

Article

Effects of Packaging and Food Waste Prevention by Consumers on the Environmental Impact of Production and Consumption of Bread in Norway

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Abstract: Bread is a staple food in Norway, with a yearly per capita consumption of 52 kg. It is an important source of energy, dietary fibre and protein as well as certain minerals and vitamins. Previous studies have shown that bread has a relatively low environmental impact compared with other foods. Food waste studies, however, have shown that bread and other baked goods have a high wastage rate in Norway. On the basis of lower Norwegian wheat yields, it is therefore expected that the environmental impact of bread could be higher than in other European countries. The purpose of this study was to assess the environmental impact of bread from cradle to grave, identify environmental hotspots, examine the role of packaging in bread waste and identify possible remediation measures with a particular focus on the post-farm value chain. The results showed that for every kilogram of bread consumed, the global warming potential was 0.99 kg CO₂-eq, the eutrophication potential was 7.2 g PO₄-eq, the acidification potential was 8.4 g SO₂-eq and the cumulative energy demand was 18 MJ. The principal uncertainty within the calculation was the use of database data for the 21 ingredients. For example, the effect of soil mineralisation, which could give significant CO₂ and N₂O emissions, was not included because figures have only been quantified for a few ingredients and there is no international agreement on the methodology. The primary hotspot was the production of the ingredients, principally at the agricultural stage, while bread waste took the second place. The highest potential for the reduction of post-farm environmental impact lies in reducing product wastage at the retail and consumer stages. Consumers already employ strategies to reduce wastage, such as using extra packaging and freezing and toasting bread. This study shows that other consumer packaging solutions can keep the bread fresh for longer, thus reducing wastage and the need for the abovementioned consumer strategies. Nevertheless, other researches in this subject have shown that consumer preferences and behaviours play a significant role in the creation of bread waste, and this should therefore be taken into account when planning reduction measures.

Keywords: bread; LCA; food waste; packaging; consumer habits; Norway

1. Introduction

The environmental impact of food from farm to fork constitutes a major proportion of the overall environmental impacts in the world. One study [1] found that 20–30% of total greenhouse gas (GHG) emissions and 59% of total eutrophication impacts come from food value chains. Another study [2] found that 26% of primary energy (in 2013) was consumed by the food value chain. Substantial quantities of water and land area are also used.

Bread is a staple food that plays an important role in the Norwegian diet. The consumption of bread in Norway is 52 kg per person per year, which equates to a total of about 275,372 tonnes a year [3–5]. This is a relatively high volume when compared with other commensurate countries, although it must be noted that the World Health Organisation recommends an annual intake of 90 kg per person. The Norwegian Government [6] recommends a daily intake of 70–90 g of whole grains, but only 1 in 4 people in Norway eat enough of it. Intake of wholegrain bread, together with oatmeal or wholegrain cereals, is an important source of fibre, vitamins (thiamine, folate, vitamin E), minerals (iron and selenium), energy and protein [7]. On the basis of consumer statistics [4] and nutritional values [7], the authors calculated that 23.5% of the Norwegian per capita protein intake is derived from cereals.

Bread consumption in Norway differs from other countries in that more whole grains are used as ingredients for bread. Consumers prefer very fresh bread with a crispy crust and a soft core, which is not easy to maintain for any length of time at home. On average, 78% of the wheat grain is utilised in food, significantly more than in many other countries [8].

Bread is also a relatively expensive food in Norway in comparison with other European countries. However, several studies have found that bread and other bakery goods have a high degree of wastage in Norway compared with other food categories. This wastage occurs in bakeries, at the retail stage and among consumers. The bread waste rate is estimated to be 22 kg edible bread per capita per year; only fruits and vegetables and leftovers from cooked main meals account for more waste than bread in Norway [9].

The aim of this study was to investigate the environmental impact of bread from cradle to grave in order to establish the environmental hotspots; to examine the role of food waste, packaging and consumer behaviour; and to identify potential measures to reduce this wastage. The focus is on the post-farm life cycle stages.

2. Background of the Study

2.1. The Environmental Impact of Bread

The environmental impact of bread has been analysed and documented in a number of life cycle assessment (LCA) studies. Although bread is a comparatively simple food item consisting of cereals, water and some minor ingredients, the results have been quite different. Kulak et al. [10] studied the value chain from cradle to consumers and found that the global warming potential (GHG emissions) was 0.8–2.3 kg CO₂-eq/kg of bread. A European study of national bread types in 21 countries [11] found an even greater variation, with GHG emissions ranging from 0.5 to 6.6 kg CO₂-eq/kg of bread from cradle to retail. Another study [12] looked at bread produced and consumed in the UK but with wheat from varying sources as well as different types of flour and packaging. The study found that the GHG emissions results ranged from 0.98 to 1.24 kg CO₂-eq/loaf of bread, corresponding to 1.2 to 1.6 kg CO₂-eq/kg of bread.

Few LCA studies of bread have been carried out within the Nordic region in recent years, although there have been two. One of these, a study in Norway [13], found GHG emissions to be 0.937 kg CO₂-eq/kg of bread from cradle to consumer. The other, a Danish study [14] of rye bread, showed a result of 0.73 kg CO₂-eq/kg of bread from cradle to consumer.

The primary hotspots in most studies have been agricultural production [10–14], baking [11,14], refrigerated storage and toasting [12], product wastage [12] and emissions from electricity generation in the national grid mix [11].

Kulak et al. [10] found different hotspots for the various indicators, production methods and countries of origin. However, in the French reference system, which is most comparable to the most common technology in Norway, the following results were obtained: For non-renewable energy use, retail and transport were the most significant; for GHG emissions, agriculture and

transport had the most importance; and for both acidification and eutrophication, agriculture had the greatest significance.

2.2. Food Waste and Packaging

The quantity of bakery goods [9] wasted in Norway is high at 110,000 tonnes per year. Of this amount, 64,000 tonnes are wasted in households. Bread waste is calculated at 22 kg per capita per year, of which 13 kg is wasted within households, 5 kg in bakeries and 4 kg in retail. The economic and environmental costs of this waste are also high. On the basis of one study [15], the cost is 147 Euro per capita per year, and the GHG emission is 13.2 kg CO₂-eq.

Packaging has a protective function. Several studies [15,16] have shown that the environmental impact of packaging is relatively low in comparison with the impact of the bread itself. Hanssen et al. [17] also showed that the life cycle cost is much lower. Despite this fact, 86% of consumers answered in a survey [18] that it was worse to discard the packaging than the bread it contained.

Life cycle assessments have clearly indicated that food waste prevention is an important strategy when looking for ways to reduce the environmental impact of bread [19]. They have also shown that the optimisation of packaging should be considered as a particularly important measure when attempting to achieve such reductions.

The most common packaging for freshly baked bread in Norway is either a bag made of 50% perforated polyethylene (PE) and 50% plain paper (about 12.5 g in total) or a bag made solely of paper (about 10 g). These packaging solutions do little to preserve the freshness of the bread, which in turn leads to food wastage [17].

2.3. The Role of the Consumer in Food Wastage

Several studies have investigated the reasons for consumer food wastage. Various drivers for wasting food, such as portioning, abundance, attitude, knowledge, lifestyle, storing and packaging, were identified by Thyberg et al. and Hebrok et al. [20,21]. Previous studies have shown that young people waste more food than older people and that income, education and gender influence the amount of food being wasted. Examples of this are given by Qvested et al. [22].

