MSc Program
Environmental Technology & International Affairs

Material Flow Analysis of Innovative Utilization Pathways of Bread Waste in Austria: Comparing Economic, Ecological and Social Criteria

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Affidavit

I, **LAETITIA SKALLA, MMSC**, hereby declare

1. that I am the sole author of the present Master's Thesis, "MATERIAL FLOW ANALYSIS OF INNOVATIVE UTILIZATION PATHWAYS OF BREAD WASTE IN AUSTRIA: COMPARING ECONOMIC, ECOLOGICAL AND SOCIAL CRITERIA", 92 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Bread ranks among the most discarded food items globally, contributing to approximately 30% of all food waste in Europe. In Austria alone, bread waste totaled 161,900 tons in 2024, with nearly 60% originating from households, followed by 32% from production and 8% from the retail sector. While public awareness and educational campaigns primarily target household-level waste reduction, this study shifts focus on evaluating innovative valorization strategies for the approximately 65,000 tons of surplus bread generated by the retail and production sectors. Specifically, it investigates the potential of converting bread waste into beer, animal feed, or bioethanol.

A material flow analysis (MFA) was conducted, supported by Sankey diagrams to illustrate both current and alternative waste pathways within the Austrian food system. To address data uncertainty, an uncertainty and error propagation analysis was applied, quantifying standard deviations for each scenario. The findings reveal that existing utilization routes result in estimated greenhouse gas savings of 32,600 ± 5,400 tons CO_2-equivalents compared to scenarios in which no repurposing occurs. Among the three valorization options, bioethanol production demonstrates the highest potential for environmental benefit, with estimated emission savings of 36,000 ± 3,370 tons CO_2-eq. In contrast, the production of beer and animal feed yields comparatively lower reductions of 29,900 ± 2,801 and 34,500 ± 3,230 tons CO_2-eq, respectively.

The study further evaluates these three pathways against the current fragmented approach, using a multi-criteria analysis incorporating environmental, social, and economic dimensions. Overall, the results highlight the substantial climate mitigation potential of bread waste valorization, with bioethanol production offering the most significant environmental advantage.

Preface

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Table of content

Abstract i

Preface ii

Table of content iii

List of abbreviations vi

Acknowledgements vii

1 Introduction 1

1.1 Global perspective 1

1.2 Food waste in Europe 2

2 Objective and Research Questions 5

3 Methodology 6

3.1 Literature research 6

3.1.1 Inclusion Criteria 6

3.1.2 Exclusion Criteria 6

3.2 Material Flow Analysis 7

3.2.1 System definition 7

3.2.2 Systemic boundary definition 8

3.2.3 Sankey visualization with Python 9

3.2.4 Identification of innovation pathways 9

3.2.5 Uncertainty analysis and error propagation 10

3.3 Qualitative Methods 11

3.3.1 Co-Creation Workshop 11

3.3.2 Semi-structured interviews 12

3.3.3 Criteria definition 13

3.3.3.1 Social Criteria 14

3.3.3.2 Ecological Criteria 14

3.3.3.3 Economic Criteria 15

4 State of the art 16
4.1 Global and EU bread production 16
4.2 Policy Frameworks (EU Level) 17
4.3 Bread waste valorization 18
4.3.1 Prevention 20
4.3.1.1 Forecasting systems 20
4.3.2 Rework 20
4.3.2.1 Reprocessing for bread making 21
4.3.3 Reuse 21
4.3.3.1 Redistribution and donation 21
4.3.3.2 Creative recipes 21
4.3.3.3 Animal feedstock production 22
4.3.4 Recycling 22
4.3.4.1 Fermentation 22
4.3.4.2 Ethanol Production 23
4.3.4.3 Biochemical production 24
4.3.5 Recovery 24
4.3.5.1 Biohydrogen production 24
4.3.5.2 Biogas production - anaerobic digestion 25
4.3.5.3 Incineration with energy recovery 26
4.3.5.4 Composting – aerobic treatment 26
4.4 Austrian bread production and waste context 26
4.5 Local initiatives 29
4.5.1 Incentives by bakeries 30
4.5.2 Making bread into alcohol for human consumption 30
4.5.3 Social organizations 30
4.5.4 Online tools 31

5 Results and Discussion 32
5.1 Material flow analysis of current situation 32
5.1.1 Status Quo 32
5.1.2 Uncertainty and error propagation analysis 34
5.1.3 Innovation pathways 37
5.1.3.1 Biorefinery 38
5.1.3.2 Animal Feed production 40
5.1.3.3 Beer production 41
5.2 Assessment Outcomes 44
5.2.1 Economic criteria 44
5.2.2 Ecological criteria 46
5.2.3 Social criteria 50
5.3 Discussion and comparison with other European countries 51
5.4 Data gaps and limitations 53
6 Conclusion 56
References 57
List of tables and figures 66
Appendix A: Interviews .... A

List of abbreviations

Anaerobic digestion	AD
AI	Artificial intelligence
Alchemia Nova Research Institute	ANRI
Bread waste	BW
CO_2-eq	Carbon dioxide equivalents
EU	European Union
FUSION	Food Use for Social Innovation by Optimizing waste prevention Strategies
g	grams
hl	hectoliter
kg	kilograms
L	liters
MJ	Mega joules
MFA	Material flow analysis
RURBANIVE	rural-urban synergies emerged in an immersive innovation ecosystem
SDGs	Sustainable Development Goals
TOC	Total organic carbon
UN	United Nations

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1 Introduction

1.1 Global perspective

Food waste stands as one of the most damaging outcomes of excessive consumption and commercial practices, and is widely seen as a failure of market systems. The World Bank reports that food valued at over USD 1 trillion is lost each year, more than one-third of all food produced globally equaling to 1.3 billion tons (Schanes, Dobernig and Gözet, 2018, FAO, 2013). This waste is not only a moral and economic issue, but also an environmental one: it accounts for roughly 8–10% of global greenhouse gas emissions releasing up to 3.3 billion tons of CO_2 per year (Vimala Ebenezer et al., 2020), and it uses up close to 30% of the world's agricultural land. Agricultural expansion, often into natural habitats, continues to be a major contributor to biodiversity loss. On a human level, the issue is equally urgent accompanied by a broad range of environmental impacts, such as soil erosion, deforestation, water and air pollution (Schanes, Dobernig and Gözet, 2018). While enormous amounts of edible food are discarded, an estimated 783 million people suffer from hunger globally. Moreover, around 150 million children under the age of five experience stunted growth due to chronic malnutrition and insufficient access to essential nutrients (UNEP, 2024).

The United Nations (UN) Sustainable Development Goals (SDGs) outline the target to "*halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses*" (UN, 2015). The most significant food losses occur during post-harvest handling, emphasizing the crucial influence of supply chains in meeting the objectives of SDG 12. Food loss and waste are present across all levels of the supply chain, not just during consumption, but also in agriculture, production, processing, logistics, retail, and hospitality sectors. However, the extent and nature of food loss and waste varies by region with big differences between developed and developing countries (Vimala Ebenezer et al., 2020). In wealthier nations, such as those in Europe and North America, losses are mainly concentrated at the consumer level while in developing countries most waste is generated post-harvesting (Schanes, Dobernig and Gözet, 2018). The farther along the chain food is discarded, the greater its environmental impact becomes, as it accumulates emissions from all previous phases such as cultivation, processing, and transportation. Essentially, when food is ultimately wasted, all the resources and emissions invested in its journey through the supply chain are wasted as well (Scherhaufer et al., 2018). While most countries found in Europe allocate substantial budget to waste handling, recovery and reduction schemes, many developing and underdeveloped countries still rely on composting or landfilling (Vimala Ebenezer et al., 2020). Still, developing countries overall generation of food waste is much lower compared to developed countries. In high-income countries, each person generates approximately 107 kilograms of food waste annually on average, whereas in low- and middle-income countries, the figure is significantly lower, around 56 kilograms per person per year (Rahman et al., 2024).

1.2 Food waste in Europe

While the generation of food waste is a global issue, positive developments can only be achieved when looking at a continental or even regional level. In the European Union, studies by Eurostat have shown that 20% of the total food produced is lost or wasted every year, while 32.6 million people cannot afford a quality meal (EC, 2023). Recent estimates indicate that approximately 88 million tons (±14 million tons) of food waste are generated annually across the European Union's supply chain. This corresponds to an average of 173 ± 27 kilograms of food waste per person each year (Scherhaufer et al., 2018). In 2012 FUSION (Food Use for Social Innovation by Optimizing waste prevention Strategies) estimated the economic cost of food waste in the EU to 143 billion euros with 88 million tons of discarded food (Vimala Ebenezer et al., 2020). A more recent estimation by Eurostat in 2022 estimated the food waste generated yearly to be over 59 million tons which equals to 132 kg per inhabitant and an associated market value of 132 billion euros (Eurostat, 2022).

Since 2015, the European Union (EU) has steadily advanced its commitment to food waste reduction through a series of strategic initiatives and policy developments. The adoption of the 2030 Agenda for Sustainable Development introduced SDG target 12.3, which aims to halve per capita global food waste at the retail and consumer levels and reduce food losses along the supply chain. That same year, the EU identified food waste reduction as a priority within its Circular Economy Communication (EC, 2015).

Between 2016 and 2021, the EU Platform on Food Losses and Food Waste carried out its first mandate, contributing to key outputs such as the publication of food donation guidelines in 2017 and feed use guidelines for food no longer fit for human consumption in 2018. In 2019, the platform delivered a set of major recommendations, laying the groundwork for more targeted policies. The 2020 *Farm to Fork* strategy intensified efforts to prevent food loss and waste across the Union (EC, 2024). Subsequent initiatives included the 2021 launch of the EU *Food Loss and Waste Prevention Hub* and the *European Consumer Food Waste Forum* project, which addresses consumption-level waste. A second mandate of the EU Platform began in 2022, accompanied by annual grants aimed at improving food waste measurement and prevention practices in member states (EC, 2024). On July 5, 2023, the European Commission proposed legally binding reduction targets under the revision of the Waste Framework Directive, currently under negotiation. These targets are aligned with Sustainable Development Goal 12.3 (UN, 2015). Based on the EU's first comprehensive food waste monitoring conducted in 2020, the proposed reduction goals include a 10% decrease in food waste from food processing and manufacturing, and a 30% per capita reduction in the retail and consumption sectors, including restaurants, food services, and households, by 2030 (EC, 2024). In 2024 the EU also released a digital toolkit for consumer-focused waste reduction actions and the launch of the *Zero Waste, More Taste!* campaign, which promotes sustainable cooking with contributions from chefs across the EU (EC, 2024).

Member States will have 20 months to integrate these rules into national legislation once the directive is formally adopted. A progress review is scheduled for the end of 2027, which will consider food losses during primary production, how shifts in production volumes affect the feasibility of targets, and whether updated goals for 2035 should be introduced. The Commission also plans to introduce a correction factor to account for tourism's impact on food waste levels and encourages member states to implement targeted actions to increase food donation and reduce avoidable waste (EC, 2015).

In recent years many advancements have been made in utilizing food waste and producing beneficial end-products. The amount of waste generated could be stabilized and the implementation of anaerobic digestors has allowed biogas production which then is converted into useful energy (Vimala Ebenezer et al., 2020). While there have been many progressions in reducing and valorizing leftover foodstuff, Europe has not yet achieved the waste reduction targets as outlined in the circular economy action plan (EC, 2015).

Addressing food waste effectively requires not only technical solutions but also systemic change that bridges rural and urban contexts. Much of this waste occurs along complex supply chains that span both rural production areas and urban consumption centers, highlighting the need for integrated, cross-territorial approaches to sustainable food system governance. Yet these regions are frequently managed in isolation, which limits the development of coordinated responses to shared challenges such as food waste, biodiversity loss, and unsustainable logistics. Enhancing rural-urban connectivity, through mutual cooperation, knowledge exchange, and policy alignment has the potential to significantly improve the efficiency and sustainability of food systems (RURBANIVE, 2025).

The EU-funded rural-urban synergies emerged in an immersive innovation ecosystem (RURBANIVE) project offers a timely and innovative response to this issue by fostering bi-directional synergies between rural and urban areas. While not exclusively focused on food waste, the project's emphasis on circular bio economy, shortening value chains, and participatory stakeholder engagement provides a framework that can directly support waste reduction initiatives. RURBANIVE promotes innovation in areas critical to food systems transformation, including biodiversity restoration, territorial awareness, cultural heritage, and sustainable mobility (RURBANIVE, 2025).

Central to the project is the establishment of a digital environment which serves as a collaborative platform for sharing practices, policies, and tools that enhance rural-urban cooperation. Coupled with immersive methodologies implemented through co-creation workshops, the project facilitates local experimentation, policy innovation, and cross-regional learning. This integrated approach aims to strengthen territorial governance and foster inclusive, well-being-oriented economies that are better equipped to address complex challenges like food waste (RURBANIVE, 2025).

By supporting territorial cohesion and enabling local stakeholders to co-design and implement context-sensitive solutions, RURBANIVE contributes to the broader EU agenda of sustainable development and circular economy. Its participatory framework and emphasis on replicability position the project as a model for addressing food system inefficiencies at the intersection of rural and urban policy domains (RURBANIVE, 2025).

This research is expected to offer significant value to Austria's bio economy, particularly in the regions of Vienna and Lower Austria, by examining existing food waste management practices and exploring innovative strategies for enhancing resource circularity. By identifying opportunities to repurpose food that would otherwise be discarded, the study aims to support the development of more sustainable and efficient utilization pathways. Ideally, this approach will reveal potential synergies that generate mutual benefits for all stakeholders involved.

2 Objective and Research Questions

This scientific study aims to collect both quantitative and qualitative data on the volume of bread waste (BW) generated along the value chain in Austria, with a particular focus on the regions of Vienna and Lower Austria. The collected data was analyzed and evaluated in terms of quality, and innovative pathways for prevention, reduction, and reuse were examined for their efficiency and effectiveness. In addition, expert interviews with stakeholders from the industry provided empirical insights and practical recommendations.

A Sankey diagram was developed to visualize the material flow of BW across the different stages of the value chain. Based on these findings, policy recommendations and potential regional synergies were identified and discussed.

Ultimately, the study aims to provide a clearer picture of the actual scale of BW, drawing on data from a range of actors such as bakeries, supermarkets, production facilities and consumption centers. It further evaluates which approaches hold the most promise for enhancing food waste reduction strategies across both urban and rural contexts.

To meet these objectives, the thesis will address the following research questions:

1. What are the current mass flows and existing uses of BW in Austria?
2. What is the potential for innovative applications of BW to create valuable by-products?
3. What criteria must be met for such innovations to be viable from social, economic, and ecological perspectives?
4. What is the ideal circularity scenario regarding the environmental impact for BW streams, considering these criteria?

3 Methodology

3.1 Literature research

A systematic literature search was conducted to identify relevant academic literature on the topic of improving the circularity of stale bread. The goal was to gather comprehensive insights into current practices, technologies, policies, and innovations aimed at reducing BW and enhancing resource efficiency within a circular economy framework.

To ensure a broad yet targeted search, a combination of keywords and boolean operators was used. The following search terms were applied individually and in various combinations: "stale bread", "bread waste", "food waste valorization", "circular economy", "food recycling", "bread upcycling", "surplus bread", "waste-to-value", "reusing bread", "bread waste management", and "circular food systems".

The literature search was performed across several academic and scientific databases to ensure a comprehensive review: Google Scholar, ScienceDirect, and SpringerLink. In addition, relevant reports and publications from organizations such as the FAO, European Commission, United Nation agencies, and Federal Ministry on the Environment of Austria were considered to include policy perspectives.

3.1.1 Inclusion Criteria

- Publications from 2010 onwards, to ensure relevance to current technologies and sustainability frameworks (exceptions taken for the methodological approach of Material Flow Analysis)
- Peer-reviewed articles, conference papers, technical reports, and dissertations
- Legal frameworks and EU-related documentation of food waste reduction schemes
- Studies focusing on bread waste management, food waste valorization, or circular economy practices in the food sector
- Research in English and German
- Practical case studies and industrial applications

3.1.2 Exclusion Criteria

- Articles not available in full text
- Publications focusing solely on general food waste without reference to bread or cereal-based products

- Studies centered exclusively on consumer behavior with no link to circularity or valorization
- Duplicates and non-academic sources with insufficient citation credibility

3.2 Material Flow Analysis

MFA is a methodological approach used to trace the movement of materials within a defined geographic region (Brunner and Rechberger, 2004). It is frequently applied in areas such as waste management, offering insightful system-level evaluations that aid in informed decision-making and the enhancement of resource efficiency within environmental sanitation systems (Vobruba et al., 2025). In this research, MFA is employed to simulate various scenarios for bread reuse, integrating both empirical findings and values from existing literature. The approach follows the foundational framework, which includes three main steps:

(1) defining the system by identifying relevant materials, processes, indicators, and boundaries;

(2) measuring the quantities of materials and key substances in the system; and

(3) visually presenting and analyzing the results to inform planning efforts.

3.2.1 System definition

The system to be analyzed can structured into four main levels:

1. Bread production and waste generation
2. Collection and sorting
3. Waste disposal
4. Different valorization pathways

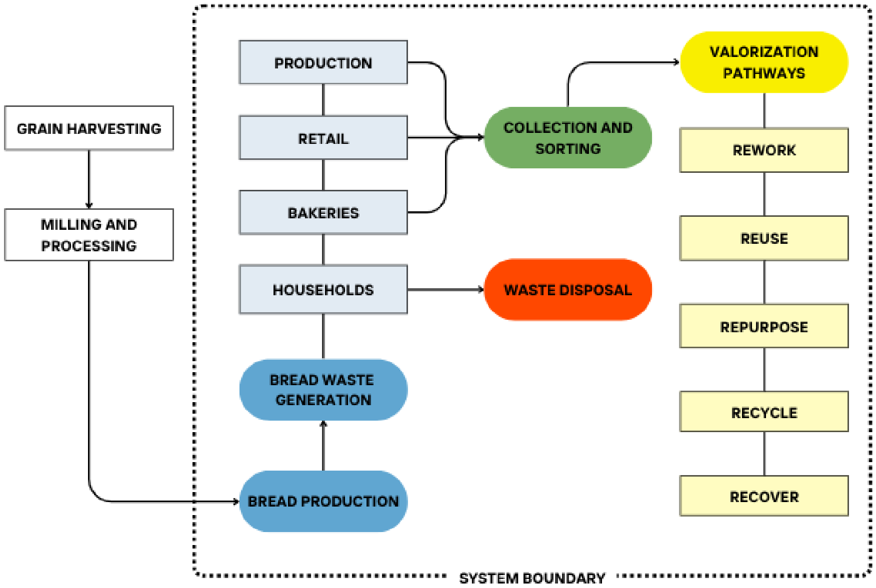

Figure 1: Visualization of the system boundary for this research project.

