. Retailers can play a vital role in this food waste reduction effort, as they have a unique opportunity to influence the prevention of surplus bread generation at all stages of the value chain. However, we need to overcome existing barriers to allow new pathways to thrive. The current approach to managing surplus bread in Sweden is problematic, as energy production (e.g. ethanol and biogas production) is currently prioritized over prevention and valorisation. The solution to the food waste issue is thereby largely framed as an efficiency problem, focusing on optimizing material flows and avoiding waste, rather than as an issue of solidarity, where already produced food is primarily redirected toward human nutrition (Mesiranta et al., 2022).

To support sustainable production and consumption of food in the future, it is crucial to prevent losses and valorise surpluses for human consumption. Producing any kind of food and using it to feed animals or for energy production should not be considered sustainable from an environmental, social, or economic point of view. On the contrary, we need strong incentives to drive the required change toward sustainable food systems, where production and consumption are in balance, and food is used to its fullest potential. Even though a system or process might be considered circular, it can still contribute to reduced sustainability or increased environmental impact if the resources required to maintain circularity outweigh the benefits. This highlights an important goal conflict between circularity and resource use, which is especially critical for food systems with high potential for increased circularity. If these goal conflicts are not recognized and adequately addressed, even well-intentioned innovations and incentives could risk contributing to reduced sustainability or increased environmental impact. Since the environmental benefits of prevention and valorisation of surplus bread were found to be offset by the climate cost of managing the bread, this aspect is also relevant to consider for bread supply chains. Therefore, any action or innovation applied to the bakery supply chain to reduce waste generation must be feasible, yet adequate. Stakeholder dialogue, modeling scenarios, policy recommendations, and industry collaboration can all be valuable tools for identifying and implementing changes to the bread supply chain, without jeopardizing profitability, development, or consumer satisfaction.

6. Conclusions

Two key outcomes of this study are, firstly, the quantification of surplus bread and bakery products generated at different stages of the supply chain, including both sweet and savoury products, and secondly the identification of current pathways used to manage surplus. The results show that just under 180 000 tonnes of baked goods, equivalent to roughly 780 million EUR, are lost or wasted annually. The majority of savoury bread consumed in Sweden was found to be sold and distributed under TBA, where 14% of production (27 000 tonnes) becomes surplus already at the supplier-retailer interface each year. The results further show that the loss rate for sweet products is overall higher compared to savoury products, with even lower loss rates for hardened products. The power of prevention and valorisation was demonstrated through scenario analyses, where innovations for waste reduction and alternative surplus pathways at the retail-bakery interface were simulated. The largest reduction potential was obtained for preventative actions, either through sharing of data or price reductions. Scenarios adopting both prevention and high-value valorisation resulted in up to ten times lower climate impact per kg bread. The outcome of this study can be directly used to support industry actors who want to implement changes that reduce waste or promote high-value valorisation pathways. The results can also provide guidance in developing policy recommendations that economically favour prevention and valorisation toward human consumption, and provide a valuable basis for future research on resource-efficient food systems.

CRediT authorship contribution statement

L. Bartek: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Sjölund:** Writing – review & editing, Methodology, Investigation, Data curation. **P. Brancoli:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation. **C. Cicatiello:** Writing – review & editing, Validation, Formal analysis. **N. Mesiranta:** Writing – review & editing, Validation, Formal analysis. **E. Närvänen:** Writing – review & editing, Validation, Formal analysis. **S. Scherhaufer:** Writing – review & editing, Validation, Formal analysis. **I. Strid:** Writing – review & editing, Supervision, Methodology. **M. Eriksson:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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