One recent consumer survey [15] in Norway showed that consumers' low tolerance for bread that is not completely fresh is, at least in Norway, an important reason for wasting bread. The packaging seems to play an important role: 97% of consumers reported changing the primary packaging of the bread, with a majority of them replacing the original packaging with a plastic bag or using both the bag and the original packaging at the same time. Consumers also stated that the amount of bread in the packaging is an important factor. The survey found that, for many households, the standard size of a loaf (750 g) was too large. Incorrect storage at home was another reason given by many.

The survey (ibid) revealed that consumer behaviour can show notable variations. It identified two groups of consumers: the high wasters (HW) and the low wasters (LW). HW are over-represented in the 26–59 age group, in households with children, among full-time employees and among people with a high income. For HW, it is important that the packaging is open in the store so that they can smell the bread. They prefer fresh bread (as opposed to vacuum-packed), and they buy bread often and many loaves at a time. LW have a stronger tendency to preserve the bread by freezing and toasting, and they are more concerned about the environmental impacts, such as the recyclability of the packaging.

Consumers use different strategies for preserving the bread for longer in order to reduce wastage. Freezing [12,15,16,21] and toasting [12,15] are the most common methods but, according to the survey, changing the packaging is also common.

Consumer habits can also have indirect impacts on bread waste in other life cycle stages. According to sources in the retail sector, it is well known that consumers expect to find their favourite bread at any time of day in the shop, even just before closing time. This means that retailers have to overstock in order to be able to meet consumer expectations.

Consumer habits can, on the other hand, play a positive indirect role. This is exemplified by their preference for fibre-rich, “brown” bread that uses more whole grains than white bread, where the bran is removed. This results in more grains being used, on average 78% of wheat, for human consumption than in other European countries. In general, the part of cereals not used for human consumption sells at a lower price than that used for human consumption. Applying economic allocation, as in this study, the environmental impact of the cereals used in bread should, on average, be lower in Norway than in countries where white bread is more prevalent.

3. Methods

3.1. General

The principal method employed in this study was life cycle assessment based on ISO 14040-44 [23–25]. LCA is known as a methodology for estimating the environmental impact of a product or a service throughout the value chain from raw material extraction to production, use and waste treatment.

The impact assessment method used for most impact categories was CML-IA baseline V3.05. For cumulative energy demand, Cumulative Energy Demand V1.10 by Ecoinvent was used. There is no internationally agreed method for adapting the LCA method specifically to cereal products, which makes comparisons between studies difficult. For example, in many cases, different life cycle impact assessment (LCIA) methods are used. For this reason, we decided to include results using the ILCD method (Midpoint 2011, version 1.10) and the ReCiPe method (2016 Midpoint (H), version 1.02) in addition to CML so that the results from this study would be more commensurate with those of other studies. The following environmental impact categories were included in this study: global warming potential, acidification potential, eutrophication potential, photochemical oxidation potential, ozone creation potential and cumulative primary energy demand. The SimaPro 8.5.2.0 software was used together with the Ecoinvent 3.5 database and Agri-Footprint 4.0 in carrying out the analyses.

3.2. Goal, Scope and Research Questions

The purpose of this study was to determine the predominant environmental and resource hotspots in the bread value chain, to analyse the impacts of different consumer behaviour with regard to food waste, to document the effects of various measures to improve the packaging of fresh bread and the systems for its distribution and to examine the efficacy of food wastage reduction measures.

The research questions in the study were as follows:

- a. What are the primary hotspots in the bread system for the different environmental impact categories, and how do the findings from this study compare with results from other studies?
- b. What is the relative importance of packaging and food waste along the bread value chain from an environmental perspective?
- c. What are the environmental impacts of processes that can extend the life of fresh bread (for example, freezing and toasting), specifically with regard to possible reductions in food waste?
- d. How can the environmental impacts of the system be reduced through measures targeting bread packaging or other aspects of the life cycle of bread?

3.2.1. Functional Unit

The functional unit was defined as follows: 1 kg of bread produced, distributed and consumed in Norway.

3.2.2. System Boundaries and Cut-off

The system that was studied included the production of raw materials (wheat, barley, rye, sunflower seeds, sesame seeds, grain, salt, etc.), milling and other processing of raw materials into ingredients (wheat flour, barley flour, rye flour, yeast) and the transport of raw materials before baking.

On-farm infrastructure was only included as a specific amount of concrete and did not cover machines and only partially covered buildings. The impact of soil organic carbon (SOC) loss was not included. The reason for employing the database for the agricultural phase, for not including SOC loss and for only partially covering infrastructure was the lack of harmonised data regarding the 21 different ingredients in the bread.

At the bakery stage, bread baking, cooling and packing were included. Packaging included consumer packaging, distribution packaging (boxes) and transport packaging (trolleys) as well as the extra plastic bags that many, but not all, consumers use as additional wrapping, either in shops after slicing the bread or at home. After the bakery stage, processes and materials that were included were transport to retail, retail, transport to consumer, end consumption and handling of bread and packaging waste from bakery, retail and consumer. The impact of the treatment of waste packaging and bread waste was included as was the benefits from such treatment.

The geographical boundary was limited to Norway. However, the completeness of data was deemed as being high because a high percentage of bread within the Norwegian market was covered. The bread that was used as a study object for analysis is one of the best-selling products in the Norwegian market, the bakery data came from one of Norway's largest bakery companies and data relating to retail came from one of the biggest retail companies in Norway.

The environmental impacts of capital goods, such as machinery and buildings relating to the bakery, retail and home consumption, were excluded because bread is a high-volume product and as such is expected to contribute little to overall environmental impacts.

3.2.3. Allocation

The principal multiple output processes in this study were (a) milling of cereals, yielding fine flour, wholemeal flour and bran; (b) transport of bread to retail; (c) retail; and (d) consumer transport.

In the milling process, economic allocation was employed because the price determines, to a large extent, which products are made. In cases (b) and (d), mass allocation was applied. In (b), it can be argued that most of the bakery goods have approximately the same density and thus occupy the same space in lorries, so mass allocation should therefore be used. In (d), the reason for applying mass allocation was that the data did not allow for a differentiation between different food products. In case (c), an economic allocation factor was employed because data on retail impacts was given per monetary unit turnover.

Bread waste gives rise to both direct and indirect environmental impacts. The direct impacts arise from transporting wasted bread to waste treatment plants and from the waste treatment itself. The indirect impacts come from the production of bread to replace the wasted bread. In this study, both indirect and direct impacts of bread waste were calculated separately. They were allocated to the life cycle stage in which the waste occurs and not to the life cycle stage where the emissions occur. The reason for this was to illustrate the environmental impacts of bread waste.

Bread waste from bakery and retail is used as animal feed. Therefore, the benefit of this usage was defined as an avoided impact for the bread system, where the bread was estimated to replace an equivalent amount of cereals in the bread.

3.2.4. Waste Treatment

The following processes regarding bread and packaging waste were included: transport of waste to treatment plant, waste treatment and the benefits of waste treatment. The benefits of waste treatment were included by system expansion through the substitution (avoided impact) method. This means that for bread, for example, a benefit of an equivalent amount of the bread ingredients was assumed but was restricted to the cereals.