3.2.2 Systemic boundary definition

To achieve results with high accuracy the system boundaries and assumptions were defined before the quantitative analysis using the Sankey tool was started.

The research focusses on BW generation in the country of Austria with primary consideration of the region of Vienna and Lower Austria. However, international case studies may be referenced if they offer transferable insights or scalable innovations.

System boundaries include that only bread is taken into consideration and other bakery goods such as cake or cookies are not included in the search; however, it is important to mention that when considering household waste often no clear distinction is possible. Moldy or bad bread products are also not considered in the evaluation and are assumed to be allocated to residual waste and incinerated.

Additionally, all numbers utilized in the MFA and visualization tool are representative of the BW collected within the year of 2024. Stale bread generated in the hospitality sector, was not taken into consideration as there was no quantitative evaluation of the amount possible. In the European Union, there is currently no legal requirement for cafés, restaurants, or hotels to report their food waste generation. While the EU has set food waste reduction targets, such as a 30% per capita reduction in the retail, restaurant, food service, and household sectors by 2030, these targets do not mandate individual businesses to report their food waste data. Consequently, a significant portion of food waste, including surplus bread, may go unrecorded and is often disposed of through general waste streams, potentially ending up in incineration or landfill facilities (Cardenas, Schivinski and Brennan, 2024).

3.2.3 Sankey visualization with Python

For the MFA a technical tool provided by Alchemia Nova Research Institute GmbH (ANRI) was employed. This tool enabled the visualization of the material flow streams of BW with the support of Excel and a Phython™-based programming application. The material flow numbers were populated into an Excel-template, then the python program accessed this data via the Anaconda© package and a pre-defined sequence of commands using Jupyter® Notebook.

To calculate the material flows, the BW data from the year 2024 published in an article of Land Schafft Leben were applied (Land Schafft Leben, 2024). Next, the percentage-based share of waste bread per treatment and disposal option in Austria were used and multiplied with the overall BW generation in tons. This allowed the visualization of the status quo bread utilization pathways. To be able to compare the numbers more easily, the per capita amount of generated BW in a year was calculated. To achieve this, a population of 9.2 million people in Austria was assumed as indicated by Statistik Austria (Statistik Austria, 2025).

For a more innovative approach, the mentioned alternative pathways were investigated based on their environmental impact as well as social and economic feasibility in Austria. Based on this rating, three hypothetical MFA were established, which illustrate possible future valorization pathways that strengthen circular practices in Austria.

3.2.4 Identification of innovation pathways

A relevant part of this thesis encompasses the development of hypothetical innovative pathways of BW valorization. In total three innovative pathways were chosen and visually represented in a Sankey diagram. The hypothetical pathways were then discussed based on social, economic and ecological criteria as defined below. The choice of innovative pathways was based on literature review and the status quo of BW valorization in Austria. In these scenarios, it was assumed that all surplus bread not originating from households is directed into the proposed valorization pathways. Additionally, the potential impact of reducing household bread waste by 50%, through the implementation of improved decentralized collection systems and the redirection of half of this waste stream toward composting, was also assessed.

The three pathways identified include (1) a biorefinery approach using enzymatic hydrolysis as described by Kumar et al. (Kumar et al., 2023a) to produce the three platform chemicals succinic acid, lactic acid, 2,3-Butendiol and bioethanol, (2) beer production following the principles of Toast Brewing and general beer brewing assumptions regarding water content and (3) animal feed production.

All numbers to develop the MFA are taken from the sources mentioned, especially chemical production techniques are assumed to have similar yields across diverse facilities. For the biorefinery approach solely the production technique of enzymatic hydrolysis was investigated to allow better comparison between the resulting base chemicals.

3.2.5 Uncertainty analysis and error propagation

Although the official figures on BW provided by *Land Schafft Leben* and other Austrian governmental sources serve as a useful starting point for analysis, significant inconsistencies within the data were identified. Consequently, a more tailored methodological approach was required to address the associated uncertainties. To mitigate error propagation in accordance with Gauss's law throughout the research process, a support tool developed by Laner et al. was employed. This tool enables a systematic evaluation of data quality and the characterization of uncertainties prior to constructing a balanced material flow model. (Laner et al., 2016).

Data quality was evaluated using a modified pedigree matrix approach, based on five indicators:

1. Reliability – transparency and method of data generation
2. Completeness – coverage of relevant flows or processes
3. Temporal Correlation – match between the data year and study year
4. Geographical Correlation – regional relevance of the data

Each indicator was scored on a scale from 1 (high quality) to 4 (low quality), based on qualitative criteria. Indicator scores were translated into quantitative uncertainty using coefficients of variation (CV), assuming normally distributed errors. The CVs were derived using exponential-type functions according to the formula:

$$CV = a * e^{b*(s-1)}$$

Where: CV = coefficient of variation; s = indicator score (1–4); a, b = sensitivity parameters depending on the indicator's relevance to the specific data. For example, flows deemed highly sensitive to a particular indicator (e.g., temporal mismatch in fast-changing technologies) were assigned a higher *a* value.

Error propagation refers to how uncertainties in measured or otherwise determined values affect the final result when those values are used in calculations. The rules for propagating errors are based on the Gauss law and depend on the mathematical operations performed on the measured quantities.

Let's assume we have two measured values, where A and B are mean values, and σ_A and σ_B are their standard deviation.

When adding or subtracting values, the absolute errors add in quadrature:

$$C = A \pm B \rightarrow \sigma_C = \sqrt{\sigma^2_A + \sigma^2_B}$$

For multiplication and division, the relative errors (fractional uncertainties) add:

$$C = A \times B \text{ or } C = \frac{A}{B} \rightarrow \frac{\sigma_C}{C} = \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2}$$

3.3 Qualitative Methods

Accompanying the quantitative methodology of producing a material flow diagram, additional empirical data was gathered in the form of interviews and a workshop. A range of stakeholders were contacted, from which following have agreed to be publicly mentioned: Erika Geier, CEO of Geier bakeries in Austria; Moritz Aschauer, bakery owner and alcohol producer out of old bread; Silvia Scherhofer, food waste researcher at BOKU Vienna; and Sarah Lerchner, StartUp Founder of Brüsli, a cereal made out of surplus bread production. All other interviewed participants prefer to remain anonymous.

Figure 2 illustrates the identified stakeholders and sorts them according to their influence and interest level. The stakeholder analysis was performed by comparison and based on the market value of the mentioned institutions.

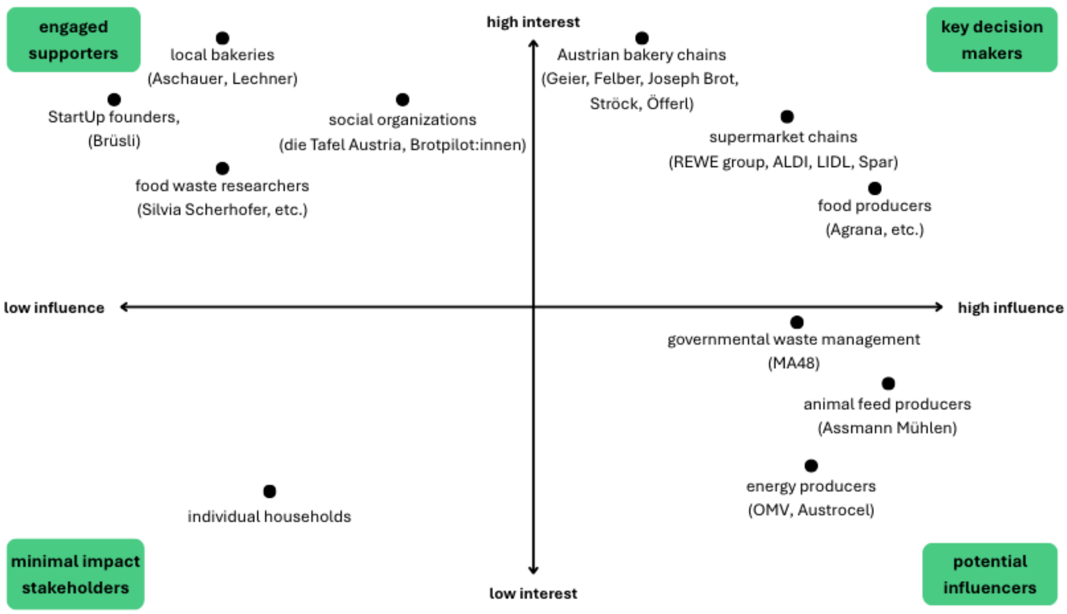

Figure 2: Key stakeholders in the Austrian bread economy according to their level of interest and influence in the Austrian economy regarding BW.

3.3.1 Co-Creation Workshop

A regional stakeholder workshop was held on the 15th March 2025 to gain empirical data on the issue and interact with stakeholders and experts in the field. ANRI together with Stadt Umland Management and and BioBase co-organized the four-hour workshop within the framework of the

RURBANIVE project. During this workshop the research question and thesis outline was presented, before an interactive discussion and brainstorming session. Although the discussions covered several food stuff categories, including used cooking oil, fruit residues and bread, this thesis concentrates specifically on the bread component. The data acquired through this co-creation workshop encompass videos, recordings, images and a poster on which new-found ideas and thoughts were summarized. The importance of transdisciplinary research and involvement of actors outside of academia was described by Lang et al. and relates to the workshop conducted (Lang et al., 2012).

The workshop aimed to achieve several objectives: (1) Examine current resource flows associated with surplus bread, (2) identify existing data gaps and practical implementation challenges in circular economy initiatives, (3) generate initial concepts for sustainable resource valorization, (4) prioritize transformation pathways with high potential for further investigation and (5) gather personal insights of the regional stakeholders on current practices, innovative applications, priority areas and information gaps.

3.3.2 Semi-structured interviews

To support the development of this study, semi-structured interviews were conducted to collect mainly qualitative data on current practices in bread valorization. This approach aligns with the idea that transdisciplinary research should include outcomes of research and practice, extending beyond purely theoretical research (Scholz and Steiner, 2015). Stakeholders were interviewed regarding perceived barriers and enablers to valorization, and stakeholder perspectives on the feasibility and desirability of various innovation pathways were assessed. The stakeholders included primary producers (e.g. bakeries), food waste researchers, supermarket chain management, and actors involved in circular economy initiatives. Additionally, entrepreneurs working on innovative applications, such as the production of cosmetics from stale bread were contacted.

Participant selection is based primarily on the existing network of Alchemia Nova, supplemented with cold outreach across stakeholder groups of the bakery industry. For example, larger bakeries were contacted to reflect the scale of processing operations, while smaller producers are included to capture diverse operational perspectives. This inclusive approach is consistent with the participatory nature of the thesis, which aims to incorporate a wide range of viewpoints into the modelling and evaluation process.

The interviews are guided by a flexible protocol, with questions slightly adapted to each stakeholder's role and expertise. Interview partners were contacted via email and meetings were held online. Stakeholders that agreed to be mentioned will be named, others will remain anonymous. The interviews held in German were translated into the English language and can be found in Appendix 1. The following set of interview questions has been prepared and discussed with stakeholders:

- What reuse or recycling pathways for surplus bread are you familiar with or currently apply within your institution?
- Approximately how much bread waste does your institution generate on a weekly basis? In your opinion, how significant is the amount of unreported bread waste across the sector?
- Why do you think restaurants and cafés are not legally required to disclose the amount of food they waste? What potential opportunities for reuse or valorization do you believe are lost due to this lack of transparency?
- Have you come across any innovative bread waste valorization methods that were not mentioned in our discussion but that you've heard of or experienced yourself?
- In your view, what are the main barriers to implementing a more circular food system? Based on your expertise, what concrete steps could individuals or institutions take to help overcome these challenges?
- Do you believe there are already enough alternatives and solutions available on the market for food waste reduction? Or do you feel that certain aspects of food rescue and reduction are still being overlooked?
- From your experience, where do you see the greatest potential for creating regional synergies between rural areas and a city like Vienna to further reduce bread waste?
- Regarding bread waste: Which social, economic and ecological criteria influence the current and future utilization pathways?

3.3.3 Criteria definition

Drawing on the co-creation workshop and the overall RURBANIVE framework, it was essential to identify social, environmental, and economic criteria to evaluate how valuable and practical each innovative bread waste utilization pathway could be. To keep the discussion focused, only the most relevant criteria for each subgroup were selected, resulting a total of nine criteria. All three innovation pathways were then compared to the current bread waste utilization practices in Austria using these selected criteria.

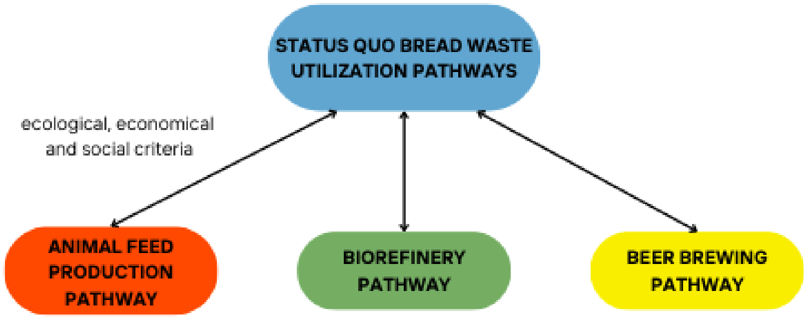

Figure 3: Visual representation of comparison approach between the current status and the three identified innovation pathways. Each pathway is compared to the status quo based on social, ecological and economic criteria defined.

3.3.3.1 Social Criteria

- Affordability and Health: Refers to the ability of consumers, across income levels, to access high-quality, nutritious, and safe products. This includes the product's pricing, its alignment with health guidelines, and its contribution to public well-being.
- Regionality/Regional identity and actors: Reflects how well the product aligns with the cultural, social, and economic characteristics of a specific region. It includes local sourcing, support for regional economies, and involvement of local stakeholders or producers, reinforcing regional pride and sustainability.
- Awareness: Encompasses public knowledge and perception of the product or practice.

3.3.3.2 Ecological Criteria

- Greenhouse gas emissions: Focuses on the total GHG emissions throughout the product's lifecycle, from raw material extraction to end-of-life disposal. Lower emissions contribute positively to climate goals and environmental responsibility.
- Transport resources: Evaluates the environmental impact associated with the logistics of the product, such as transportation distances, modes of transport, and resulting emissions. Shorter, more efficient supply chains are typically preferred.
- Energy demand: Assesses how much energy is required at various stages-production, processing, packaging, and distribution. Emphasis is placed on energy efficiency and the use of renewable versus non-renewable sources.

3.3.3.3 Economic Criteria

- Market integration: Measures how readily the product or practice can be integrated into existing market systems and its potential to gain customer and stakeholder acceptance. This includes compatibility with current regulations, supply chains, and consumer preferences.
- Market readiness: Refers to whether the product can be reliably produced, distributed, and sold at scale.
- Infrastructure availability: Assesses whether the necessary facilities and technologies exist (or can be feasibly developed) to process the product efficiently. Lack of infrastructure can be a significant barrier to scaling.

4 State of the art

4.1 Global and EU bread production

Around half of the world's primary crop output comes from just four key crops: sugarcane, maize, wheat, and rice. Among these, cereals were the most heavily traded agricultural commodity by volume in 2022. Globally, cereals also occupy more than 50% of all harvested agricultural land. The FAO includes a wide range of crops under cereal production, such as wheat, paddy rice, maize, barley, popcorn, rye, oats, sorghum, millets, buckwheat, quinoa, fonio, triticale, canary seed, mixed grains, and other cereals not elsewhere specified. Europe and the Americas lead in cereal exports, while Asia stands as the largest importer (FAO, 2024).

Bread is an essential part in the diet worldwide with an average consumption of 59 to 70 kg per capita per year. Wheat is the primary grain used in bread production due to its ability to form dough with favorable characteristics when combined with yeast. Additionally, it serves as a staple food for around 40% of the global population, largely because of its valuable nutritional content. As a result of its versatility and capacity to grow in diverse climatic environments, wheat accounts for 27% of the total cereal production worldwide (Mesta-Corral et al., 2024).

Globally, more than 100 million tons of bread are produced annually, with consumption reaching 129 million tons in 2016. However, due to its limited shelf life and frequent overproduction, approximately 10% of bread, equivalent to about 900,000 tons, is lost along the supply chain, from production to final consumption. This level of BW presents a significant issue across the supply chain. BW represents a substantial portion of overall food waste worldwide with nearly 29.1% discarded and is especially problematic in Europe, where the market accounts for the highest share (53.6%) (Ben Rejeb et al., 2022, Kumar et al, 2023). Bread is one of the most frequently wasted food items at multiple points in the supply chain, and in many countries, it forms a major part of national food waste. For example, BW contributes 13% in Finland, 22% in the Netherlands, 23% in New Zealand, 27% in Norway, 7.9% in Portugal, 18.7% in Saudi Arabia, 2.2% in South Korea, and between 12–17% in Sweden (Kumar et al., 2023).

This widespread loss has both environmental and economic consequences. As organic waste, bread emits greenhouse gases like carbon dioxide and methane. An 800 g loaf can generate around 100 liters of biogas, over 60% of which is methane, contributing significantly to air pollution. Its carbon footprint ranges from 977 to 1244 g of CO_2 (Ben Rejeb et al., 2022).