Consumer bread and packaging waste were assumed to be treated as average Norwegian household wet organic, paper and plastic waste.

4. Materials: Life Cycle Inventory

4.1. Data Gathering and Sources

Calculations relating to the impact of the milling of cereals, transport of raw materials to processing, processing of most of the raw materials into ingredients, transport of ingredients to the bakery, baking of products, packaging, transport to retail, amounts of bread waste, handling of bakery and retail bread waste and data relating to consumer behaviour were based on site-specific or primary data. Calculations regarding the impact of the cultivation of cereals and other ingredients, processing of some raw materials into ingredients, retail impacts and consumer transport were based on general database data.

Data concerning the origin of wheat, on milling, transport of wheat and packaging was supplied by the milling company. Data relating to bread (recipe, weight), packaging, baking process and transport to retail came from the baking company. Information regarding consumer behaviour in relation to shopping, storing, processing and wasting of bread was based on data from a consumer survey [15]. Information on consumer transport was taken from Pretty et al. [26]. Data pertaining to the processing of bread waste into pig feed was obtained from the processing company.

In Table A2 (Appendix B), a list of the most important database processes used in this study is given.

4.2. Composition of Bread

The total mass of the bread itself was 736 grams. Data on the composition of the bread is given in Table 1. The bread is one of the leading market products in Norway. The data in Table 1 refers to bread after baking. The amount of water in the dough was higher than the amount shown in the table.

Table 1. Composition of bread.

Ingredient	Amount (%)	Origin
Water	25	Norway
Wheat and wheat by-products	56	Norway and Poland
Rye	7.6	Norway
Barley	1.2	Norway
Salt and yeast	3.3	Unknown
Seeds (linseed, sunflower seed, sesame seed)	3.0	Unknown
Other ingredients	3.5	Unknown

4.3. Cultivation and Transport of Raw Materials

The proportion of wheat coming from Norway varies greatly from year to year depending on the weather and other external factors. However, information from the milling company shows that over a period of several years, an average of 65% of the wheat has been coming from Norway and the remaining 35% from Poland.

Data on the cultivation of raw materials was obtained from the databases Agri-Footprint 4.0 and Ecoinvent 3.5.

4.4. Processing

The predominant ingredients in bread are cereals. The cereals are dried, stored and processed into flour or other ingredients. Most of the cereals contained in the product in this study came from dry milling. Some minor cereal ingredients came from wet processing. Drying of cereals was expected to take place in the country where the cereals were grown. Data from the database Agri-Footprint v 4.0 and Ecoinvent 3 was used in the calculations. Data regarding the transport of raw materials to the mill and energy consumption at the mill was provided by the milling company (see Table 2). Transport of

other ingredients was not included because the exact geographical origin of these ingredients was not known.

Table 2. Processing data.

Process/Item	Data	Data Source
Transport producer to mill	Norwegian wheat, barley and rye: 500 km road transport. Imported wheat: 350 km road transport and 723 nautical miles sea transport.	Mill company
Mill energy consumption	129 kWh electricity per ton of flour produced.	

Data for economic allocation of mill products and allocation factors are shown in Table 3.

Table 3. Data for allocation of wheat and rye products in flour mill.

Material	Material Balance and Allocation Factors	Data Source
Wheat flour products (% w/w)	67.1% refined flour, 13.8% whole flour, 19.1% bran.	Primary data from mill company
Wheat, economic allocation factors	Refined flour 78.5%, whole flour 14.2%, bran 7.3%.	
Rye flour products (% w/w)	16.5% refined flour, 72.6% whole flour, 10.9% bran	
Rye, economic allocation factors	Refined flour 16.8%, whole flour 78.8%, bran 4.4%.	

Some of the products used in the bread came from wet processing of cereals. The baking company had no information on the origin of these cereals.

4.5. Packaging

Data for the packaging system is given in Table 4. The packaging system consists of consumer packaging, which is used only once, and distribution packaging plus transport packaging, which are reused many times. In addition, most consumers use an extra bread pouch (see Table 6). This pouch can be had for free in the shops where the bread is bought and is normally used when consumers are cutting the bread in machines available in the shops; it is for this pouch that data was gathered. Some consumers use another plastic pouch for the bread; no data were available for these pouches, but the packaging material and weight is not expected to deviate significantly from the pouch given for free in shops.

Table 4. Data on packaging.

Packaging Element	Materials	Data Source
Consumer packaging	1.9 g, PET (*), 14.4 g paper	Baking company
Distribution packaging	4 kg box, HDPE (**), containing 12 loaves, estimated lifespan 6 years.	
Transport packaging	2.5 kg trolley, HDPE (**), containing 60 loaves, estimated lifespan of 10 years.	
Proportion of consumers using extra packaging	91%	[15]

(*) Polyethylene terephthalate. (**) High density polyethylene.

Data on production and retail bread waste was gathered directly from the baking company. The wastage along the value chain of bread is shown in Table 4.

4.6. Bread Production

Data on bread production and transport to retail is shown in Table 5. This is primary data gathered from the involved companies.

Table 5. Data on bread production and transport to retail.

Process	Data	Source
Transport from mill to baker	438 km on >32 tonne truck	Mill company
Baker energy consumption	0.297 kWh electricity and 0.115 kWh natural gas per bread	Baking company

4.7. Retail

Transport of fresh bread to retail in Norway is generally direct from bakery to retail without going through wholesale. The transport is usually carried out by the baking company, as in this case. The average driving distance for Norway is 0.5 km per loaf of bread. The bread is transported in small lorries, and the same vehicle that transports the bread to retail transports unsold bread back from retail to the bakery.

4.8. Consumer

The data that formed the basis of the calculation of consumer impacts are summarised in Table 6. The data is mostly secondary data except for the extra packaging.

Table 6. Data related to consumer impacts.

Process	Data	Source
Consumer transport	0.185 km by car and 0.0085 km by bus per kg product bought.	[26]
Extra packaging used by some consumers	3.55 g PE	Packaging producer
Reducing temperature from room temperature to below freezing	0.11 kWh/kg of bread, 417 kJ per kg of water. It is assumed that the same amount of energy is used for bread.	Physical tables.
Freeze storage of bread (keeping bread at −18 deg C)	Energy consumption of 4.2 Wh per litre per day. It is assumed that a loaf of bread occupies 2 L and is stored for two weeks.	Process “Freezer, big, B” in the LCA Foods DK database. Space requirement: Own measurement. Time: own assumption.
Toasting of bread	0.047 kWh/slice bread; 25 slices per kg of bread assumed.	[12]

4.9. Bread Waste

Bread and other bakery goods have some of the highest wastage rates among food products in Norway. Table 7 shows the amount of bread wasted in production, retail and in consumers’ homes.

Table 7. Data on bread waste along the value chain.

	Amount Wasted as % of Bread Entering the System	Source of Data
Bakery waste	3.3	Baking company
Retail waste	11.4	Baking company
Consumer waste	8.2	Calculated from consumption data in Reference [3] and wastage data in Reference [9].

4.10. Waste Management

The principal waste produced in the bread life cycle is bread waste and packaging. Table 6 contains data employed in the calculations relating to bread waste. Table 8 contains information used to calculate the environmental impacts of bread waste.

Table 8. Data on waste management.

Process	Data	Source
Bakery and retail bread waste	Used as feed for pigs. Energy required: 0.00397 kWh electricity and 0.70 MJ natural gas.	Baking company
Pig feed production from bread waste	Transport distances (road): 100 km from shop to processing plant and 60 km from processing plant to pig farmer. 10% product loss in the process, assuming avoided impact based on cereal content of bread.	Feed processing company
Consumer bread and packaging waste	Average waste treatment for Norwegian household waste: food: 5.0% landfill, 49% incineration, 21% composting, 25% biogas; plastic: 7.2% landfill, 67% incineration, 25.8% material recycling; paper: 0% landfill, 4.4% incineration, 95.6% material recycling. Transport distances and other data for calculating waste treatment impacts is given by Raadal et al.	[27] [28]

4.11. Division into Life Cycle Stages

For the purposes of gaining a clearer picture of the results, the processes were divided into life cycle stages.

- Ingredients: Agricultural production (including production of inputs and handling of all outputs), drying, processing and transport of ingredients used in bread.
- Bakery: Impacts of baking process, indirect and direct impacts of bread waste.
- Packaging: Production of consumer, distribution and transport packaging and the raw materials for the packaging; waste treatment of consumer packaging.
- Transport: Transport of ingredients to the bakery and of finished bread to retail.
- Retail: Energy consumption in retail.
- Consumer: Transport of bread from retail to consumer, freezing and toasting, indirect and direct impacts of consumer bread waste, extra packaging used by consumers and waste treatment of consumer packaging.

5. Results

5.1. Total Life Cycle Impacts

The total life cycle impacts using the CML method are shown in Table 9. Results calculated using the other LCIA methods (ReCiPe 2016 Midpoint Hierarchist and ILCD Midpoint) are shown in Table A1 (Appendix A).

Table 9. Impact of bread from cradle to grave.

Impact Category	Unit	Result
Global warming potential	kg·CO ₂ -eq	0.99
Photochemical oxidation potential	g·C ₂ H ₄ -eq	0.20
Acidification potential	g·SO ₂ -eq	8.41
Eutrophication potential	g·PO ₄ -eq	7.2
Abiotic Depletion Potential, elements	g·Sb-eq	0.002
Abiotic Depletion Potential, fossil	MJ·LHV	10,1
Water use	m ³	4,2
Cumulative energy demand	MJ	18,0

5.2. Hotspots

The contribution to the total impacts made by the varying stages in the food chain, exemplified by the GHG emissions, is shown in Figures 1–3. Figure 1 shows the distribution of impacts for individual processes and materials across the value chain. As can be seen, the greatest life cycle GHG emission came from the production of bread ingredients, chiefly from the cultivation of wheat. Consumer and retail bread waste were other important contributing factors, although bread waste from retail is utilised as pig feed and thus replaces other feed.

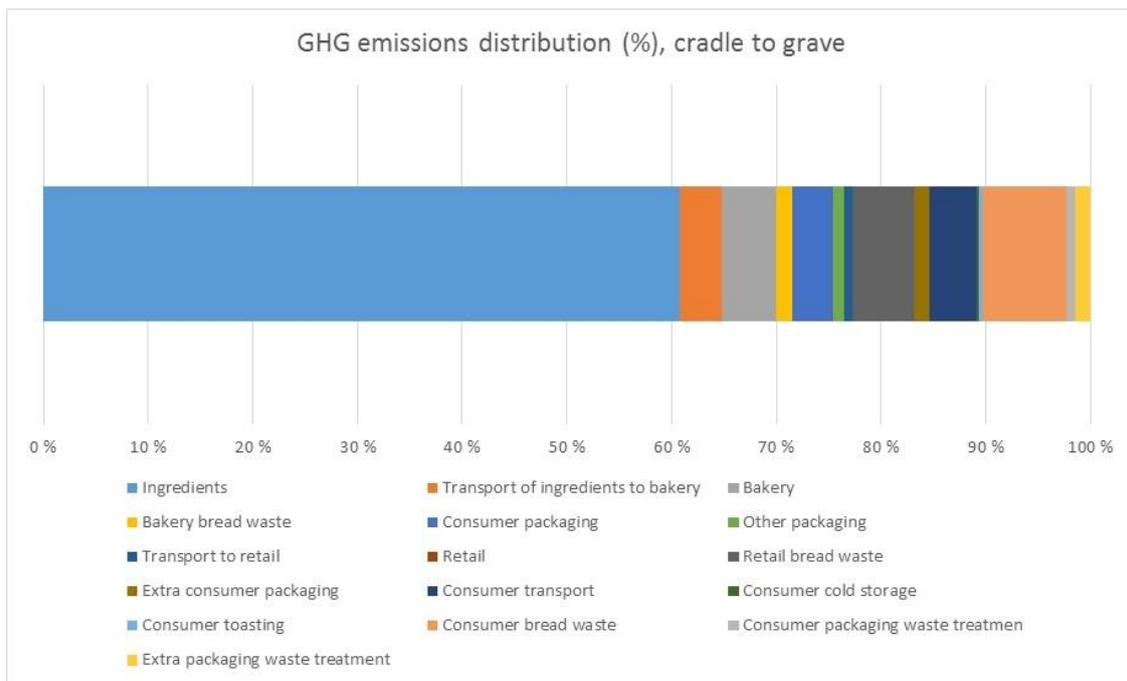


Figure 1. Distribution of GHG emissions across the value chain from cradle to grave.

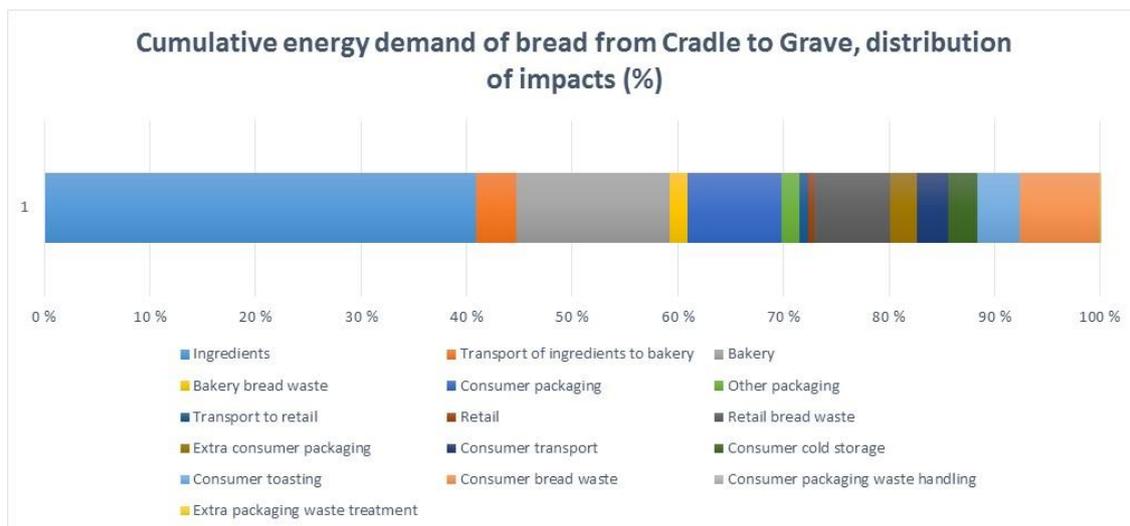


Figure 2. Cumulative energy demand across the value chain from cradle to grave.