In Italy, 6,780 kg of monthly BW from 113 sale points resulted in over 721 kg of CO_2 emissions, comparable to a car traveling nearly 6,000 km annually. The UK discards 20 million slices daily, leading to 584,000 tons of CO_2 each year. Economically, BW is also costly. Globally, about 900,000 tons are lost yearly, around 24 million slices per day. In Flanders 25% of bread production is wasted annually, while the Netherlands sees losses exceeding USD 464 million. In France, annual BW is valued at over EUR 16 billion (Ben Rejeb et al., 2022). In general, it was found that 800 grams of bread responsible for generating 100 liters of biogas (over 60% methane, and the rest is CO_2) and between 977 to 1244 grams of CO_2 (Melikoglu, Lin and Webb, 2013).

4.2 Policy Frameworks (EU Level)

In 2019 the EU platform on food losses and food waste have proposed recommendations for action in food waste prevention. According to these recommendations food manufacturers and public authorities should encourage the development and sale of co-products by creating innovative food items that incorporate such co-products. Increased investment, both public and private, should be directed toward research and innovation to support the creation of new products made from these co-products, which could be particularly advantageous for small and medium-sized enterprises (EU Platform on Food Losses and Food Waste, 2019). Creative examples of using surplus food and co-products in new ways were highlighted, such as turning spent grains and leftover bread into beer (Toast Brewing, 2025). The framework generally introduces recommendations for different levels of the value chain: recommendation for action for primary production, at manufacturing stage, at retail stage, in hospitality/food services, at consumer level and for food donation (EU Platform on Food Losses and Food Waste, 2019).

A 2018 report published by the European Commission on Best Environmental Management Practice for the food and beverage manufacturing sector proposes unsold BW reduction schemes. An effective strategy for reducing BW is to implement return systems where unsold bread is sent back to the bakery for temporary storage and reuse. Depending on its condition, the bread can be processed into new food products like breadcrumbs, donated to approved organizations if still edible, or used for non-food applications such as animal feed. In some cases, authorized collectors may retrieve the bread directly from retailers (EC, 2018).

In response to the food safety crises of the 1990s, particularly the bovine spongiform encephalopathy, also known as mad cow disease outbreak, the European Union enacted Regulation (EC) No 1774/2002 to govern the use of animal by-products not intended for human consumption. A central aim of this regulation was to prevent the recycling of animal proteins into the same species' feed, effectively banning intra-species protein feeding. This led to a broad prohibition on the use of animal-derived proteins in livestock feed, even in cases such as bakery products containing trace amounts of animal ingredients (EC, 2002).

The regulation initially encountered opposition from agricultural and food industry stakeholders, particularly farmers and bakers. In response, temporary exemptions were introduced through Regulations (EC) No 197/2006, No 832/2007, and No 129/2009, allowing former foodstuffs to be used in animal feed under tightly controlled conditions (European Commission, 2006, 2007, 2009).

The original legislation was eventually superseded by Regulation (EC) No 1069/2009, which remains in force and outlines a classification system for animal by-products into three risk-based categories (Scherhofer and Schneider, 2011).

Waste bread typically falls under Category 3, materials deemed safe for animal feed despite no longer being intended for human consumption due to commercial or technical defects. However, strict restrictions remain. Article 11 of the regulation prohibits feeding animals processed protein from their own species. For example, bread containing pork derivatives cannot legally be fed to pigs. Despite these limitations, Category 3 materials can still be used in animal feed production if specific sanitary processing standards are met, such as pressure sterilization, and if the facility is duly approved or registered (Scherhofer and Schneider, 2011).

Aside from feed applications, other permissible disposal routes for waste bread in the EU and Austria include aerobic composting and anaerobic digestion (AD). However, landfilling is generally not allowed. Directive 1999/31/EC mandates the pre-treatment of biodegradable waste to mitigate environmental hazards, particularly those stemming from organic carbon degradation (European Parliament and Council, 1999). In Austria, this has been reinforced by national legislation requiring pre-treatment of any waste with a total organic carbon (TOC) content exceeding 5% by mass. Given that waste bread has an average TOC of approximately 45% dry matter, it is unsuitable for landfill disposal without treatment (Tintner et al., 2010, Federal Ministry of Agriculture, Forestry, Environment and Water Management, 2025) .

4.3 Bread waste valorization

Bread undergoes staling before it becomes food waste, during which it experiences various physical and chemical changes that begin right after baking. This process affects key qualities like taste, texture, and softness, ultimately leading to a firmer crumb and reduced freshness. A comprehensive review of the factors contributing to staling found that ingredients, particularly flour quality and the presence or absence of components like amylose, play a crucial role (Ben Rejeb et al., 2022). Starch retrogradation is initiated by the crystallization of amylose, followed by the gradual re-association of amylopectin, a process that may extend over several weeks, with a significant increase in amylopectin crystallization typically observed after approximately 13 days (Dymchenko, Geršl and Gregor, 2023). Certain additives, such as fats, emulsifiers, and specific compounds like monoglycerides and sodium stearoyl lactylate, were shown to slow down firmness development. In addition, staling is also influenced by production methods, including baking techniques, fermentation with sourdough, and storage conditions (Ben Rejeb et al., 2022).

In recent years, research regarding circularity in the food industry has proposed several approaches to reintroduce BW specifically as a valuable resource. Through the review of existing literature, four primary strategies for diverting bread waste from landfill have been identified:

prevention, reuse, repurposing, and recovery (Sulis et al., 2024). Each of these methods have the aim of reducing bread loss, but show their effect at different stages of the value chain. Only if no other method is used for valorization, BW ends up in the residual waste stream and is incinerated or composted. By understanding the process of waste generation proper mechanisms can be introduced to prevent it (Ben Rejeb et al., 2022).

A commonly applied conceptual framework in the context of food waste management is the food recovery hierarchy, also referred to in various EU documents as the food waste hierarchy, waste management hierarchy, or food wastage hierarchy. This model seen in Figure 4 classifies interventions into two overarching categories: waste prevention measures and waste treatment strategies. The environmental and social outcomes associated with these approaches can differ significantly, depending on regional characteristics such as population density and proximity to industrial or agricultural infrastructures (Goryńska-Goldmann et al., 2021). Food waste prevention remains the most promising approach followed by donating excess food and redistribution (Sulis et al., 2024). The repurposing of food waste is the next best solution, then aerobic digestion and compositing. Biogas production and incineration with energy recovery were considered a possible method and as a last resort the food waste is added to the incineration plant without recovery or landfilled (Zero Waste Europe, 2019).

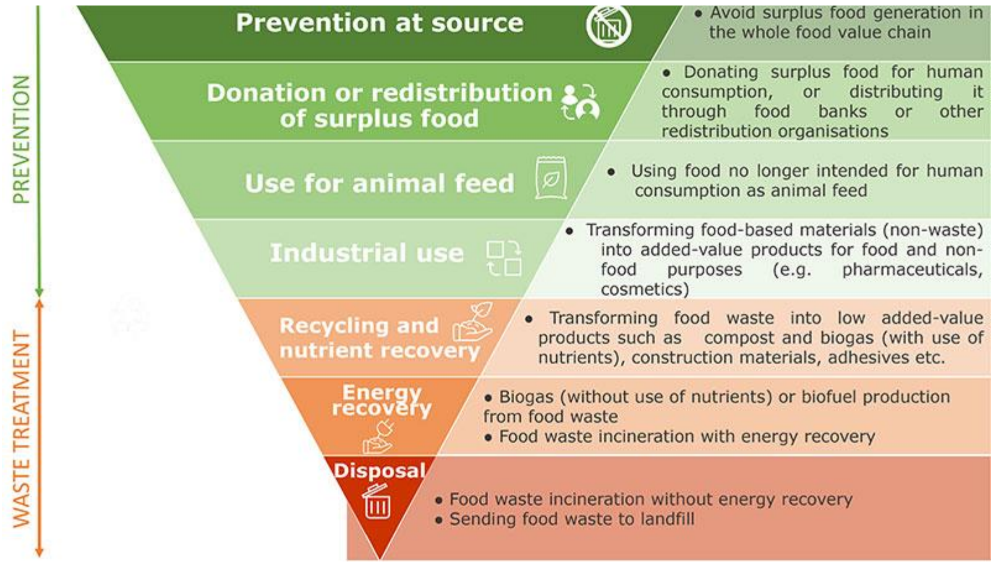

Figure 4: Food waste hierarchy. Adopted from EU (Zero Waste Europe, 2019).

Here the potential strategies for minimizing BW are categorized into five key approaches: prevention, rework, reuse, recycling, and recovery.

4.3.1 Prevention

To minimize overproduction in bakeries, a more limited range of core products is offered during evening hours. Additionally, returned goods are systematically monitored, and if notable changes in return volumes are observed, targeted measures are implemented to address the issue. Staff training plays a key role in raising awareness and reducing production errors that can lead to waste. To extend the shelf life of products and avoid unnecessary disposal, previous-day baked goods are sold at discounted prices. Furthermore, surplus items are redirected for alternative uses: for example, stale bread is used in the production of bread-based beer, while excess dough is reworked in the next bread batch. Technological advancements, such as the introduction of cleanroom processing environments, have also been adopted to extend the minimum shelf life of products by several weeks, contributing to more efficient and sustainable food production practices (Pladerer and Hietler, 2019).

4.3.1.1 Forecasting systems

Multiple institutions and bread production facilities have started to implement smart forecasting systems, many of them utilizing artificial intelligence (AI). Generally, theses platforms allow for a calculated approach of generating supply. Given that the demand for bakery products fluctuates significantly due to various external influences, machine learning can be leveraged to analyze historical data and uncover patterns that improve demand forecasting. These forecasts tend to be more accurate than human estimates, as machine learning models can detect complex and subtle trends that are difficult for people to identify. The demand predictions are based on several key inputs: (1) Historical sales data, (2) Weather conditions (e.g., temperature, precipitation, wind) for both past and upcoming days, (3) Calendar events, such as holidays, long weekends, and bridge days, (4) Promotional campaigns, (5) Competitor closures, which can temporarily increase traffic in nearby stores and (6) Special occasions, including events like Mother’s Day or local festivals (Fries and Ludwig, 2024).

Having an efficient forecasting system in place can also help reducing BW generated at home. By planning your meals and writing shopping lists you can buy only what you consume and therefore become a valuable part of reducing food waste generation (Schanes, Dobernig and Gözet, 2018).

4.3.2 Rework

Reworking is defined as reprocessing surplus bread within the same facility before it becomes waste.

4.3.2.1 *Reprocessing for bread making*

Reprocessing of substandard or returned bread is an increasingly adopted practice in the baking industry, aimed at reducing waste and enhancing resource efficiency. This approach not only conserves raw materials but also offers notable economic advantages to producers. While recycled bread typically exhibits lower sensory quality, affecting its texture, aroma, taste, and visual appeal, the advancement of cost-effective processing methods supports its continued relevance. Nevertheless, inadequate storage conditions can lead to fungal growth, resulting in the enzymatic breakdown of proteins, fats, and carbohydrates, which compromises the bread's sensory and structural integrity (Ben Rejeb et al., 2022).

A study by Savkina et al. assessed the impact of incorporating recycled breadcrumbs into rye sourdough, substituting wheat flour at various levels (15% to 100%). Results indicated that substitutions up to 25% did not adversely affect nutrient content or microbial safety, and the final product showed sensory properties comparable to conventionally produced bread, despite a reduction in crumb firmness. Notably, microbial assessments revealed no significant increase in contamination risks such as molds or yeasts (Savkina et al., 2020). To improve safety and consistency in reprocessing, specialized additives have been developed; inhibiting the growth of spoilage organisms, including spore-forming bacteria, resulting in bread that is not only safer but also softer and more flavorful (Ben Rejeb et al., 2022).

4.3.3 Reuse

Redirecting surplus bread for the same or a similar use outside the original operation facility.

4.3.3.1 *Redistribution and donation*

A recommended approach to reducing BW is implementing bread return schemes. In Germany, some bakeries have adopted a system where unsold bread is returned to the bakery. Fresh bread is delivered to stores in the morning, and the same truck picks up any unsold products from the previous day. These items are then stored at the bakery and can be used to make bread crumbs or dumplings, or they may be donated to charities or waste management companies if still safe for consumption (EC, 2018).

4.3.3.2 *Creative recipes*

Many international and local incentives have shared various recipes on how to turn stale bread found at home to another food stuff. The easiest reuse option for bread at home is to make bread crumbs as topping for soups or salads. There are also companies utilizing old bread to make cereal, crackers or chips out of leftover bread. The biggest potential to reuse left-over bread;

however, is found in private households. Before disposing stale bread, alternative options should be considered as there are plenty of recipes publicly available that make use of old bread (Hietler et al., 2021).

4.3.3.3 Animal feedstock production

If further reduction of BW is not feasible or leftover food is not suitable for human consumption, converting it into animal feed can be considered. (Narisetty et al., 2021).

Feeding waste bread to animals is the most widely used method of recycling it, commonly adopted by both large-scale bakeries producing over 1,000 tons annually and smaller operations. Bread is a highly digestible and energy-rich feed option for pigs, offering between 13.8 and 16.6 MJ of metabolizable energy per kilogram (based on 88% dry matter). To ensure safety and prevent spoilage, the bread must be processed promptly, following strict hygiene regulations such as EU Regulation No. 1069/2009, which mandates pressure sterilization. Additionally, BW containing animal proteins from the same species it would feed is prohibited (Scherhofer and Schneider, 2009).

4.3.4 Recycling

Recycling involves converting food waste into food or non-food outputs through biological or chemical transformation that destroys the original food form. The primary aim is to extract energy and recover nutrients, not to preserve the food's original value or use.

4.3.4.1 Fermentation

BW is rich in starch, which makes up approximately 50–70% of its composition. This starch consists of two polysaccharides: amylose and amylopectin. Amylose is a linear chain of glucose molecules: contrary to amylopectin which is a highly branched molecule. Breaking down starch into simple glucose units requires hydrolyzing these bonds, a process that can be achieved using acids (such as sulfuric or hydrochloric acid) or specific enzymes like α-amylase and glucoamylase. To effectively use BW as a sustainable raw material, it needs to undergo either pre-treatment or hydrolysis to convert its starch content into fermentable sugars (Kumar et al., 2023).

An alternative and more environmentally friendly method is enzymatic hydrolysis, which involves heating starch to gelatinize it, then using enzymes like α-amylase and glucoamylase to break it down into glucose. This process avoids harmful chemicals and operates at lower temperatures, though enzyme costs remain a challenge. Still, advances in enzyme production and process optimization continue to improve the feasibility of this method for sustainable resource recovery from BW (Kumar et al., 2023).

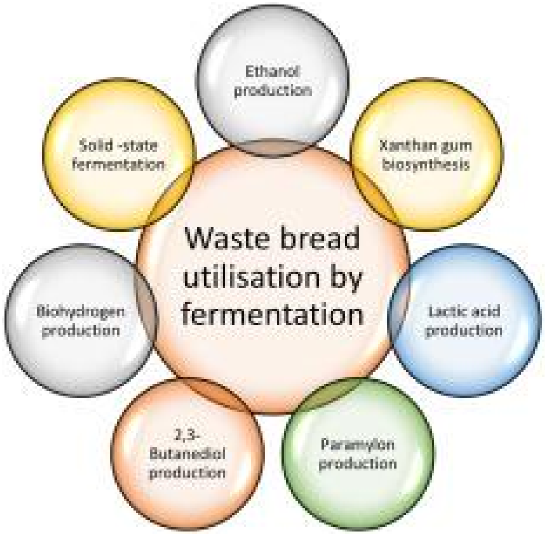

Figure 5: Visual summary of bread waste utilization potential with fermentation (Dymchenko, Geršl and Gregor, 2023).

BW has found application in brewing, this not only maintains product quality but also showcases the broader potential of bread upcycling in the food and beverage industry. Kvass, an eastern European drink is also produced out of fermented bread and is a low-alcoholic alternative to beer. (Ben Rejeb et al., 2022).

4.3.4.2 Ethanol Production

As a starchy food product, bread can be efficiently hydrolyzed into fermentable sugars, particularly glucose, using enzymatic or microbial methods. These sugars are then converted into ethanol through fermentation, offering an environmentally friendly alternative to fossil fuel-based energy sources (Ben Rejeb et al., 2022).

Several studies have explored different approaches to optimize this process. Mihajlovski et al. utilized crude enzymes derived from *Hymenobacter sp*., producing a hydrolysate rich in dextrins and glucose that, when fermented with waste baker's yeast, yielded 1.73% ethanol. Although modest, this method highlights the potential of cost-effective enzyme sources (Mihajlovski, Rajilić-Stojanović and Dimitrijević-Branković, 2020). In contrast, Narisetty et al. reported significantly higher ethanol concentrations, up to 114.9 g/L, by employing *Saccharomyces cerevisiae* and enzymatically pretreated BW. Their process demonstrated high conversion efficiency and productivity, with glucose yields reaching up to 97.9 g/L depending on the hydrolysis method (Narisetty et al., 2022a). Complementing these results, Pietrzak and Kawa-Rygielska investigated various pretreatment techniques, including enzymatic, microwave, and ultrasonic methods, to enhance the efficiency of ethanol fermentation. Untreated waste bread already provided an ethanol yield of 80%, and pretreatment further improved this by 3–8%. Their findings support the idea that optimizing substrate preparation can significantly boost output without requiring chemical additives or complex processing steps (Pietrzak and Kawa-Rygielska, 2014).

4.3.4.3 Biochemical production

The three biochemicals succinic acid, lactic acid and 2,3-Butanediol (BDO) have various applications in the pharmaceutical, plastic and chemical industry.

Succinic acid is a valuable platform chemical used in bioplastics, solvents, and pharmaceuticals with a worldwide worth $160.8 million in 2022. Microorganisms like *Actinobacillus succinogenes* can efficiently convert hydrolyzed BW into succinic acid under anaerobic conditions. Studies have shown that hydrolyzed BW can produce yields comparable to glucose-based media, making it a sustainable alternative to pure carbohydrate substrates (Hafyan et al., 2024).