Consumer packaging, baking and consumer transport were other major contributors.

Figures 2–4 show the distribution of other impacts from cradle to grave for bread. In all cases, the production of ingredients gave the highest impact, but the distribution of other impacts varied.

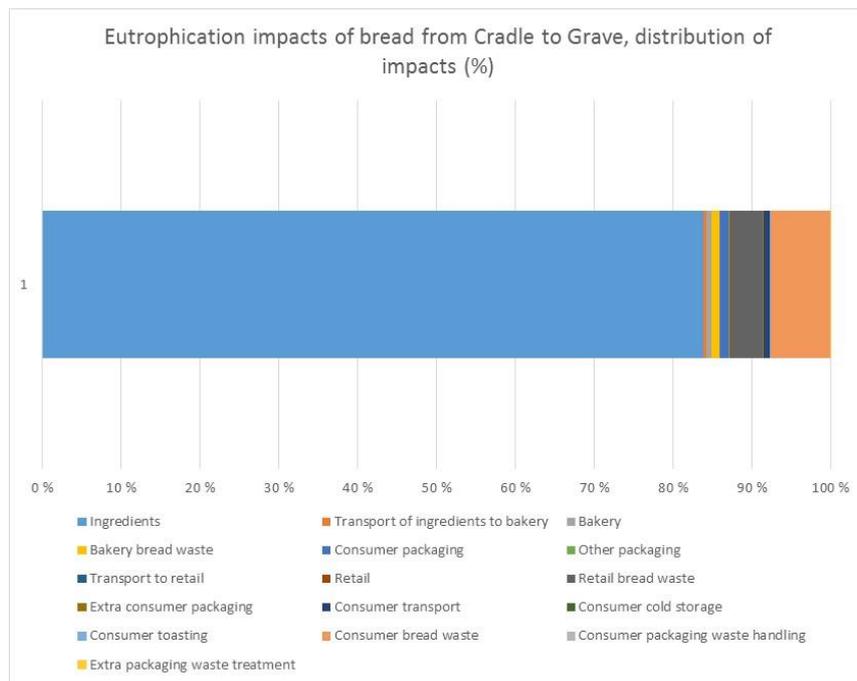


Figure 3. Eutrophication impacts across the value chain from cradle to grave.

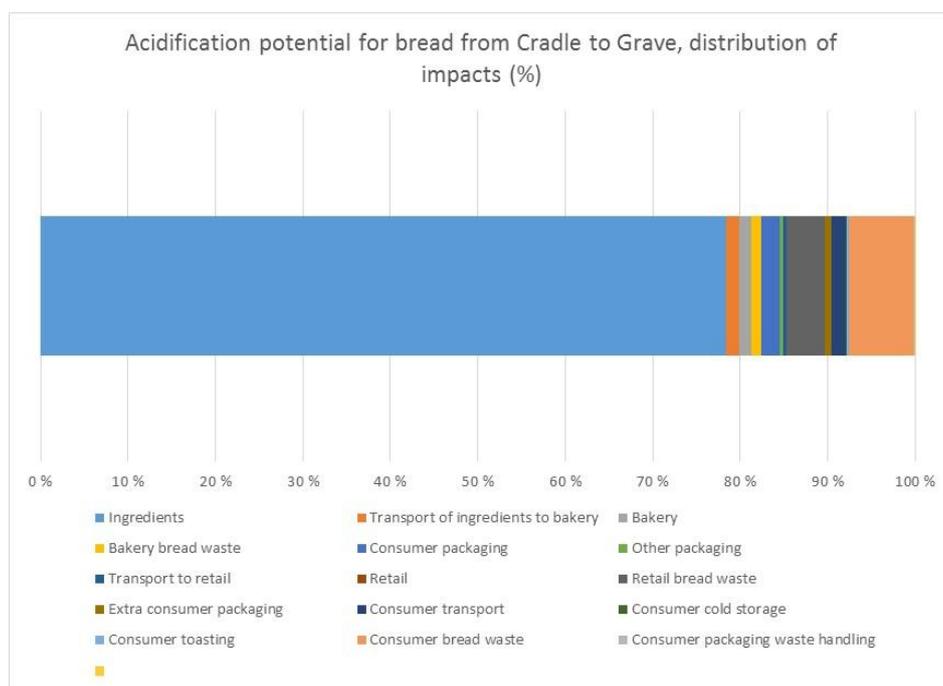


Figure 4. Distribution of acidification impacts across the value chain from cradle to grave.

Figure 2 shows that while the ingredient stage had the highest impact and bread waste was important for cumulative energy demand, the baking stage and consumer packaging also had a relatively high significance for GHG emissions.

Figures 3 and 4 show that in the case of eutrophication and acidification, the production of ingredients dominated completely and that the contribution made by the waste of bread by consumers was also noteworthy.

Figure 5 shows the distribution of GHG emissions at a more aggregate level. Again, the production of ingredients dominated, but the consumer stage was the second greatest contributing factor to GHG

emissions. For the production of ingredients, data on product wastage was not known, hence no data is given. For the distribution stage, the wastage was negligible. Packaging in this signifies the impact of production of raw materials, of the packaging and the waste handling. The impact shown in the figure is the impact of producing packaging and raw materials connected to bread waste as well as waste treatment for this packaging. In this figure, the indirect and direct impacts of bread waste are included in the section where the waste occurs. Retail wastage impacts, for example, are included in the retail section. However, influences across life cycle stages, such as the effect of consumer behaviour on retail bread waste, are not shown.

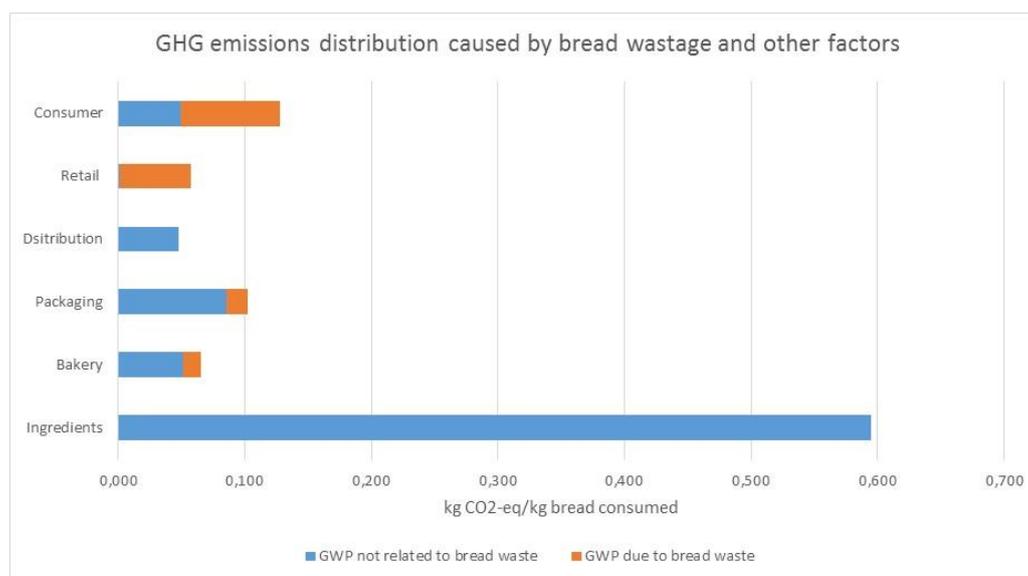


Figure 5. Distribution of GHG emissions for different life cycle factors.