Lactic acid is widely used in food preservation, pharmaceuticals, and biodegradable plastics, has a market potential of $2.64 billion and can be efficiently produced via fermentation of BW. After enzymatic hydrolysis of bread into fermentable sugars, lactic acid bacteria such as *Lactobacillus casei* can convert these sugars into lactic acid under controlled pH and temperature conditions (Cox et al., 2022).

BDO is a versatile chemical used in synthetic rubber, plastics, and fuels, and can be biosynthetically produced from BW via microbial fermentation. The market is expected to grow to around $220 million by the year 2027. After saccharification of bread into glucose and maltose, bacteria like *Enterobacter ludwigii* can ferment these sugars to produce BDO. Studies have reported high yields of BDO using pretreated bakery waste, making it a promising substrate for low-cost, renewable chemical production (Narisetty et al., 2022).

4.3.5 Recovery

Recovering the energy via production of biofuels or biogas without recovering nutrients as well as food incineration with energy production are the main goals. The last resort and most unfavorable option would be to incineration without recovering the energy or landfilling.

4.3.5.1 Biohydrogen production

Hydrogen is increasingly viewed as a promising clean and renewable energy source, largely due to its exceptionally high energy content of 142 MJ/kg, over three times greater than that of traditional fuels such as diesel or gasoline. Its combustion produces only water, meaning it offers significant potential for reducing greenhouse gas emissions. While several methods exist for hydrogen production, including steam reforming, and electrolysis, biological fermentation has emerged as a favorable option, thanks to its lower energy demands and minimal environmental impact (Ben Rejeb et al., 2022; Dymchenko, Geršl and Gregor, 2023). The production process is generally divided into two phases: hydrolysis and fermentation (Dymchenko, Geršl and Gregor, 2023). In the first step, complex molecules like starch and proteins are broken down into simpler compounds such as glucose and amino acids. Han et al. demonstrated the successful use of crude enzymes, cultivated through solid-state fermentation, to hydrolyze BW. This process yielded a hydrolysate containing glucose and free amino nitrogen, which was subsequently fermented in a continuous stirred tank reactor using anaerobic sludge. The result was a hydrogen output of 109.5 mL per gram of BW, equivalent to 1.6 mol H_2/mol of glucose (Han et al., 2016).

Earlier research by Doi et al. marked one of the first efforts to utilize BW in continuous anaerobic hydrogen fermentation. Their experiments employed hydrogen-producing bacteria, achieving hydrogen yields of up to 1.3 mol H_2/mol glucose (Doi et al., 2009). More recent advancements by Jung et al. examined dark fermentation under mesophilic conditions using immobilized microbial consortia. Although still in the experimental stage, their system achieved a hydrogen yield of 1.25 mol H_2 per mol of hexose consumed (Jung et al., 2021). Beyond conventional fermentation methods, novel hybrid techniques are showing considerable promise. Adessi et al. developed a sequential process combining lactic acid fermentation with photofermentation. This integrated approach significantly improved hydrogen yields, reaching up to 3.1 mol H_2 per mol of glucose (Adessi et al., 2018).

4.3.5.2 Biogas production - anaerobic digestion

Biogas production through AD of BW offers a sustainable solution to food surplus management by converting organic residues into renewable energy. Bread, being rich in carbohydrates and easily degradable, serves as an efficient feedstock for anaerobic digesters. During the process, microorganisms break down the BW in oxygen-free conditions, producing biogas primarily composed of methane and CO_2. This biogas can be used for heat, electricity, or upgraded to biomethane for use as a vehicle fuel. Additionally, the remaining digestate can be utilized as a nutrient-rich fertilizer, contributing to circular economy practices in food and energy systems (Kulkarni and Kodag, 2018).

For instance, a study by Al-Wahaibi et al. evaluated the biogas production potential from various food wastes, including bread, and found that BW produced significant volumes of biogas, making it a viable feedstock for AD processes (Al-Wahaibi et al., 2020). Additionally, research has shown that co-digestion of BW with other substrates, such as sewage sludge, can enhance methane production, further improving efficiency (Ching, Johori and Hasan, 2024).

4.3.5.3 Incineration with energy recovery

BW which is incinerated or processed through mechanical-biological treatment usually comes from the residual waste stream. This primarily includes bread products that contain meat and thus are unsuitable for animal feed or bread that has become spoiled and is no longer fit for consumption or reuse. The waste is transported from the households to the incineration facility and burned at high temperatures in a controlled way. The heat generated from combustion is used to produce steam, which drives turbines to generate electricity or provides heat for district heating systems (Malinauskaite et al., 2017). This process reduces the volume of waste and recovers some of its energy content, though it is less environmentally preferable than reuse or recycling options (Scherhaufer and Schneider, 2011).

4.3.5.4 Composting – aerobic treatment

The breakdown of bread in compost contributes significantly to the development of nutrient-rich soil, enhancing its fertility and supporting healthy plant growth. As bread decomposes, it releases valuable nutrients that integrate into the compost matrix, thereby improving soil quality. Notably, even moldy bread can be composted, as the presence of mold organisms can expedite the degradation process, further facilitating organic matter transformation (Govindaraju, Fuloria and Sathasivam, 2024).

Only a small number of bakeries use aerobic treatment as an option for waste bread. Rather meat containing bread is going this way. It is mixed with other organic waste, green waste and grass cuttings leading to a conventional rotting process.

4.4 Austrian bread production and waste context

Just in any other country, food waste and losses are a considerable issue in the Austrian economy. Avoidable food waste accumulates throughout the entire value chain, spanning agriculture, production, trade, gastronomy, and households. According to Hietler, a researcher at the Austrian Institute of Ecology, current estimates show that 577,000 tons of food waste is generated annually, with 121,800 tons originating from domestic food production. The bakery sector is responsible for nearly half (45.3% of the total amount) of all avoidable food waste in food production, amounting to 51,700 tons (±12%). Considering production standards, a surplus of 1.5 to 2% is regular to ensure delivery reliability. Weather and seasonal fluctuations further influence the volume of returned goods. 35,600 tons are bread and pastries, which food retailers return to producers as unsold or free returned goods (Land Schafft Leben, 2024). A very small portion of avoidable food waste (0.3%) ends up in residual waste. Additionally, 62,700 tons (55%) of organic by-products are primarily generated at the grain mills (Paderer and Hietler, 2019).

Based on historical developments and traditions, Austria next to other countries in middle and northern Europe showcase a huge bread culture. Thus, in this study, BW was used as a representative example of food waste to explore potential strategies for its disposal or valorization. Approximately 10 million tons of bread, 10% of global production, ends up as food waste each year (Jung et al., 2022).

In the Austrian bread production sector, 90% of the market is made up of artisanal bakeries, while the remaining 10% is covered by industrial producers (Pladerer and Hietler, 2019). Between 2005 and 2021, the total number of bakeries holding valid business licenses declined from 1,920 to 1,441, marking a net reduction of 479 establishments. Only 1% of these bakeries employ more than 250 people, yet this group generates 20% of the industry's total revenue. In contrast, the majority of bakeries (61%) are micro-enterprises with fewer than 10 employees, contributing only 10% to total sector revenue. The remaining 70% of revenue is attributed to medium-sized bakeries, which employ between 10 and 249 staff. This distribution highlights a pronounced imbalance in the sector, where economic output is heavily concentrated among a minority of larger firms, while the majority of businesses operate on a much smaller and economically less impactful scale (Land Schafft Leben, 2024).

According to Statista Austria, 430,500 tons of bread and baked goods were produced in 2022 year in Austria, of which 22,500 tons were exported as seen in Figure 6. With an additional imported amount of 55,700 tons of bread, the Austrian society consumed a total of 463,700 tons that year (Land Schafft Leben, 2024). In 2022, the majority, 84.9 percent, of produced bread and pastries were sold in supermarkets. 10.7 percent are sold over the counter in bakeries, and the remaining 4.4 percent are divided among other sales outlets such as gas stations, farmers' markets, or frozen food home delivery services (Land Schafft Leben, 2024). The per capita consumption of bread and baked good was found to be 51.20kg in the same year, representing an increase of approximately 10kg compared to 2005 (Land Schafft Leben, 2024).

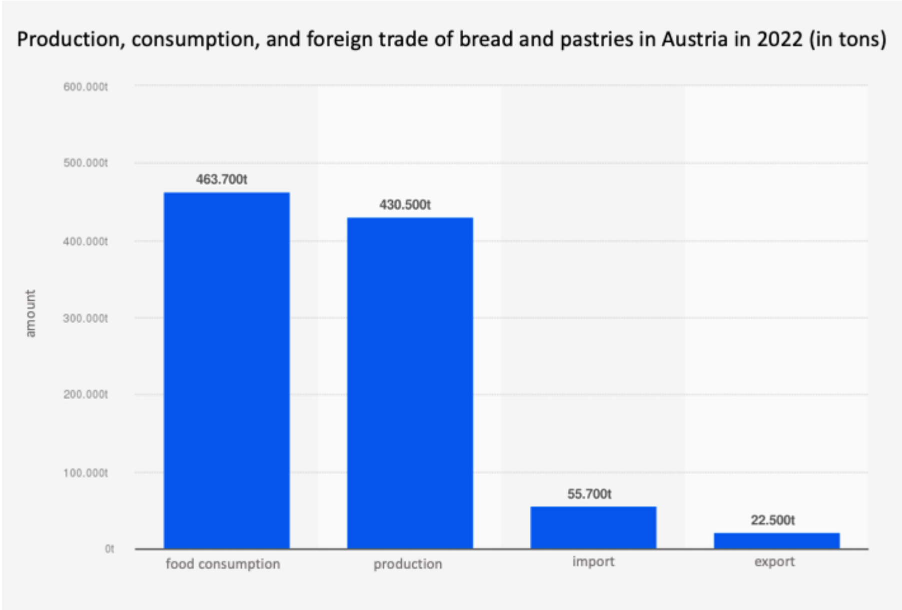

Figure 6: Production, consumption and foreign trade of bread and pastries in Austria in 2022. Figure translated and adopted from Statista (Statista, 2022).

Annually, approximately 161,900 tons of bread and baked goods are disposed of in Austria, representing at least 20% of the total avoidable food waste, which amounts to around one million tons of avoidable food waste each year. Foods deemed "avoidable" are those that are still fit for consumption at the time of disposal or could have been eaten if used before expiration. This includes a wide range of items, from perfectly intact, packaged yogurt to moldy bread left in private kitchens (Land Schafft Leben, 2024). The numbers describing the production waste have been researched by Pladerer and Hietler in 2019 (Pladerer and Hietler, 2019). How much BW is generated by supermarkets in Austria has been investigated by Lebersorger and Schneider, two scientists from the BOKU university, in 2014 with an exact number of 12,700 tons (Lebersorger and Schneider, 2014). The data related to BW generated in households is based on three different publications, which analyzed the components of household waste in three different years: 2012, 2018/2019 and 2020 (Beigl, 2020, Land Schafft Leben, 2024).

Figure 7: Bread waste generated in Austria in 2024 (Adopted by Land Schafft Leben, 2024).

Schneider et. al from the BOKU University of Life Sciences has significantly shaped the understanding of BW generation and management in Austria (Schneider, 2013; Lebersorger and Schneider, 2014, Scherhofer and Schneider, 2011). Regarding leftover bread coming from retail and production 86.62% of BW is repurposed to animal feedstock, followed by biogas production (4.38%), rework (3.34%) and prevention mechanisms in the form of donation to social organizations (3.33%). 2.27% of BW is disposed of via the biogenic waste stream, either at aerobic or anaerobic treatment plants depending on the region. Since it is unclear at which treatment facility the BW will be processed and no direct allocation takes place, biogenic waste is stated as a separate possible pathway. Only 0.02% of BW is directly allocated to composting. Disposal via residual waste stream (0.01) and other treatment options (0.03%) only make up a small fraction of the share of BW (Scherhofer and Schneider, 2011). BW generated in households is automatically allocated to the residual waste stream and not included in Figure 8.

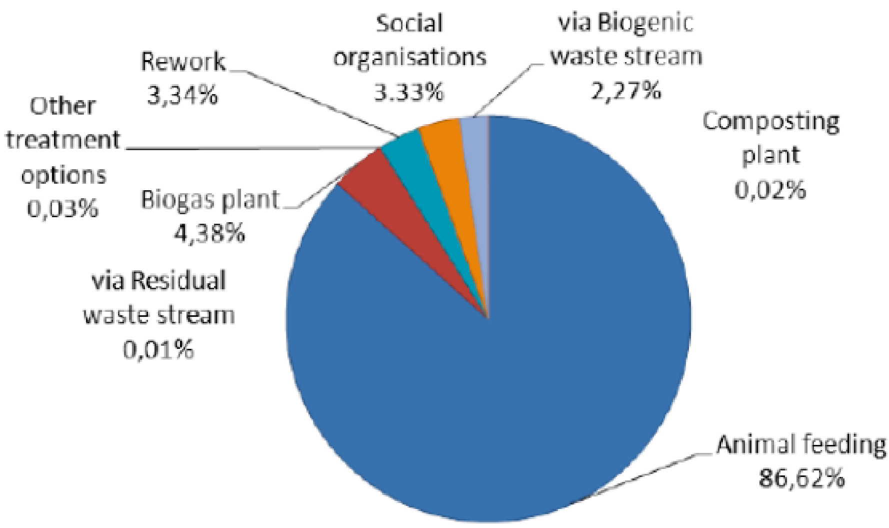

Figure 8: Share of waste bread per treatment and disposal option in Austria in companies representing approximately 22% of the Austrian production volume (Scherhofer and Schneider, 2011).

4.5 Local initiatives

The Austrian economy has introduced take-back schemes for bread production facilities. This means that the bread suppliers, often big production companies which sell to local supermarkets have agreed to take back any unsold and left-over bread as long as it stems from their site. Similar schemes have been introduced in other European countries such as Sweden (Brancoli et al., 2019).

Retailers often sell bakery products on a commission basis, allowing them to return unsold bread and pastries to the supplying bakeries. Although these returns are typically not classified as food losses, since they don't result in a financial loss for the retailer, they still represent a significant source of food waste (Scherhaufer and Schneider, 2011). As such, this paper includes those quantities in its analysis, recognizing their relevance for waste reduction strategies.

In general, the bakeries are responsible for the disposal or reprocessing activities themselves. An interview with the Austrian bakery chain *Geier* and a smaller Lower Austrian bakery *Aschauer* both reported no leftover bread from both their production and returned bread. They both utilize donation, animal feed production, rework and *Aschauer* specifically also produces high percentage alcohol as a beverage out of the leftover bread. A possible waste-reduction approach includes: Precise daily planning, no returns policy, Redistribution of excess bread via social institutions, Repurposing into breadcrumbs and dumpling bread

4.5.1 Incentives by bakeries

In collaboration with a multidisciplinary expert team, *Felzl* bakery launched a project in 2014 to combat BW. Unsold bread is placed in vending machines at closing time and sold at reduced prices overnight. Leftovers are creatively repurposed into almond croissants, bread chips, muesli, and nut crunch. Mangold Bakery sells day-old bread at half price in a dedicated store and supports social projects through part of its proceeds, reducing food waste while giving back to the community. Martin Auer Bakery also offers previous-day bread at half price and promotes mindful consumption and has generated 40,000 EUR for social causes (Hietler et al., 2021).

4.5.2 Making bread into alcohol for human consumption

To prevent BW, *Therese Mölk* bakery established a distillery where surplus bread is turned into high-proof alcohol like gin and schnapps. Collaborating with *Bierol Brewery*, they also produce a bread-based beer called Baker's Bread Ale and a premium gin (Hietler et al., 2021). The bakery *Aschauer* sells beer, gin and ouzo under the name "Hochbrotzentig" collaborating with multiple bakeries all over Austria.

4.5.3 Social organizations

Die Tafel Österreich, Austria's oldest environmental and social non-profit organization, has been operating since 1999 with a dual mission: reducing food waste and addressing poverty. More than 75.000 people affected by poverty are provided with free food in around 160 social service stations in Austria, including BW. Their initiative to repurpose old bread includes a cookbook with various recipes, donating to people in need and education. *Geier*, an Austrian bakery which has also been interviewed as objective of this study has been closely working with *Tafel Österreich* since 2006 and offer same-day bread for lower prices and donate 50 cents to the social organization per purchased bread-bag (Hietler et al., 2021).

Since 2016, *Brotpilot:innen* collects unsold bread from partner bakeries and resells it at reduced prices at two Saturday markets in Vienna. They rescue bread from being wasted and distribute it the next day at two locations in Vienna. They also offer catering services, which have already been featured at several Zero Waste Austria events supported by the EU (Hietler et al., 2021).

foodsharing is a volunteer-driven, non-commercial initiative aiming to eliminate food waste and promote sustainable food systems. It envisions a world based on food sovereignty, where locally produced food nourishes all people equitably, and systemic overproduction and waste are eradicated. As a member you have access to a platform and community, in you are able to share your extra food such as bread with the community or help save valuable products by gathering surplus food from restaurants or other food service facilities (Foodsharing, 2025).

While the take-back schemes enable supermarkets and bakeries to reduce their BW tremendously, the hospitality and restaurant sector remains to produce a lot of avoidable food waste. In 2016, Unilever organized a Stakeholder Dialogue with the goal of halving all avoidable food waste in the Austrian out-of-home catering sector by 2020. The study showed that a total of 175,000 tons (+/- 10%) of food is wasted every year resulting in a loss of 320 million EUR. These numbers equal to 12kg of food being wasted daily, being equal to around 22 EUR. On an annual basis this avoidable food waste causes 398,000 tons of CO_2 equivalents, 27.6 billion liters of water consumption, and the use of 36,300 hectares of land (Unilever, 2016).

4.5.4 Online tools

Many bakeries and food retailers now allow customers to pre-order bread online for pickup, minimizing overproduction and waste. The application *Too Good To Go* connects consumers with surplus food from bakeries, restaurants, and supermarkets at reduced prices just before closing time. It reduces waste and fosters customer awareness and loyalty. Currently 175.000 companies are members and offer their food for reduced prices (Hietler et al., 2021).