5.3. Product Wastage and Packaging

The impact of bread waste comprises not only waste transport and waste handling but also the production of ingredients, the baking of the bread, distribution and all other impacts associated with producing new loaves to replace the wasted bread. In Figure 5, the effects of product wastage are visualised, with the exception of those at the ingredient production stage where data was not available. It is clear from the figure that the impact of product wastage gave rise to a significant proportion of the total GHG emissions at the consumer and retail stages. When comparing the total impacts in the different categories, we see that the share was also significant: 15.3% of total GHG emissions, 10.7% of eutrophication, 11.9% of acidification, 16.6% of ADP fossil (abiotic depletion potential, fossil resources), 19.4% of water usage and 16.4% of CED (cumulative energy demand).

It can be observed from Figures 1–4 that consumer packaging and waste handling made a relative low contribution compared with the other impact categories. For GHG emissions, the relative contribution was higher but still low in comparison with the other impacts. The whole packaging system was calculated here to include the total impacts from the production and waste handling of consumer, distribution and transport packaging. The impacts of this system when compared with the total impacts were 7.5% of total GHG emissions, 3.3% of acidification, 1.5% of eutrophication, 2.1% of water use, 11.6% of ADP fossil and 13.0% of CED. The impact of the packaging can thus be seen to be well below that of the bread waste.

The effect of product wastage is mitigated by the utilisation of bread waste from both bakery and retail as animal feed. The GHG emissions of 1 kg of bread used for feed was -0.26 kg CO₂-eq/kg of bread wasted, which decreased the GHG emissions of 1 kg of bakery bread waste by 37% and that of retail bread waste by 33%. However, the treatment of consumer waste in municipal waste treatment was less beneficial, giving a net impact of 0.04 kg CO₂-eq/kg of bread.

5.4. Impact of Processes That Can Extend the Life of Bread

Several processes or products have the potential to extend the life of bread. The most obvious example is the packaging, which protects the product from drying out as well as from microbial contamination and other degrading factors. Consumers also employ strategies to preserve the freshness of the bread. These include frozen storage, toasting or changing the packaging. Our analysis showed that the impact of the consumer's use of extra packaging was low at only 2.8% of the total GHG emissions. The impact of freezing and toasting was even lower at only 0.6%. In the case of CED, the share of total consumption was higher at 1.8% and 2.9%, respectively. These calculations were made using specific figures on consumer behaviour, which showed that almost 100% of consumers use an extra bag, whereas only 43% use freeze storage and 31% toast the bread.

5.5. Potential Measures for Reducing the Environmental Impact of Bread

A number of possibilities exist for reducing the environmental impact of bread, and some have already been exploited. One example is the utilisation of wasted bread from retail and bakeries as feed for pigs. Most consumer bread waste is sent for biological treatment or incineration. Very little household waste is sent to landfill in Norway, and this prevents significant emissions.

Looking at the results, several measures can be identified that offer a theoretical potential for reducing the environmental impact of bread. A 50% reduction in production waste would reduce GHG emissions by 0.9%, and reducing retail waste to 10% would give a 0.8% reduction. Completely eliminating retail waste would, however, reduce GHG emissions by 6.3%. If consumer waste was halved, that would create a 4% reduction in GHG emissions, whereas the elimination of such waste would result in 8% lower overall GHG emissions.

It is clear that measures targeting bread waste could have a major impact. One possibility is to further increase the amount of bread that is frozen and/or toasted. This would probably lead to a reduction in bread waste, but the total impact is difficult to calculate without further studies. The negative impact from such a measure is low, even if all bread is stored frozen and toasted before use, the consequence would be an increase in GHG emissions of 1.7 %, thus only a slight increase

If the original packaging is so good that consumers feel no need to choose to use an extra bag, the reduction in total GHG emissions would be 2.8%.

Alternative packaging solutions have been tested within the Breadpack project [29], of which this study forms a part. The first test, which was on a consumer packaging similar to that in existing use but with a different composition of cellulose fibres, showed that the bread remained fresh for an additional day (measured in crust firmness). This indicates that a change of packaging material could be an important measure in the prevention of food waste. A consumer test with a perforated paper bag coated on the inside with 5% PE showed that the bread was perceived by consumers as staying fresh for as long as four days after production. These tests ought to be carried out on a larger scale and in the actual value chain before any conclusions can be drawn. There is, however, a strong indication that environmental impact could be reduced as the bread would stay fresh for longer, and the consumer would be more likely to consume the entire loaf. The negative environmental impact of producing the bag and its raw materials is virtually identical, hence the overall substitution of the original packaging with either of the two tested packaging would probably be positive. Another possibility is to offer smaller-sized loaves. Such products have already been introduced into the Norwegian market, but it is still difficult to show their effect on bread waste.

6. Discussion

6.1. Total Impacts

The GHG emissions result in our study was 7% higher than a previous study [13] for Norwegian bread. Results for other impact categories could not be compared with that study because it is not clear which version of ReCiPe was used in that study. Comparison of aquatic eutrophication

with those found by Kulak et al [10] showed that the results were in the lower end in this study: 0.005 kg N-eq compared to 0.003–0.06 kg N-eq and 0.00021 kg P-eq compared to 0.00018–0.0016 kg P-eq. Other comparisons were difficult to make because the other published studies calculated GHG emissions only or used obsolete LCIA methods or LCIA methods that were unavailable in our software. By publishing results in several different LCIA methods, we hope to increase comparability in future bread studies.

The previous Norwegian study [13] did not take product wastage into account, so a lower GHG emissions result was to be expected. However, that study found very high CO₂ emissions from changes in SOC, whereas this study did not include that effect.

The reason that SOC was not included was partly because there is no internationally accepted methodology for calculating SOC changes in LCAs. The other justification is that the methodology used in Reference [13] was based on measurements made between the 1950s and 2001 [30], and it is not clear if these changes could be extrapolated and applied in 2018 or if a new steady state has been achieved. It is also not clear whether current users of the soil should be allocated emissions from a change in management practices and crop rotations that occurred 60 or 70 years ago. Another study [31] used a different methodology and had also found very different results, albeit in another geographical area. A sensitivity analysis was performed adding the SOC impacts (0.14 kg CO₂-eq/kg wheat) found by Bonesmo et al. [32] for all Norwegian wheat used in the bread but not the imported wheat. The effect was an increase of 0.06 kg CO₂-eq/kg of bread, i.e., +6%. This is a significant increase. If the SOC effect had been calculated for all 21 ingredients, it is possible that the increase might have been much higher. In future, more research ought to be carried out on the impact of SOC changes in the cultivation of cereals.

These two factors (SOC change and bread waste) have contrasting effects, which could explain the close similarity in the GHG emissions results. In the other impact categories, there was no clear pattern. Some results were lower, while others were higher. One difference in methodology could explain part of the variance. Korsæth et al. [13] used input–output methodology to calculate the impact of buildings, whereas regular LCA modelling was used in this study based on the simplified farm infrastructure included in the Agri-Footprint database. This gave a much lower impact of infrastructure for all impact categories in this study than in the Korsæth et al. study [13]. For example, the impact of infrastructure on the toxicity indicators was high, thus partly explaining the difference in toxicity impacts. In addition, the infrastructure impact of GHG emissions was much higher in the Korsæth et al. [13] study.

In comparison with the studies by Notarnicola et al., Kulak et al. and Espinoza-Oriaz et al. [10–12], the GHG emission result of the present study was at the lower end, although it was far higher than for the Danish rye bread [14]. In the case of Notarnicola et al. [11], this can be explained by the fact that the national bread types investigated in that study were for many countries. Rather than the staple, everyday bread, they were bread for special occasions. Many of these bread types contain significant quantities of ingredients of animal origin, thus explaining the high GHG emissions. In the study of bread from cereals produced using low input agriculture, the difference in GHG emissions can largely be explained by the much lower yield of such systems compared with the conventional agricultural systems supplying grains used in the bread in our study.

The reference systems used Kulak et al. [10] gave results at the same level as our study.

The carbon footprint study [12] produced significantly higher results than this study. The main difference was the impact of the consumption stage as a result of the refrigeration and toasting of the bread. This was because the UK electricity used in Espinoza-Oriaz et al. [12] is 71–76% of fossil origin. The actual consumption of electricity was higher in that study than the study here for storage (0.047 vs. 0.17 kWh) but lower for toasting (0.059 vs. 0.078). Nevertheless, even using the higher number for storage in this study would have a very low impact on the total GHG emissions.

The Danish study of rye bread [14] gave a GHG emissions result of 0.731, but it included an effect of the waste management of wasted bread (29% wasted in Denmark) of 325 g CO₂-eq/kg of

bread. This provided a major benefit when compared with the total GHG emissions. In this study, the net benefit of the wasted bread (21.3% wasted in Norway) was calculated as being just 33 g CO₂-eq/kg of bread. In Norway, the waste management of bread from households gave a net negative impact of 4.5 g CO₂-eq, which is in stark contrast to the huge positive impact of incinerated bread in Denmark. The reason for this is probably that the Danish energy system is dominated by fossil fuels, whereas electricity and district heating in Norway are largely produced from renewable sources.

6.2. Hotspots

The primary hotspot for all impact categories was the production of ingredients, or in other words, agricultural production. The production and processing of wheat gave rise to a majority of ingredient emissions, for example, 83% (0.50 kg CO₂-eq per kg of bread) of total GHG emissions. Of the total wheat-related GHG emissions, 37% (or 31% of total ingredient GHG emissions) came from wet-processed wheat. This wheat is not produced in Norway. In case of wheat produced in Norway, the main hotspots (as a percentage of GHG emissions) were N₂O emissions (38%), fertiliser production (25%) and fuel combustion and production (19%).

This is the same finding as in many other studies [11–14]. The bakery GHG emissions, however, was found to be relatively small compared with the findings by Notarnicola et al. and Espinoza-Oriaz et al. [11,12]. Refrigerated storage and toasting also contributed little, in contrast with the findings by Espinoza-Oriaz et al. [12].

The energy used in the baking, refrigeration and toasting was electricity. Emissions from electricity generation in the national grid mix was relatively low, whereas this was a hotspot for Notarnicola et al. [11]. This can in part be explained by the fact that the Norwegian electricity grid mix is dominated by hydroelectricity, which produces very low emissions in comparison with other electricity sources. Thus, baking, refrigeration and toasting had few consequences for the overall environmental impacts.

In this study, product wastage played a major role in the environmental impact, which was only found by Espinoza-Oriaz et al. [12].

Kulak et al. [10] found different hotspots for the various indicators and food networks. For some types of impacts, agriculture was most important, whereas transport or baking had the most significance for other impacts. This was not the case in this study, where the manufacture of ingredients dominated in all the impact categories.

6.3. Environmental and Economic Impacts of Product Wastage and Packaging

Packaging preserves products and limits product wastage. The results showed that the environmental impact of the packaging was significantly less than the impact of the bread waste. The GHG emissions of the packaging was approximately 7.5% of the total, whereas the GHG emissions of the product waste was 15.3% of the total. In another study [17], the economic cost of the packaging was found to be less than 10% of the cost of the food waste. These results contradict popular opinion among consumers that packaging is more of a problem than food waste [18]. Raising consumer awareness by communicating these findings could reduce bread wastage. Another implication of the fact that bread waste creates greater impacts is that an increase in the impact of the packaging could be justified if it led to lower product wastage.

The fact that bread is wasted at a certain life cycle stage does not imply that the bakery, retail shop or consumers are responsible for all the wastage that occurs at their respective stages. There can be factors in other parts of the value chain that contribute to this wastage. Consumers in Norway, for example, expect their favourite bread to be available at any time of day. The consequence of this is that retail shops overstock bread to ensure that all their bread products are available, even just before closing time. This results in an increase in retail waste, but the explanation lies in consumer expectations and preferences.

6.4. Potential Measures to Reduce Environmental Impact

Several possible measures exist with the potential to reduce environmental impact in the production of ingredients. At the agricultural stage, increasing yields while maintaining inputs at the same level offers significant potential. Uhlen et al. [33] reviewed several possible agronomic measures that would reduce impacts, while Korsæth et al. mentioned measures such as precision fertilisation and pest control [13]. Infrastructure impacts could be reduced if farm equipment is used over a more extensive area (ibid). Another promising reduction potential lies in the use of crop rotation for legumes and oil crops [34]. This improves soil structure, increases yields and reduces the incidence of plant disease compared with the cereal monoculture systems that is now commonly applied in Norway.

It is difficult to assess the actual effect of measures to prevent bread waste without carrying out tests in the market, but it would be reasonable to expect that frozen storage and toasting of bread would extend the shelf life of bread and thus reduce bread waste. The negative impact of toasting and frozen storage in this study was low (0.6% of GHG emissions), but the basis for calculation was uncertain. The impact of freezing was determined using old database data for storage and a theoretical calculation for the freezing using water as a proxy for bread. The impact of toasting was calculated using old figures from the UK [12] in the absence of newer data for Norway. The authors' own experiments suggest a much lower energy consumption per slice of bread, but in order to obtain a correct picture, consumer behaviour would have to be taken into account. Overall, the impact of toasting and frozen storage is shown in this study to be so low that the uncertainty in the area of electricity consumption has little effect.

In the Breadpack project, which this study formed a part of, one important aim was to reduce bread waste by developing a packaging that was more effective in preserving freshness. This would make consumers more willing to eat bread for a longer period after it was baked and would thus reduce bread waste.

The current packaging is not optimal for maintaining product freshness and thus limiting bread waste. New tests [29] on a packaging with a composition of cellulose fibres that differs from previous packaging has shown that the bread will keep fresh for an additional day (measured in crust firmness). This would indicate that a change of packaging material could be an important measure in the prevention of food waste. Further tests with a perforated paper bag coated with 5% PE on the inside showed it kept the bread fresh for as long as four days after production. This would help consumers to consume all the bread that they have bought.