Figure 9: company logo from Too Good To Go Application.

Foodtracks is an artificial-intelligence-based software used by bakeries to optimize ordering schemes and could already achieve a 20% reduction in returned bread goods. They offer order tuning programs, not only using sales data from the inventory management system but also external data such as weather, holiday, and vacation information. From this, optimal order quantities are determined and automatically placed. Processes and products are analyzed based on their performance levels and can be adjusted as necessary (FoodTracks, 2025).

5 Results and Discussion

5.1 Material flow analysis of current situation

It has shown to be difficult to access data on the most recent numbers of BW generation in Austria. The most comprehensive study on unsold BW was published by the European Commission in 2018 and drew upon numbers from 2011 as researched by Scherhaufer S. and Schneider F (Scherhofer and Schneider, 2011, EC, 2018). For the approach presented here, the numbers as of 2011 were utilized; however, uncertainty and error-propagation analyses were included to guarantee more significant results.

5.1.1 Status Quo

In order to calculate the mass flows of the current utilization pathways in Austria, two main data sources were used: (1) numbers published by Land Schafft Leben (Land Schafft Leben, 2024) and (2) share of treatment and disposal option as described by Scherhofer and Schneider (Scherhofer and Schneider, 2011). While there are clear numbers of how much BW is generated by supermarkets each year, bakeries and other retailers including gas stations and farmers market are assumed to only generate negligible amounts of waste. Interviews with various bakeries could support this assumption.

Figure 10 provides a visual overview of the current valorization pathways for BW in Austria in 2024. A considerable portion of surplus bread is generated during the production phase, which, together with returned products from the retail sector, is directed into various waste streams. At the consumer level, unconsumed bread contributes to household bread waste, the majority of which is disposed of through incineration alongside residual waste. This represents the largest proportion of bread waste treatment, followed by its use as animal feed.

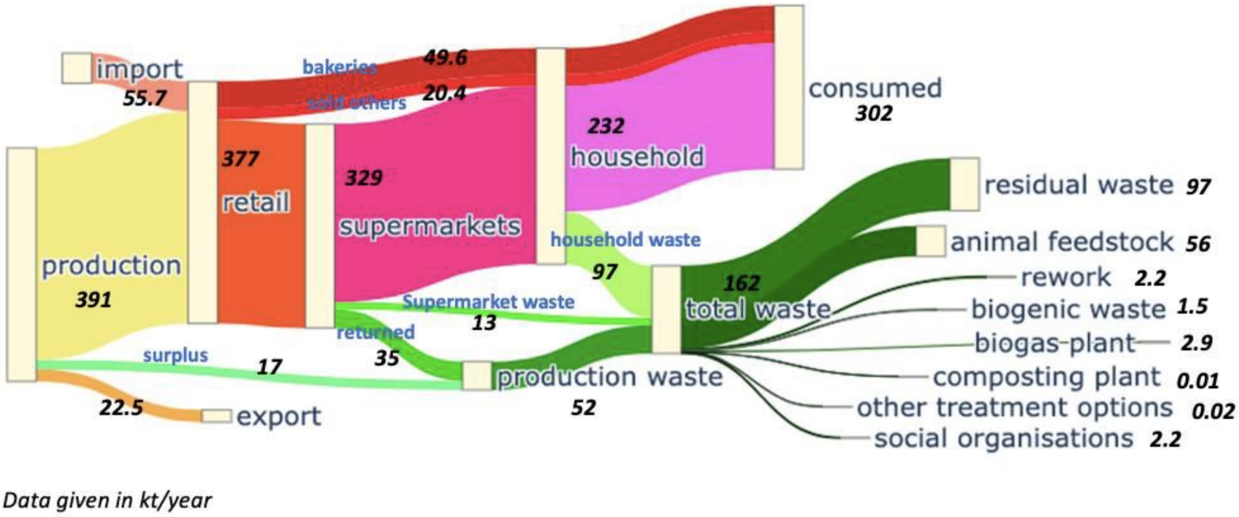

Figure 10: MFA of bread from production until waste visualized as a Sankey Diagram. Each stream represents a flow of bread, the thickness of the flow chart indicating how the numbers are. Numbers provided are given in kt unless other provided.

In order to represent the results in a more comparable way the amount of BW generated in tons per year was recalculated to present kg per person over a single year. The highest waste per person is generated in households seen in light green in Figure 11 with 10.5 kg per person, production waste with 5.65 kg include returned products and surplus production. BW generated in supermarket account for 1.4 kg per person each year.

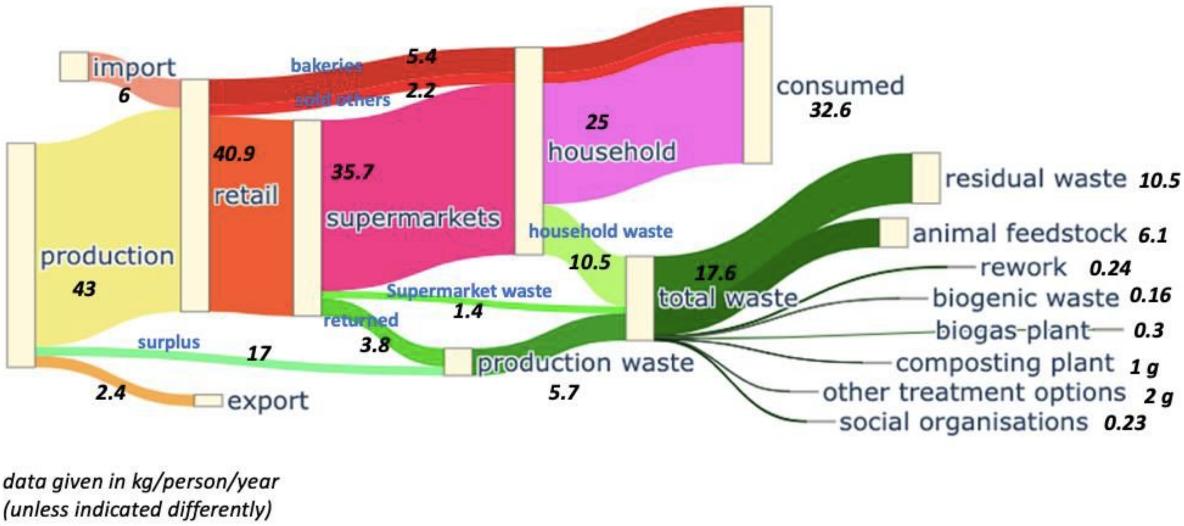

Figure 11: MFA of bread waste calculated for each person living in Austria over the representative year of 2024.

According to Lebersoger and Schneider food loss amounts to 2.8% of the sales of bread & pastry with returned bread amounting to additional 9.7% of the sales of bread & pastry. (Lebersorger and Schneider, 2014). This is in accordance with the numbers outlined here as the total bread offered for sales accounting for supermarkets, bakeries and other sellers amount to 48.5 kg bread sold per person. Of this 1.4 kg bread is wasted from the retail sector (supermarkets) equaling to 2.8% of the total sold bread per person. 3.8 kg of all bread offered in retail is returned to the producer assumed that only supermarkets generate BW the amount of bread offered for consumption in supermarkets (40.9 kg) is used to calculate the return rate of 9.2% with a total loss of 12% at retail level. This slight difference in percentages can be explained by reduced returns achieved in the last 10 years by introducing more efficient ordering schemes.

The numbers were gathered from 612 retail outlets all over Austria, which were monitored over a year and their discarded food was analyzed in a small sample of retail outlets (Lebersorger and Schneider, 2014). The study also revealed that over one-third (42%) of retail stores refrain entirely from donating unsold bread and pastry items. Bread and pastry products represent a significant portion of the economic value lost through food waste, making up approximately 25% of the total. Furthermore, returns of these baked goods contribute to an additional 85% of all recorded food losses, highlighting their major role in retail-level waste (Lebersorger and Schneider, 2014). Additionally, food loss rates vary notably between urban and rural areas. Retail outlets in rural settings tend to experience higher losses of bread and pastry compared to those in urban areas. However, rural stores return a smaller share of unsold bread to bakeries than their urban counterparts (Lebersorger and Schneider, 2014).

5.1.2 Uncertainty and error propagation analysis

In order to properly estimate the accuracy of the data shown here an uncertainty analysis was conducted investigated and rating the data points regarding reliability, completeness, temporal and geographical accuracy and other correlations. First, the data from bread production until waste generation are analyzed regarding their uncertainty and the relative and regular standard deviation for each number was calculated (Table 1).

Table 1: Standard deviation and relative standard deviation of mean values of Austrian bread waste generation numbers. Uncertainty analysis of data for MFA of valorization streams. All numbers were estimated to three stages.

Name of data	Mean [tons, or %]	Standard deviation [tons, or %]	Relative standard deviation [%]
bread production	430,500 t	21,800 t	5.1%
export	22,500 t	1,140 t	5.1%
import	55,700 t	2,820 t	5.1%
offered for consumption	463,700 t	23,500 t	5.1%
total production waste	52,000 t	10,6670 t	20.5%
surplus production	17,000 t	2,360 t	13.9%
returned goods	35,000 t	4,850 t	13.9%
supermarket waste	13,000 t	5,370 t	41.3%
household bread waste	96,000 t	4,860 t	5.1%
total waste	161,900 t	3,670 t	2.3%
sold in supermarket	84.9%	7.0%	8.2%
sold in bakeries	10.7%	0.9%	8.2%
sold in others	4.4%	0.4%	8.2%

While most uncertainties remain in the realm of 5%, some show higher relative standard deviations, for example production waste and supermarket waste. This is due to the outdated information these numbers are based on. The publication which analyzed the amount of household BW generated in Austria was published in 2014 and therefore does not offer accurate temporal correlation. The deviation of production waste including surplus production and returned goods can be explained for the same reasons. Figure 12 provides a visual representation of the relevant numbers in the Austrian bread production and waste generation processes. Mean values and standard deviation are provided for each step involved from production until BW generation.

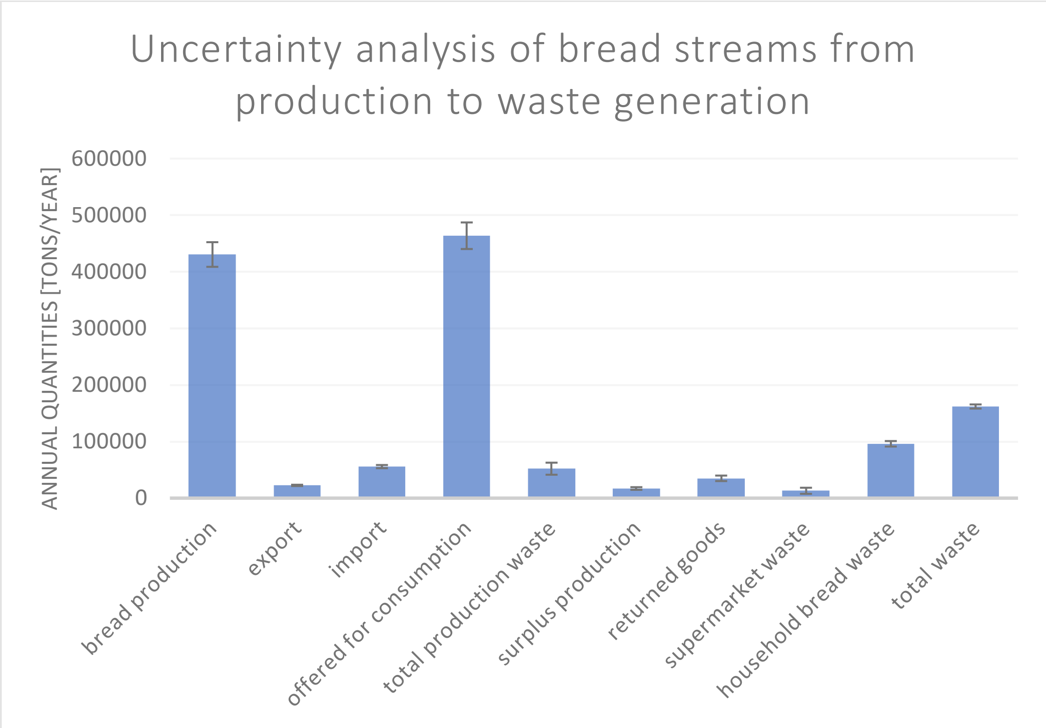

Figure 12: Bar chart representing the mean values ± standard deviation of bread streams defined by the system boundary from production to waste management in Austria from year 2024.

The utilization processes of BW were examined using two methodological approaches, which were subsequently compared. In both cases, a standard uncertainty analysis was conducted; in the second approach, this analysis was extended through error propagation. The findings indicate that for the quantity of bread waste allocated to the residual waste stream, the data could be defined with greater precision, resulting in a significant reduction of the standard deviation from over 40% to just 6%. This improvement is largely attributable to the high certainty that all household bread waste is directed into this stream, while only minimal quantities from the retail and production stages contribute to it. In contrast, the standard deviations associated with other valorization pathways exhibited only minor changes, suggesting that the initial estimates were already relatively accurate as seen in Table 2.

Table 2: Comparison of uncertainty analysis of bread waste valorization pathways with and without error propagation analysis after gauss. Numbers are estimated to three positions.

	without error propagation			with error propagation analysis		
Data	**Mean (in tons)**	**Standard deviation (in tons)**	**Relative Standard deviation**	**Mean (in tons)**	**Standard deviation (in tons)**	**Relative standard deviation**
residual waste stream	96,900	40,065	41.3%	96,900	5,980	6.2%
animal feedstock production	56,300	23,300	41.3%	56,300	23,400	41.5%
biogas plant	2,850	1,180	41.3%	2,847	1,180	41.5%
rework	2,210	919	41.6%	2,171	902	41.5%
social organizations	2,160	895	41.3%	2,160	899	41.5%
biogenic waste stream	1,480	610	41.3%	1,480	613	41.5%
other treatment options	20	8.1	41.3%	20	8.1	41.5%
composting plant	13	5.4	41.3%	13	5.4	41.5%

5.1.3 Innovation pathways

A key objective in exploring innovative valorization pathways for stale bread is to significantly reduce the proportion of BW currently ending up in residual waste streams and incineration, an issue largely driven by household-level disposal. Therefore, targeted interventions aimed at minimizing household bread waste are essential. Among the potential solutions, fermentation emerges as a particularly promising technology, although it has not yet gained widespread adoption in Austria. This process not only allows for the hygienic transformation of contaminated bread into reusable resources but also offers a sustainable means of valorization (Kumar et al.,2023).

Additionally, there is untapped potential in recognizing that up to half of household bread waste could be composted, rather than incinerated, offering further environmental benefits. Building on these insights, three hypothetical scenarios were developed to assess different innovative utilization strategies for stale bread. The first scenario explores the complete redirection of wasted bread into animal feed. The second considers beer production as a creative and value-adding reuse pathway. Finally, the third scenario evaluates the potential of biochemical production as a sustainable solution for managing stale bread.

5.1.3.1 Biorefinery

Platform chemicals such as lactic and succinic acid derived from food waste are particularly interesting as they can replace primary chemical production (Hafyan et al., 2024).

Biochemicals regularly utilized from pharmaceutical and plastic production include lactic acid, succinic acid and BDO as well as bioethanol (Kumar et al., 2023). All three are considered in developing an innovative pathway for Austrian bread valorization. It is assumed that all gathered BW, excluding household BW, is transported to a biorefinery facility in which base chemicals are produced via enzymatic hydrolysis and fermentation. The total waste is assumed to be split equally among the production techniques. Hafyan et al. propose a process integration option, in which BW can be chemically utilized, while downstream losses and organic matter waste can be added to AD treatment and again re-used to produce fertilizer and biogas (Hafyan et al., 2024).

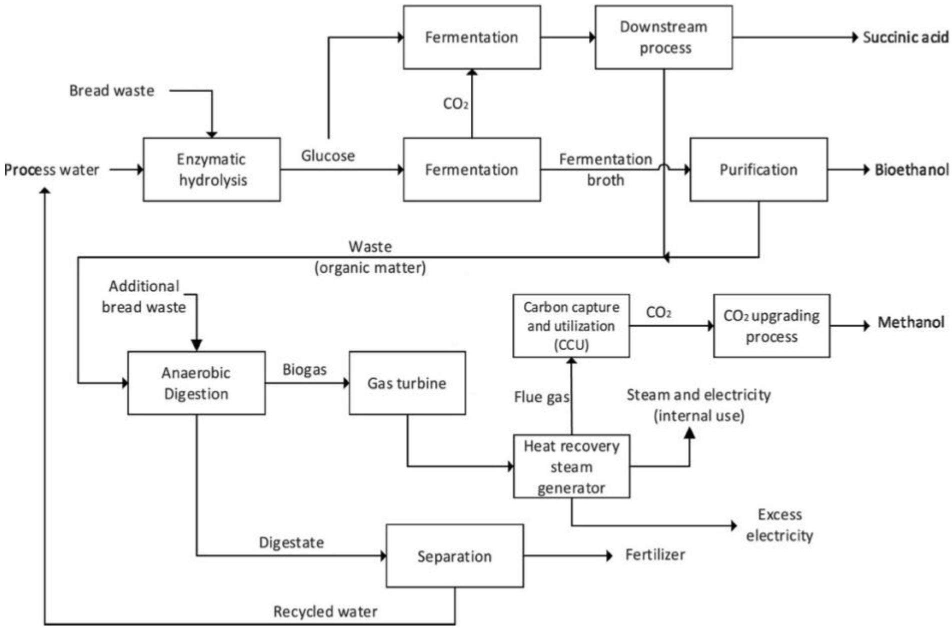

Figure 13: Process integration of bioethanol and succinic acid production of BW valorization (Hafyan et al., 2024).