One of the most avoidable environmental impacts is, in all likelihood, that caused by product wastage. However, judging from the authors' interviews with market players, it could be difficult to achieve a major reduction in bread waste. One reason for this is consumer behaviour and expectations. Norwegian consumers are generally unwilling to eat bread that is more than two days old. Another important factor also has to do with consumer behaviour. Consumers expect their favourite bread to be available in shops all day, even just before closing time. Because of fluctuations in sales, this means that stores always overstock and order more bread than they expect to sell. Thus, the elimination of bread waste becomes an unrealistic goal unless consumer expectations change. Retail shops do, in general, have take-back agreements with the bakeries. This means that the shop does not have to pay for unsold bread and that bakeries collect this bread at no cost to the shop. As shown in a previous study [35], this provides little incentive for the retail shops to reduce waste and may be an important contributor to retail bread waste. In many cases, however, it is the bakeries that have control; they know the stock levels (in real time) in many of the shops through their automated till systems and are therefore able to decide how much bread (and which type) should be re-stocked.

Despite the abovementioned difficulties, it is probable that bread waste levels will decrease because the motivation to achieve such a reduction is currently high. The food industry has signed a voluntary agreement with the Norwegian Government and other interested parties that has as a target of 50% reduction in food waste by 2030.

Another means of reducing the environmental impact of bread would be by increasing the efficiency of waste treatment. This could be achieved by utilising the bread as a source for biogas production. The environmental benefit of such treatment would strongly depend on how the produced biogas (for example, for fuel), and residual matter (for example, for fertiliser) were used and what they replaced [36].

7. Conclusions

The environmental impact of bread, per kg produced and consumed in Norway was as follows: global warming potential of 0.99 kg CO₂-eq, eutrophication potential of 7.2 g PO₄-eq, acidification potential of 8.4 g SO₂-eq and cumulative energy demand of 18 MJ. The impacts are at the same level, or lower, in comparison with other studies of bread, even though the wastage of bread in Norway is high and the climate is cold, giving lower grain yields than further south in Europe.

The primary hotspot for bread in Norway is the production of bread ingredients, followed by product wastage. The reduction of bread waste has a high potential in the reduction of bread-related environmental impacts. Changing the consumer packaging to a specific new variety, which was tested within this project, has a major potential for lessening environmental impacts through the reduction of bread waste. The environmental impacts of the packaging system are low, and the results of this change in consumer packaging would be negligible. Consumer behaviour affects bread wastage rates negatively because of a reluctance to eat bread that is not completely fresh and an expectation of finding one's chosen product on the shop shelves at any time of day. Consumers do, however, also employ strategies for keeping the bread fresh and thus reducing waste. They include extra packaging, freeze storage and toasting. These strategies have fewer consequences for environmental impact but a positive impact on bread consumption. In addition, the preference in Norway for wholegrain-based bread gives a relatively lower impact than in countries where white bread is most popular.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A.

Table A1. Results using other LCIA methods.

ILCD Method		
Impact Category	Unit	Result
Climate Change	Kg CO ₂ -eq	8.8×10^{-1}
Ozone depletion	kg CFC-11 eq	6.7×10^{-5}
Human toxicity, non-cancer effects	CTUh	2.0×10^{-6}
Human toxicity, cancer effects	CTUh	3.8×10^{-8}
Particulate matter	kg PM2.5 eq	6.0×10^{-1}
Ionizing radiation HH	kBq U235 eq	6.4×10^{-2}
Ionizing radiation E (interim)	CTUe	3.5×10^{-7}
Photochemical ozone formation	kg NMVOC eq	2.9×10^0
Acidification	molc H+ eq	1.4×10^{-2}
Terrestrial eutrophication	molc N eq	6.0×10^{-2}
Freshwater eutrophication	kg P eq	2.9×10^{-1}
Marine eutrophication	kg N eq	1.1×10^1

Table A1. Cont.

Freshwater ecotoxicity	CTUe	1.8×10^1
Land use	kg C deficit	1.9×10^1
Water resource depletion	m ³ water eq	3.6×10^{-3}
Mineral, fossil and re n resource depletion	kg Sb eq	3.1×10^{-2}
ReCiPe Method		
Global Warming	kg CO ₂ -eq	1.0×10^0
Stratospheric ozone depletion	kg CFC11 eq	9.7×10^{-6}
Ionizing radiation	kBq Co-60 eq	4.2×10^1
Ozone formation, Human health	kg NO _x eq	2.1×10^0
Fine particulate matter formation	kg PM _{2.5} eq	1.7×10^0
Ozone formation, Terrestrial ecosystems	kg NO _x eq	2.2×10^0
Terrestrial acidification	kg SO ₂ eq	9.2×10^0
Freshwater eutrophication	kg P eq	2.8×10^{-1}
Marine eutrophication	kg N eq	2.9×10^{-3}
Terrestrial ecotoxicity	kg 1,4-DCB	3.0×10^0
Freshwater ecotoxicity	kg 1,4-DCB	3.3×10^{-2}
Marine ecotoxicity	kg 1,4-DCB	4.2×10^{-2}
Human carcinogenic toxicity	kg 1,4-DCB	1.6×10^{-2}
Land use	m ² a crop eq	1.7×10^0
Mineral resource scarcity	kg Cu eq	1.7×10^{-3}
Fossil resource scarcity	kg oil eq	2.3×10^{-1}

Appendix B.

Table A2. Overview of secondary data used in the study (most important processes).

Process or Material	Database	Database Process
Wheat	AgriFootprint	Wheat grain, dried, at farm/PL Economic
		Wheat grain, dried, at farm/NO Economic
Rye	AgriFootprint	Rye grain, dried, at farm, NO economic
Barley	AgriFootprint	Barley grain, dried, at farm/SE Economic
Wheat gluten	AgriFootprint	Wheat gluten meal, from wet milling, at plant/DE Economic
Water as Ingredient	Ecoinvent	Tap water {Europe without Switzerland} market for Cut-off, U
Salt	Ecoinvent	Sodium chloride, powder {RER} production Cut-off, U
Yeast	Ecoinvent	Yeast paste, from whey, at fermentation/CH U
Sunflower seed	Ecoinvent	Sunflower seed {FR} sunflower production Cut-off, U
Sesame seed	Ecoinvent	Sunflower seed {FR} sunflower production Cut-off, U (as proxy)
Linseed	Ecoinvent	Linseed {RoW} linseed production Cut-off, U
Electricity	Ecoinvent	Electricity, low voltage {NO} market for Cut-off, U
Road transport	Ecoinvent	Transport, freight, lorry 16-32 metric ton, EURO5 {RER}
(Transport to retail)		Transport, freight, lorry 16-32 metric ton, EURO5 Cut-off, U
Road transport (other transport)	Ecoinvent	Transport, freight, lorry >32 metric ton, EURO5 {GLO} market for Cut-off, U
		Polyethylene terephthalate, granulate, amorphous {RER} production Cut-off, U
Consumer packaging	Ecoinvent	Kraft paper, bleached {RER} production Cut-off, U
		Extrusion, plastic film {GLO} market for Cut-off, U
Consumer extra packaging	Ecoinvent	Packaging film, low density polyethylene {GLO} market for Cut-off, U
Consumer transport	Ecoinvent	Transport, passenger car, small size, diesel, EURO 5 {RER} transport, passenger car, small size, diesel, EURO 5 Cut-off, U

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