According to the approach described in Figure 13, a Sankey diagram based on the current BW generation in Austria was generated. It was assumed that half of the left-over bread from households could be collected and added to an AD plant. The remaining BW was used in biorefinery to be enzymatically hydrolyzed and fermented to produce lactic acid, succinic acid, bioethanol and BDO. The organic losses from the chemical production process were recovered in an AD plant. In order to understand how much of the stale bread can actually be converted into biochemical compounds, the yields are given in Table 3.

Table 3: Yield of different biochemical production pathways as published by (Kumar et al., 2023).

Biochemical produced	**Biochemical yield from bread achieved by enzymatic hydrolysis (60 °C, 48 h)**	**Microorganism applied**
Succinic Acid	0,55 g/g feedstock	*Actinobacillus succinogenes*
Lactic Acid	0,42 g/g feedstock	*Bacillus coagulans*
Bioethanol	0,24 g/g feedstock	*S. cerevisiae (yeast)*
BDO	0,19 g/g feedstock	*Enterobacter ludwigii*

To be able to compare the production outcome, the same strategy for chemical conversion based on enzymatic hydrolysis was assumed for all four biochemicals. However, several publications suggest that lactic acid productivity of 0.57 g/g could be achieved utilizing fed batch fermentation of crust BW under non-sterile conditions using thermophilic *Bacillus coagulans DSM1* (Cox et al., 2022). Yield of BDO could be increased by liquefaction and saccharification of BW and fed-batch fermentation to 0.39 g/g feedstock (Kumar et al., 2023d).

Figure 14 depicts the results of introducing biochemical production as main utilization pathway of BW in Austria. Succinic acid production shows the highest yield, while BDO has the highest losses in relation to the other depicted biochemicals. The losses of biochemical production are assumed to be directed to an AD plant.

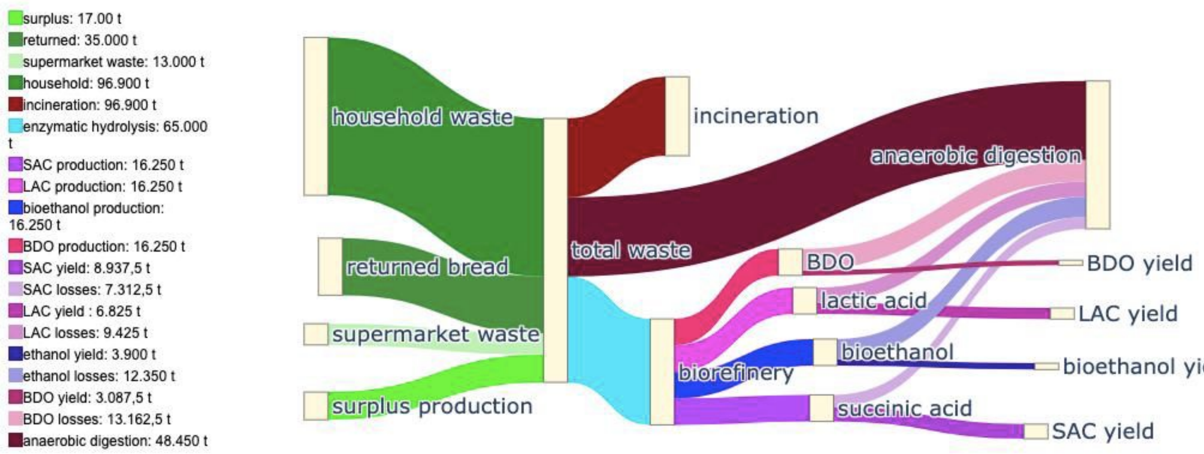

Figure 14: MFA presented as Sankey Diagram using the innovative pathways of Biorefinery based on Austrian bread waste generation.

5.1.3.2 Animal Feed production

As animal feed is the largest single cost item of livestock production accounting for 60–85% of the total costs per year, several ways have been investigated to find a more sustainable approach. Currently, between 32 and 68% of all grains worldwide are fed to animal livestock. Former food stuff can be used as an alternative biomass to feed livestock and an effective option to develop a more circular economy and reduce food losses will effectively reusing resources (Pinotti et al., 2021). Depending on the additives and animals fed, BW can be added to the animal feed in different percentages. For pigs it has been shown that adding 30% of bakery products to their regular feed does not impede animal performance and improves food efficiency (Hartinger et al., 2024). For sheep the same was found and for dairy cows adding 30% of bakery by-products to their feed even improved performance (França et al., 2012; Kaltenegger et al., 2021). Based on this literature we can assume that up to 30% of all needed animal feed can be substituted with BW, the other 70% remain basis feed consisting of mainly maize.

In 2024 there were about 2.5 million (2,534,439) pigs living on 16,600 farms in total according to Statistics Austria and are the most abundant livestock. Almost 700,000 of these pigs live in Lower Austria (692.420) (Satistics Austria, 2024). Around 2.8 to 2.9 kilograms of feed are needed for a pig to gain one kilogram in weight, while on average, fattening pigs gain around 820 grams per day. This means that an average pig eats approximately 2.3 kg per day not accounting for organic pig production (Land Schafft Leben, 2025). This means that in 2024 approximately 2.13 million tons (2,127,661 tons) are needed to feed pigs, 30% equaling to 638,298 tons. In Lower Austria, pigs consume approximately 581,000 tons of feed per year assuming the average intake is 2.3 kg per pig per day.

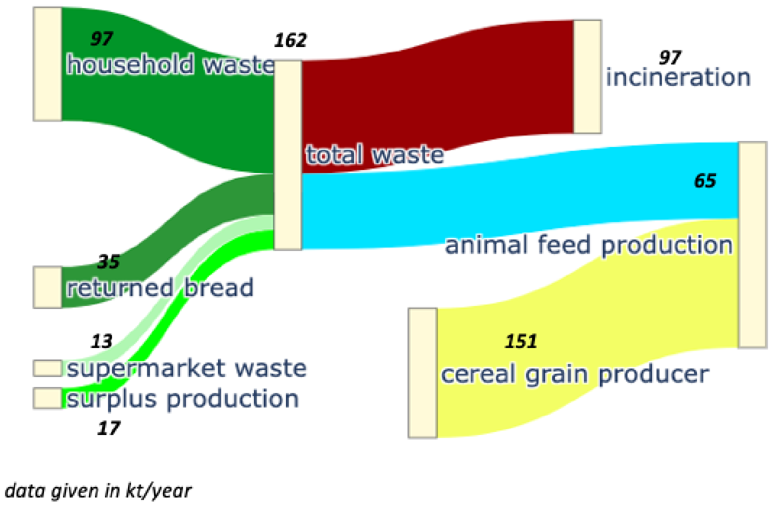

Figure 15: Sankey diagram describing the utilization pathway of animal feed production. 65,000 tons of bread waste is added in the regular animal feed accounting for 30% of the total produced 216,600 tons of feed.

Assuming that 65,000 tons of BW are equal to 30% and 70% being added as regular corn meal, 216,600 tons of pig feed can be produced accounting for less than half of what is needed to feed the pigs in Lower Austria alone.

5.1.3.3 Beer production

According to Martin-Lobera et al., up to 50% of malt in beer production can be substituted with bread, offering significant cost savings for the brewing industry (Martin-Lobera et al., 2022). While traditional beer recipes use only malted barley for sugar extraction, the approach by Toast Brewing, a UK company uses a blend of 75% malt and 25% bread. In the mash, breadcrumbs are added to hot water along with barley, about 115 kg per 5000 liters of water. The enzymes in barley break down starches into sugars, which yeast later ferments into alcohol. This method not only benefits the environment but also produces a flavorful beer with a rich, malty aroma (Toast

Brewing, 2025). According to their website once brewing is complete, local farmers collect the spent grain to use as animal feed, and they also take the used hops for composting. Additionally, all wastewater from the brewing process is treated to ensure that the water returned to the environment is of higher quality than what was originally used (Toast Brewing, 2025).

The brewery industry is typically consumes 4–6 liters of water for every liter of beer produced (Diro et al., 2024) and on average, roughly 0.2 kilograms of spent grain are generated per liter of beer produced (Agrawal et al., 2023).

For the calculation regarding the Austrian bread industry, it is assumed that 5 liters of water are needed for every liter of produced beer. From 65,000 tons of leftover bread, using the Toast Brewing method and industry-average water usage of 5 liters per liter of beer, about 565 million liters of beer can be produced. The calculation steps are provided in Table 4.

Table 4: Calculation steps for beer production out of bread waste.

Step	Description	Assumptions/Formula	Calculation Result
1	Total Bread Available	Given	65,000 tons = 65,000,000 kg
2	Bread Proportion in Mash	Bread makes up 25% of the total fermentable material	Total mash = Bread / 0.25 = 260,000,000 kg
3	Total Barley Required (75% of mash)	Barley = Total mash – Bread	260,000,000 – 65,000,000 = 195,000,000 kg
4	Bread per Batch	115 kg bread per 5000 L water (Toast Brewing ratio)	115 kg bread → 5000 L water → 5000 L beer
5	Beer per kg of Bread	5000 L / 115 kg bread	~43.48 L beer/kg bread
6	Total Beer Volume Produced	Total bread × 43.48 L/kg	65,000,000 × 43.48 = ~2,826,200,000 L
7	Total Water Required	5 L water per 1 L beer (Austrian brewing industry average)	2,826,200,000 / 5 = ~566,000,00 L beer
8	Spent Grain Produced	0.2 kg spent grain per 1 L beer	566,014,000 × 0.2= 113,202,800 tons spent grain

It is relevant to mention, that the Sankey diagram depicted in Figure 16 solely provides a visualization as due to a change in sizes from tons to liters a fully representative diagram could not be achieved. In order to produce 566 million liters of beer utilizing all 65,000 tons of bread with 195,000 tons of malt (25:75 ratio), 2.8 billion liters of water are needed. Beer brewing being a very water intensive industry has long been known and discussed in the light of several sustainability challenges (Diro et al., 2024). The beer produced has an alcohol content of about 4.6%. Various other studies have shown that it is possible to add up to 50% old bread to the malt, utilizing the food waste even more efficiently. However, these studies report an alcohol level of 2%, significantly below a standard beer's average level (Coelho, Prista and Sousa, 2024).

In the year 2024, 10.09 million hectoliters of beer were produced in Austria (Statista, 2024). Using beer brewing as the main valorization pathway of old bread can produce up to 5.6 million hectoliters of beer, which equals to 56.09% of the Austrian beer production.

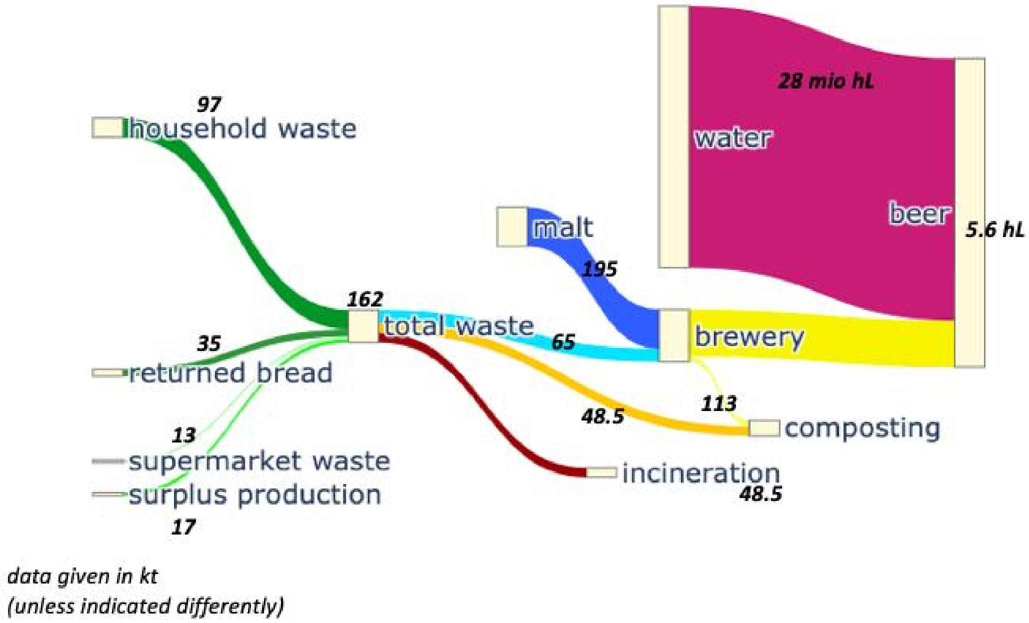

Figure 16: Sankey diagram visualizing the potential of beer brewing as the main pathway to utilize leftover bread in Austria.

As the number of 5.6 hl seemed to be very high, a counter calculation was done to ensure correct results. Carbohydrates are the major non-volatile compound in beer accounting for 3.3–4.4% of a regular beers' content (Li, Du and Zhang, 2020). A study by Ferreira shows that "*total carbohydrate content of lager and ale beers range between 10–30 and 15–60 g/l, respectively with a general carbohydrate level range from 20 to 30 g/l*" (Ferreira, 2009). Bread has been analyzed to have a carbohydrate level between 35 and 60 g per 100 g of bread depending on bread type (Carocho et al., 2020). Another study found that the mean carbohydrate content of 17 studied breads was approximately 50% (Alkurd et al., 2020). Since the exact carbohydrate content of bread and beer can vary depending on several factors, a simplified assumption was made: beer contains about one-ninth the amount of carbohydrates found in bread. Based on this, if one kilogram of bread contains approximately 40 grams of carbohydrates, then one liter of beer would contain around 4.4 grams of carbohydrates. Using this ratio, the potential amount of beer that could be produced from BW can be estimated. In retail and production, around 65,000 tons of bread are wasted. When this amount is multiplied by the factor of 9, it results in the equivalent of 585,000 tons of beer. This corresponds to approximately 5.8 million hectoliters, which closely matches the previously calculated value of 5.6 million hectoliters.

5.2 Assessment Outcomes

The valorization of BW is an emerging field with low technology readiness level. Despite potential benefits, commercial-scale production of biochemicals or other pathways for reuse need to be explored while considering social, economic and ecological aspects (Hafyan et al., 2024).

Based on literature findings and interviews with several stakeholders of the bakery industry showed that prevention of BW is the most effective method and reducing BW at its point of origin yields the highest environmental benefit. Secondary valorization options such as conversion into animal feed, charitable donation, and the use of bread as a substrate for beer or bioethanol production offer moderate sustainability advantages, with no distinct preference among these pathways. In comparison, AD and incineration contribute the least to environmental savings (Narisetty et al., 2021). AD presents lower environmental savings when compared to other microbial valorization pathways such as the production of animal feed, beer and ethanol (Kumar et al., 2023).

For the assessment regarding economic, ecologic and social criteria three utilization pathways were chosen: (1) Animal feed production, (2) biochemical production using a biorefinery approach and (3) beer brewing.

5.2.1 Economic criteria

Economic criteria chosen to investigate the potential for BW utilization pathways include: Market integration and technological readiness, product maturity, location dependency and availability of processing infrastructure and job creation.

The investigated pathways showed different levels of market readiness. While animal feed production is already standard in Austria and nearly 90% of all leftover bread are utilized in that sector already, using bread as a substrate for biochemical production remains to be introduced. The infrastructure decides to a large degree whether novel utilization pathways are feasible or not. Regarding the transformation to animal feed, a large production facility can be found in Lower Austria with many retail shops and bakeries using their service and pig farmers also being close by. The demand for animal feed in Lower Austria is therefore given. The third pathway, beer brewing shows technological readiness and several bakeries in Austria already utilize bread that way. However, location dependence and availability of processing infrastructure or finding collaboration partners could be a potential limit for more bakeries to start brewing beer out of bread.

Looking more into the pathway of chemical fermentation, the majority of companies are situated in and around Vienna. While there are multiple pharmaceutical and chemical production sites that could possibly utilize bread as a chemical building block for their industry, their willingness of cooperation presents a considerable hurdle. On a positive note, utilizing bread for research would offer jobs in high-paying fields and could allow Austria to position itself as an early adopter of novel food research. For smaller bakeries producing alcoholic beverage seems to be an option with high economic feasibility; however large production sites can struggle with strict regulations and the unclear definition of food waste.

Despite its importance, economic evaluations of BW-based processes remain limited. For instance, Mailaram et al. investigated large-scale lactic acid production using BW and found it to be capital- and energy-intensive, largely due to slow fermentation and complex separation stages. The study identified high feedstock costs and energy use as key economic challenges, though utility savings of up to 15% were achieved through optimizing the thermal energy techniques. Nevertheless, the research emphasized the need for cost reduction strategies, including process optimization, efficient downstream processing, and financial support to reduce feedstock costs (Mailaram et al., 2023).

Lam et al. examined succinic acid production from BW and found raw material costs (especially CO_2) and steam consumption to be significant contributors to operational expenses. Despite a relatively high capital investment, the process yielded a return of investment of 12.8%, with profitability depending heavily on product pricing and plant capacity (Lam et al., 2014; Hafyan et al., 2024). Among the various biochemicals, succinic acid demonstrates the highest production yield, with 550 grams generated per kilogram of bread waste, underscoring its strong economic potential. A recent study by Hafyan et al. examined an integrated biorefinery system that co-produces bioethanol and succinic acid, revealing favorable economic and environmental outcomes. The most efficient scenario reported a short payback period of 2.2 years, an internal rate of return of 33%, and a net present value of $163 million, emphasizing the significant advantages of comprehensive bread waste valorization (Hafyan et al., 2024).

Regarding the development of additional innovative solutions, market readiness and product maturity the conversation with Sarah Lechner, the start-up founder of *Brüsli* gave valuable insights. The vision of turning leftover bread into a marketable cereal product provided valuable insights into the economic viability and challenges of producing innovative food items. The major drawbacks were of logistical and monetary nature. It proved to be very challenging to find supply of old bread that offers the quality needed for human consumption. The price of gathering and transporting left-over bread and the production process to produce the final product exceeded the value. Buying the resources needed to produce the cereal from a primary retailer would have been cheaper than using stale bread, which ultimately lead to the closure of the business.

5.2.2 Ecological criteria

Ecological criteria used to assess different BW valorization pathways include greenhouse gas emissions, transport resources and energy demand of the different processes required. Before investigating the proposed pathways regarding their ecological potentials, a framework of comparison is introduced.

A study by Eriksson et al. investigated the environmental impact of various food waste management options in Sweden. They found that the BW stream offered the greatest potential for reducing greenhouse gas emissions compared to other food stuff. Bread is an energy-rich product with a relatively low carbon footprint thus increasing the possibilities for replacing fossil energy carriers (Eriksson, Strid and Hansson, 2015). Most research on managing food waste has concentrated on conventional methods like landfilling, incineration, composting, and AD. These approaches, while common, are considered less favorable within the waste hierarchy due to their lower sustainability value. Only a limited number of studies have explored the use of surplus food as animal feed, and even fewer have compared this with higher-priority strategies such as waste prevention or redistribution through donations (Eriksson, Strid and Hansson, 2015). Some studies have acknowledged the environmental value of preventing food waste, but thorough assessments of how to implement such measures or what their economic implications are lacking. (Eriksson, Strid and Hansson, 2015). Moreover, there has been little differentiation between prevention and donation in terms of impact, and some analyses have calculated the environmental value of donated food based solely on production emissions, without considering the broader implications of offsetting new food production (Schneider, 2013).

Two different sources are taken to provide an overview of the possible environmental savings related to various BW valorization pathways seen in Table 5.

Table 5: The greenhouse gas emissions associated with each waste management option for bread. Adopted by Eriksson et al (Eriksson, Strid and Hansson, 2015).

Valorization pathway	CO_2 impact (kg CO_2-eq/kg bread)	Source
Prevention	-0.66	(Brancoli, Bolton and Eriksson, 2020)
Landfill	1.9	(Eriksson, Strid and Hansson, 2015)
Incineration	−0.08	(Brancoli, Bolton and Eriksson, 2020)
Composting	0.043	(Eriksson, Strid and Hansson, 2015)
Anaerobic digestion	−0.02	(Brancoli, Bolton and Eriksson, 2020)
Animal feed	−0.53	(Brancoli, Bolton and Eriksson, 2020)
Donation	−0.61	(Eriksson, Strid and Hansson, 2015)
Beer Brewing	−0.46	(Brancoli, Bolton and Eriksson, 2020)
Bioethanol	−0.56	(Brancoli, Bolton and Eriksson, 2020)

Using the data presented in Table 3, it is now possible to compare the different innovation pathways regarding their environmental impact. 65,000 tons of old bread being transformed to animal feed can lead to CO_2 savings of 34,450 tons CO_2-eq compared to a situation where no reuse of bread takes place. The status quo in Austria shows that 86,62% of BW from retail and production level are processed to animal feed with an environmental saving of (65,000 t * 0.8662 * -0.53) 29,840 tons CO_2-eq. When increasing the bread flowing to animal feed production to 100%, increased CO_2 savings of 23% could be achieved. Including the other current utilization pathways of donation (3.33%), biogas production viewed as AD (4.38%), rework interpreted as prevention (3.34%), composting (0.02%) and incineration from residual waste (0.01%) as defined in Table 5 even more savings can be achieved. The amount of BW currently going to the biogenic waste stream (2.27%) is halved and assumed to go to composting (50%) and biogas production (50%). Taking into consideration all sources as defined in Figure 8 besides other treatment options and multiplying them with the CO_2 equivalents as given in Table 5 and doing an uncertainty analysis results in possible CO_2 savings of approximately 32,600 tons.

Because no specific data on the environmental savings of succinic acid, lactic acid and BDO could be found in literature the next calculation only considers bioethanol production. Assuming that one fourth out of all wasted bread is transformed into bioethanol then 9,100 tons CO_2-eq can be saved. However, if the total number of 65,000 tons of old bread goes into bioethanol production then savings of 36,000 tons CO_2-eq can be achieved. Beer brewing seem to achieve lower CO_2 savings with 29,900 tons CO_2-eq per 65,000 tons of utilized bread.

Figure 17 shows that highest CO_2 savings can be achieved when producing bioethanol, followed by animal feed production, then current fragmented approach and lastly beer production. These numbers serve as an estimate and while uncertainty analysis show the standard deviation, various other factors are not taken into consideration such as transport emissions and distance between processing sites.

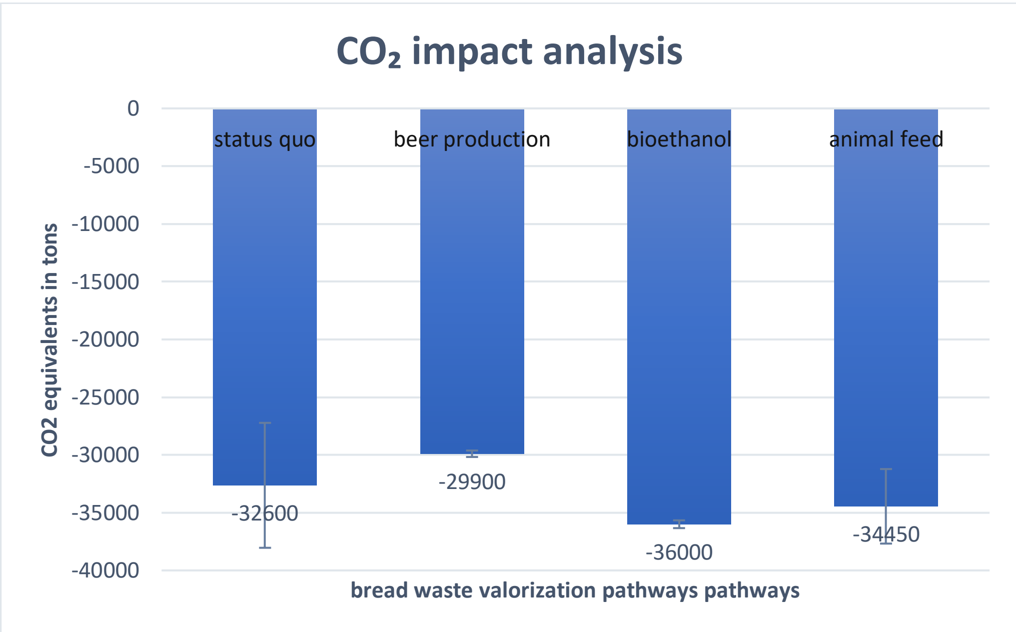

Figure 17: Utilizing all bread waste generated in retail and in production for either beer production bioethanol or animal feed production could lead to CO_2 savings of 29,900 tons CO_2-eq (SD = -2801), 36,000 tons CO_2-eq (SD = -3,372) and 34,450 tons CO_2-eq (SD = -3,227). The current pathways used in Austria generate savings of up to 32,600 tons CO_2-eq. SD = standard deviation. Household BW has not been included in this figure.

Regarding the environmental impact of succinic acid production, a study by Hafyan et al. could show that utilizing biological waste is superior than regular succinic acid production regarding the ecological criteria defined here. The comparison between fermentative succinic acid production from biological waste and conventional fossil-based methods demonstrated that the biological waste-derived approach has a reduced environmental footprint. The main sources of greenhouse gas emissions were attributed to the use of steam and heating oil in the production process. The study also emphasized the opportunity to utilize solid biomass residues as fish feed, offering additional environmental benefits. Reducing reliance on steam and heating oil was identified as a key strategy for lowering both energy consumption and emissions (Hafyan et al., 2024).

For the pathway of biochemical production, it was assumed that half of the household waste is being anaerobically digested as it offers a valuable option to recover the organic byproducts. AD is considered an effective method for eliminating food waste; however, it comes with several drawbacks. A significant portion of carbon is lost during the process due to microbial activities like biomass formation, as well as the release of carbon dioxide. While methane is the primary output of AD, it is considered a low-value product and offers fewer environmental benefits compared to alternative microbial valorization routes like converting food waste into animal feed, beer, or ethanol.

Due to its relatively low water content, bread is suitable for incineration with energy recovery. Composting, on the other hand, produced only minor greenhouse gas emissions but is considered a disposal method rather than a recovery process, as it does not retain or reuse the nutrients present in the waste. Introducing a nutrient recovery system that could offset the need for synthetic fertilizers might enhance the effectiveness of this option. Without such a system, however, composting ranks among the least preferable strategies for food waste management (Eriksson, Strid and Hansson, 2015).

For all valorization pathways considered it is essential to factor in the transportation distances as they considerably affect the environmental impact of each investigated route. A study by Brancoli et al. done in Sweden estimate that surplus bread is transported 730 km to plants that produce animal feed, ethanol or beer that to plants for AD or incineration. In case transportation distances exceed this range, the environmental and economic advantages of these options may diminish. Each scenario should be evaluated on a case-by-case basis, especially when deciding between producing feed, beer, or ethanol, as transport logistics can play a crucial role in determining the most sustainable option (Brancoli, Bolton and Eriksson, 2020).

5.2.3 Social criteria

When considering the social dimension of BW valorization pathways, several key criteria come into focus: affordability and health, regional relevance, and public awareness and acceptance. These elements are essential, as social sustainability encompasses the broader societal impacts of waste management choices. While environmental and economic metrics are often more quantifiable, social outcomes tend to rely on qualitative assessments, making standardization difficult. Affordability ensures equitable access to products derived from BW, while health considerations address food safety and nutritional quality, particularly relevant in pathways such as animal feed or human consumption. Regionality emphasizes the importance of adapting valorization solutions to local cultural norms, infrastructure, and governance, reinforcing the idea that a one-size-fits-all approach is inappropriate. Each waste management system is dependent on a local context, the waste hierarchy must still be seen as a rough generalization (Eriksson, Strid and Hansson, 2015).

All interviewed stakeholders have mentioned and agreed that current alternatives are not sufficient and additional utilization frameworks should be introduced. One interviewee even reported that "*as long as there is bread going to the residual waste stream, there is room for improvement.*" While the need for improved handling of bread waste has been acknowledged, social aspects seem to remain a noteworthy hurdle in implementation. Around 60% of the generated BW comes from private households, validating the importance of social criteria and awareness building. Lost appreciation for traditional bread making and bread being sold by supermarkets for lower prices has led to structural differences and the decrease of the number of bakeries because they just cannot compete with the cheaper supply of supermarkets leading to increased production waste. Thus, a big focus should be put on the affordability and accessibility of the alternatives according to two bakeries interviewed. They also highlighted that the consumer-side shows the highest potential of reducing overall BW, next to more efficient agricultural techniques. Lack of education considering how to properly store and reuse stale bread in recipes are common issues alongside the misconceptions about the environmental consequences of wasting food.

One reason environmental impact may play a minor role in consumer attitudes toward food waste is the general lack of awareness about its ecological consequences. Studies have shown that many individuals underestimate or misunderstand the environmental impact of food waste. For instance, a significant portion of people believe that packaging is more harmful to the environment than discarded food. Furthermore, some research reveals that individuals often fail to make the connection between food production and greenhouse gas emissions, highlighting a broader gap in environmental literacy related to food systems (Schanes, Dobernig and Gözet, 2018).

Social sustainability focuses on evaluating the social costs and benefits of a system, typically using qualitative or semi-quantitative data, which presents challenges when attempting to measure impacts per functional unit. Moreover, social assessments in biorefinery contexts should be context-specific, reflecting local social and political conditions. Key considerations include equitable labor practices, community engagement, inclusivity, transparency, and responsibility in product disposal (Hafyan et al., 2024). Despite its relevance, there is currently a lack of studies applying social implications specific to biological waste valorization technologies. Thus, the valorization pathways introduced in this research paper cannot be adequately analyzed regarding social parameters.

5.3 Discussion and comparison with other European countries

Based on the findings, the variation in BW utilization in Europe is interesting to mention. While in Austria the biggest fraction of stale bread is repurposed to animal feed, the United Kingdom focusses on the technology of aerobic digestion (Narisetty et al., 2021). In Sweden AD and incineration are the most common waste management systems (Brancoli, Bolton and Eriksson, 2020). While AD could be considered a more innovative pathway, it is not more environmentally friendly than animal feedstock production. The example of the UK shows that transitioning from AD to the bioconversion of BW into biofuels such as ethanol can result in savings of approximately 0.56 kg CO_2 equivalent per kilogram of BW. This translates to an annual reduction of around 163,520 tons of CO_2, based on an estimated 292,000 tons of BW generated in the UK each year. Similarly, repurposing BW as animal feed could lead to an annual decrease of approximately 1,549 kg CO_2 equivalent resulting in three times higher reductions of the global warming potential (Narisetty et al., 2021). According to Brancoli et al., producing feedstuffs, beer and ethanol are the best alternatives for recycling bakery waste in terms of environmental impact along with donations while AD and incineration are the worst recycling variants (Brancoli, Bolton and Eriksson, 2020; Dymchenko, Geršl and Gregor, 2023).

In the United Kingdom, data from the Waste and Resources Action Program (WRAP) gathered in 2021 indicate that BW constitutes approximately 10% of the nation's total food waste. Bread is identified as one of the most frequently discarded food items, with an estimated 20 million slices wasted each day. This amounts to around 292,000 tons of BW annually, contributing to approximately 584,000 tons of CO_2-equivalent emissions (Hafyan et al., 2024). When compared to Austria, where around 161,900 tons of bread are wasted each year, the scale of waste in the UK is considerably higher both in volume and associated environmental impact. However, when taking the population of both countries into consideration Austrians waste over four- times more bread per person annually compared to people in the UK.

Brancoli et al. (2019) have estimated that 80,410 tons of bread is wasted in Sweden each year, which is the equivalent of 8.1 kg per capita/year (Brancoli et al., 2019). The results from this study show that in the year 2024 approximately 17.6 kg of BW was generated per capita in Austria taking into consideration supermarket, household and production waste. In Sweden the total BW generated in households is estimated to be 29,870 tons per year, much lower than the Austrian number of 96,900 tons even though 800,000 more people live in Sweden compared to Austria.

While the exact reason for the more efficient BW reduction in Sweden and the UK is not clear from the literature, several aspects have to be considered such as prevention mechanisms, collection infrastructure with centralized supply chains, technological advancements in bioprocessing, as well as differences in policies. Cultural bread consumption variations also play a role, where Austrians and Swedes may consume more fresh bread daily, while in the UK bread often comes in pre-sliced in plastic.

It is apparent that in Austria some aspects of BW prevention or reduction are still not employed to their full potential. While a reduction of BW from 210,000 to 161,900 could already be achieved from 2020 to 2024 mainly regarding the BW generation in households (Obersteiner, 2020; Obersteiner et al., 2024), it is still necessary to ensure more BW is allocated to valorization pathways or included in other processes.

The study by Zarzycki et. Al has investigated the potential of bread in reusing by-products of the fruit industry. They propose incorporating fruit industry by-products into bread, which can significantly enhance its nutritional value by increasing fiber content, adding bioactive compounds, and improving antioxidant capacity. Fruit residues such as apple pomace, grape pomace, and olive pomace contribute beneficial compounds like pectins, polyphenols, and healthy fatty acids. These additions not only improve the health profile of bread but can also positively influence the breads' sensory qualities (e.g., taste, texture, and aroma) when properly processed and dosed. Main challenges remain regarding food safety, as there is limited data on potential contaminants or anti-nutritional factors in such by-products as well as different structural properties of dough affected by the added residues (Zarzycki et al., 2024). A research team in Finland even proposed using BW as a substrate to grow fungi and develop leather-like textiles. While this project is still in the experimental stage, it might offer valuable future utilization in reusing BW (Wijayarathna et al., 2022). A promising start-up from Poland called *REBREAD* became true pioneers in the field of BW reduction, creating impressive products that give bakery leftovers a new life. They craft distilled spirits from surplus bread collected from local bakeries, use BW as a base for cosmetics, soft drinks, and even biodegradable packaging. REBREAD doesn't only produce products; they also develop technologies that they can license to enable similar waste-free solutions globally (BIOECO-UP, 2024).

5.4 Data gaps and limitations

Despite the growing interest in reducing BW in Austria, significant data gaps and structural limitations persist, particularly regarding the origin, composition, and treatment of BW across the supply chain. This chapter outlines the most pressing shortcomings in current data collection and management systems and identifies underexplored areas where future improvements are crucial.

Incomplete data on household BW

One of the largest blind spots in Austria's BW management is the household level. While retail and production waste are relatively well-documented and often uncontaminated, BW generated in homes remains largely challenging to assess. It is commonly mixed with other organic or municipal waste, making accurate measurement and valorization extremely difficult. The lack of separate collection systems for bread at the household level represents both a practical and financial barrier to better waste diversion.

Behavioral uncertainties and consumer-level data gaps

Though studies such as Schanes et al. explore psychological and behavioral drivers of household food waste, quantitative data on actual BW volumes per household is sparse (Schanes, Dobernig and Gözet, 2018). There's limited insight into how different socio-economic or cultural groups in Austria waste bread, or how effective educational campaigns and mobile apps are in changing behavior. These behavioral patterns remain poorly integrated into broader waste tracking frameworks, resulting in missed opportunities for targeted intervention.

Unclear fate of returned bread in retail

In retail, significant volumes of bread are returned to bakeries under commission models. While these returns do not count as financial losses for retailers, they are rarely included in food waste statistics (Scherhofer & Schneider, 2011; Lebersorger & Schneider, 2014). This lack of standardized classification blurs the actual scale of the problem. Moreover, the end use of this returned bread is often undocumented, whether it's repurposed, discarded, or valorized, contributing to a high level of unmonitored surplus.

Unmonitored losses in valorization processes

The valorization options presented here, such as animal feed, beer brewing, and biochemical processes, are theoretically feasible, yet their real-life implementation lacks transparency. It is unclear how much bread could actually reach these processing facilities and what losses occur during transport or handling. There is limited tracking of logistics flows from waste generation points (e.g., bakeries or supermarkets) to valorization sites, which makes it difficult to assess the efficiency and environmental benefits of these pathways.

Structural and legal barriers limiting data availability

Several bakery and retail stakeholders interviewed reported legal constraints that hinder their ability to repurpose BW. For instance, stringent animal feed regulations exclude any bakery product containing traces of animal-derived ingredients, even in minimal amounts. These legal limitations not only restrict valorization efforts but also prevent data collection on potentially reusable bread. Often, the stakeholders are forced to stick with already well-established repurpose technologies due to time and policy limitations.

Gaps in retail-specific interventions and outcome monitoring

While several interventions have been suggested, like better forecasting, improved packaging, and employee training, there is little published evidence on the effectiveness of these strategies. For instance, the impact of shifting from take-back agreements to retailer-owned inventory remains underexplored, and sales data is rarely linked to waste outcomes in a systematic way.

Several recommendations have already been developed to enhance existing monitoring, prevention, and utilization strategies, specifically aiming to address data gaps and overcome current challenges. The suggestions most applicable to the Austrian context are outlined below. Effectively reducing household food waste will require an integrated approach that combines economic, regulatory, and educational measures.

Recommendations to Address Data Gaps

To effectively tackle household food waste, a combination of economic, regulatory, and educational instruments should be considered.

- Economic measures such as volume- or weight-based waste have shown promise in encouraging waste reduction by linking disposal costs directly to consumer behavior.
- Information and education campaigns remain essential in raising awareness and addressing specific knowledge gaps. Successful initiatives combine practical advice on food storage, date labeling, and cooking flexibility with targeted messaging and delivery formats tailored to different demographics. Personalized campaigns have been shown to foster more sustainable habits (Schanes, Dobernig and Gözet, 2018).
- Applications that provide tips on meal planning, storage, and leftover use can improve household efficiency. At the same time, food-sharing platforms allow surplus food to be reallocated within communities.

Retailers occupy a strategic position in the food supply chain and are uniquely positioned to influence both upstream suppliers and downstream consumers.

- Enhancing employee awareness and skills is a promising strategy to minimize food losses. To achieve this, it is essential to formulate tailored guidelines for individual businesses, taking into account their specific characteristics, production type, and operational scale (Goryńska-Goldmann et al., 2021).

- Efficient ordering schemes have shown to have the potential to reduce BW generation. Employing forecasting systems and consistent stakeholder dialogues with the supply bakeries can improve the waste management of bread (Brancoli et al., 2019).
- Advances in packaging technology, such as multilayer barriers or Modified Atmosphere Packaging, can extend shelf-life and enhance product preservation (Schanes, Dobernig and Gözet, 2018).
- Misunderstandings around food expiration dates often lead to the premature disposal of still-edible products. Clearer and more consistent labeling, such as revising the distinction between "use by" and "best before" dates, could reduce consumer confusion.
- Moving away from promotions like "buy one get one free" and instead offering staggered purchase options, such as “buy one now, get one later,” can reduce overstocking in households.

Regarding the conducted interview and gaining insights of several bakeries and industry players, following recommendations could be formulated:

- Logistics remains one of the biggest hurdles to reduce BW. By utilizing unrelated transport vehicles, which are partly empty to move old bread from the site of generation to the site of valorization, costs can be minimized and energy more efficiently allocated.
- Regular reminders of how to properly store bread and plan your shopping trips facilitated by posters in bakeries and supermarkets.
- Multiple stakeholders interviewed have mentioned the limitations of legal frameworks regarding bread valorization. Legal barriers to bread valorization, especially concerning animal-derived ingredients, were identified by industry stakeholders as a key challenge. Adjusting regulations could expand reuse options for large-scale food businesses.

6 Conclusion

According to the European Commission (2015), shifting towards a bio-based economy offers considerable potential for enhancing industrial profitability, reducing environmental harm, and fostering employment. In line with this objective, utilizing waste as a feedstock could minimize the need for virgin resource extraction and replace conventional waste management methods associated with greater ecological burdens (Kumar et al., 2023).

Austria has shown to have the highest BW generation compared to two other European Countries, Sweden and the UK. In order to efficiently tackle this issue in the future this study aimed to develop three innovative utilization pathways to consider for BW and answer the question of how an ideal circularity scenario for BW streams could be created. The research presented here shows that the current main valorization pathway of non-household BW found in Austria is animal feed production (87%). While the current pathway is environmentally favorable, increased CO_2 savings may be achieved by introducing additional utilization pathways. Producing bioethanol proves to have environmental benefits and can be used as a sustainable fuel alternative. OMV and Austrocel are two big players in the energy and fuel sector and could potentially benefit from introducing bioethanol production. Interestingly, beer brewing from stale bread has shown to have lower environmental savings compared to the status quo, animal feed and bioethanol production. This can be explained by the intense water consumption connected to the hydrolyzation process.

While it was difficult to rate the three pathways based on economic and social criteria since the data necessary are not easily accessible, it is possible to state here that small regional bakeries could definitely benefit from introducing beer production as a second stream of income. Making beer out of BW shows high market readiness and more than half of the Austrian beer production could be reached by utilizing bread. Regarding social aspects, more focus and responsibility should be put on the customer by introducing attractive incentives.

The current fragmented utilization of BW in Austria already facilitates considerable environmental benefits thus providing a relatively positive example of repurposing food waste. A potential question to answer would be whether an even more fragmented approach with many different utilization pathways could be superior to focusing only on a single one. Speaking to diverse stakeholders has also shown that based on current regulations and limited infrastructure does not allow one centralized approach. Thus, finding solutions on a regional level, facilitating cooperation between bakeries and chemical companies, breweries or farmers allow a diverse profile of BW utilization and also enables smaller stakeholders to play a role in reducing the amount of bread landing in residual waste.

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List of tables and figures

Figure 1: Visualization of the system boundary for this research project. 8

Figure 2: Key stakeholders in the Austrian bread economy according to their level of interest and influence in the Austrian economy regarding BW. 11

Figure 3: Visual representation of comparison approach between the current status and the three identified innovation pathways. Each pathway is compared to the status quo based on social, ecological and economic criteria defined. 14

Figure 4: Food waste hierarchy. Adopted from EU (Zero Waste Europe, 2019). 19

Figure 5: Visual summary of bread waste utilization potential with fermentation (Dymchenko, Geršl and Gregor, 2023). 23

Figure 6: Production, consumption and foreign trade of bread and pastries in Austria in 2022. Figure translated and adopted from Statista (Statista, 2022). 28

Figure 7: Bread waste generated in Austria in 2024 (Adopted by Land Schafft Leben, 2024). 28

Figure 8: Share of waste bread per treatment and disposal option in Austria in companies representing approximately 22% of the Austrian production volume (Scherhofer and Schneider, 2011). 29

Figure 9: company logo from Too Good To Go Application. 31

Figure 10: MFA of bread from production until waste visualized as a Sankey Diagram. Each stream represents a flow of bread, the thickness of the flow chart indicating how the numbers are. Numbers provided are given in kt unless other provided. 33

Figure 11: MFA of bread waste calculated for each person living in Austria over the representative year of 2024. 33

Figure 12: Bar chart representing the mean values ± standard deviation of bread streams defined by the system boundary from production to waste management in Austria from year 2024. 36

Figure 13: Process integration of bioethanol and succinic acid production of BW valorization (Hafyan et al., 2024). 39

Figure 14: MFA presented as Sankey Diagram using the innovative pathways of Biorefinery based on Austrian bread waste generation. 40

Figure 15: Sankey diagram describing the utilization pathway of animal feed production. 65,000 tons of bread waste is added in the regular animal feed accounting for 30% of the total produced 216,600 tons of feed. 41

Figure 16: Sankey diagram visualizing the potential of beer brewing as the main pathway to utilize leftover bread in Austria. 43

Figure 17: Utilizing all bread waste generated in retail and in production for either beer production bioethanol or animal feed production could lead to CO_2 savings of 29,900 tons CO_2-eq (SD = -2801), 36,000 tons CO_2-eq (SD = -3,372) and 34,450 tons CO_2-eq (SD = -3,227). The current pathways used in Austria generate savings of up to 32,600 tons CO_2-eq. SD = standard deviation. Household BW has not been included in this figure. 48

Table 1: Standard deviation and relative standard deviation of mean values of Austrian bread waste generation numbers. Uncertainty analysis of data for MFA of valorization streams. All numbers were estimated to three stages. 35

Table 2: Comparison of uncertainty analysis of bread waste valorization pathways with and without error propagation analysis after gauss. Numbers are estimated to three positions. 37

Table 3: Yield of different biochemical production pathways as published by (Kumar et al., 2023). 39

Table 4: Calculation steps for beer production out of bread waste. 42

Table 5: The greenhouse gas emissions associated with each waste management option for bread. Adopted by Eriksson et al (Eriksson, Strid and Hansson, 2015). 47

Appendix A: Interviews

Interview with Erika Geier-Tschernig, CEO of Geier (all answers translated to English):

1. What reuse or recycling pathways for surplus bread are you familiar with or currently apply within your institution?

"Yes, so in our case, we primarily work with Tafel Österreich – the Austrian food bank – which we see as a really meaningful way to redistribute bread that's still perfectly fine. In fact, bread is rarely really 'old' the next day, so that makes redistribution even more sensible. Then there's the method of reintegrating old bread back into new doughs. We do this ourselves, and we have a cap on it – we never go over 20% old bread in any new mix. Some of our colleagues also actively market products made with old bread, and that's something we find worth supporting. Of course, if something can't be reused or donated, it eventually gets incinerated – but that's really the last resort."

2. Approximately how much bread waste does your institution generate on a weekly basis? In your opinion, how significant is the amount of unreported bread waste across the sector?

"That varies, but I'd say it ranges somewhere between 8 to 15 percent, depending on the week and demand. In really good weeks, we're maybe closer to 8 percent, but in others it can go up. Particularly with pastries, where we use perishable ingredients like whipped cream or buttercream, or when you're dealing with snacks that contain dairy products – those can spoil faster, and so there's more risk of waste."

"It's definitely high – I think a lot more disappears than what's officially reported. Especially when you look at gastronomy and private households. I mean, that's where a huge part of the loss happens, next to actual production. There's certainly a gap between what's measured and what actually gets thrown away."

3. Why do you think restaurants and cafés are not legally required to disclose the amount of food they waste? What potential opportunities for reuse or valorization do you believe are lost due to this lack of transparency?

"That's an interesting point. I think part of it is that most businesses already do some internal tracking through their cost accounting systems. So, while there's not a legal obligation, they do monitor waste to a certain extent because it affects their bottom line. From their perspective, they might not see a lack of transparency as a real problem, even though from a broader societal or policy perspective, it definitely is."

"Well, if we don't know how much is being wasted or where exactly it's happening, then we can't really figure out where to intervene. So yes, there's a lot of potential being missed out on – both for reusing that bread and for improving systems in general. But without data, you can't act effectively."

4. Have you come across any innovative bread waste valorization methods that were not mentioned in our discussion but that you've heard of or experienced yourself?

"Sure, there's quite a bit happening already, which is great. For instance, fermentation processes can be used to make alcohol – and that's something that's actually already being done. Biofuels and biogas are another avenue – OMV, for example, is partially doing that. But by far the biggest share of old bread still goes into animal feed. And one thing I've seen and still find a bit troubling is how supermarkets operate – especially when bread is sold on consignment. Bäckereien often don't get back their unsold goods, and that's a burden. There's still not enough accountability there. As for platforms like Too Good To Go – well, it started out with good intentions, but now it's more of a business model. I mean, how's a restaurant supposed to know five days in advance how many surprise bags they'll have? It's tricky."

5. In your view, what are the main barriers to implementing a more circular food system? Based on your expertise, what concrete steps could individuals or institutions take to help overcome these challenges?

"It's mainly about awareness – or rather the lack of it. A lot of people just don't value food enough anymore. That comes down to how you were raised, and how much importance your family placed on not wasting. And then there's the system itself – circularity takes real effort, knowledge, and often a bit of heart. It's not something that happens on its own. The structures and incentives aren't quite there yet, even though it's getting better."

"Well, first of all, you need people who actively look for ways to reuse bread – that's what we try to do at Geier. We're always looking for partnerships or processes to bring old bread back into circulation. Then institutions like food banks can do a lot, especially if they have the infrastructure to take regular deliveries. And for individuals, it really comes down to education – helping people understand the value of what they're throwing away."

6. Do you believe there are already enough alternatives and solutions available on the market for food waste reduction? Or do you feel that certain aspects of food rescue and reduction are still being overlooked?

"No, not yet. I mean, if there were, we wouldn't have to keep searching for where to bring our leftover bread. That alone tells you the system still has gaps. It's not that there are no solutions – but the ones that exist are limited, or they don't scale well enough to meet the need."

7. From your experience, where do you see the greatest potential for creating regional synergies between rural areas and a city like Vienna to further reduce bread waste?

"Definitely between Lower Austria and Vienna – we're active in both, and there's a lot of potential for cooperation. In rural areas, you've got more facilities like biogas plants, which can handle old bread effectively. In the city, on the other hand, redistribution is easier. So if we manage the logistics right and avoid unnecessary transportation, it can work really well and still be sustainable."

8. When reused, what resources could old bread replace? Consider ecological, economic, and social criteria.

"Ecologically, you're reducing waste, which is always a plus. You're also potentially avoiding the need to produce new raw materials. Economically, it's about saving costs – it's expensive to dispose of bread, and it's expensive to buy fresh ingredients, so if you can use what you already have, it makes sense. Socially, it's about awareness and education – people need to be reminded that food has value. That includes giving to institutions who can manage and redistribute it, and maybe even giving consumers tools to see the bigger picture. We're working on something like a material flow analysis to show where bread comes from and where it ends up. That could really help identify the critical points where interventions would make the most difference."

Interview with Scherhaufer, researcher from BOKU university (all answers translated to English)

1. What reuse or recycling pathways for surplus bread are you familiar with or currently apply within your institution?

"The majority of surplus bread – including returned goods and production excess – is used as animal feed. It is also partially utilized by the biscuit industry. Some bread is processed into breadcrumbs or directly reworked into dough. In Austria, there are also large animal feed producers that process surplus bread. An innovative pathway is fermentation, for example, for the production of lactic acid or biofuel."

2. Approximately how much bread waste do institutions generate on a weekly basis? In your opinion, how significant is the amount of unreported bread waste across the sector?

"About the amount of bread waste per week—based on what I've heard, roughly 10–15% of bread is not sold and ends up as Altbrot. If that bread isn't resold, that's a loss to the food production system. If it's used as animal feed, that's still acceptable. If it goes to a biogas plant, that's okay too. But in the end, a resource like wheat goes through all the effort of being planted, harvested, milled, turned into flour and bread, transported—and then ends up back as feed. It's a lot of unnecessary steps. So, many initiatives and measures are needed. Some progress has been made in Austria in recent years, but more is needed."

„Past studies showed that 10-15% of the produced bread is not sold, which accounts for the most relevant number of left-over bread. However, the true numbers are likely to be higher because many bakeries or retailers have different definitions of stale bread and do not declare it as such. For example, if a bakery cooperates with a farmer to produce animal feed out of bread it is often not considered as bread waste; however it still is part of the unsold fraction of bread produced and thus should be considered in accounting for old bread. Residue waste analyses of private households and biological waste have shown that the bread waste coming from private homes is even larger than from production and retail."

"It's hard to say exactly which cake or bakery product is found throughout the entire supermarket, and you can never be completely certain when it comes to production numbers, as sample sizes and methodologies vary. I know that the sample used by the Institute for Food Production Studies back in 2014 was quite comprehensive, covering the entire Austrian market. I believe that included a major share of the market, meaning the data is very reliable. Back then, we had access to scanner data, so the quantity of bread and baked goods sold in 2013 was well documented and reliable."

"When it comes to *old bread* (Altbrot), definitions vary significantly depending on whom you talk to. Some define it simply as surplus—bread that was produced in excess, not sold on the market, and also not used for animal feed. From a waste management perspective, such bread is considered a loss, and we can comfortably call it Altbrot. Still, misunderstandings often arise because many bakers claim that they have no Altbrot. But upon closer questioning, they admit to having dough remnants that are reprocessed. As long as there's a market for it, it can be classified as a by-product. But when there's no market, it becomes waste—even if it's the same product. This varies by country."

If you want a complete picture, you also need to consider by-products. It's important to be careful when discussing this with bakeries or retailers; don't just say "you produce a lot of waste." Household waste composition in Austria is quite representative. But of course, you have to also consider what ends up in organic waste bins. There is a recent study on this topic as well, so it could be that household waste accounts for even more than previously assumed. It always comes down to definitions and perspectives, which leads to different figures being reported.

3. Why do you think restaurants and cafés are not legally required to disclose the amount of food they waste? What potential opportunities for reuse or valorization do you believe are lost due to this lack of transparency?

„Transparency is missing, as there is no rule to calculate and monitor the waste. Chances for reuse or new valorization pathways are definitely lost. The project United Against Waste also explored product groupings and quantities, and what can be done with them. Are there any innovative methods for reusing bread that haven't been mentioned? Fermentation is a big one—

you can do a lot with that: beer, biofuel, even lactic acid production. But whether that's viable in our industrial context remains to be seen."

4. Have you come across any innovative bread waste valorization methods that were not mentioned in our discussion but that you've heard of or experienced yourself?

„Yes, fermentation seems to be a big topic; next to lactic acid and biofuels other chemical basis connections can be produced. Whether these technologies will be used in an industrial scale in Austria remains open."

5. In your view, what are the main barriers to implementing a more circular food system? Based on your expertise, what concrete steps could individuals or institutions take to help overcome these challenges?

"Reliable planning and overcoming unfair trading practices are major points. So are return agreements, which need to be questioned. Better forecasting, more efficient production, and better household planning (e.g., shopping lists) could all help. Storage is a key issue. Bread is often thrown away because it was forgotten or stored improperly. And many people don't value a bread roll that only costs 20 cents. The perceived value of the product doesn't align with the actual environmental impact if it goes to waste."

6. Do you believe there are already enough alternatives and solutions available on the market for food waste reduction? Or do you feel that certain aspects of food rescue and reduction are still being overlooked?

"In a recent EU project, we also dealt with Altbrot. In our case studies, we compared Italy, Finland, and Sweden. In Finland and Sweden, there's mostly large-scale industrial baking; in Italy, the industry is more artisanal and fragmented. In large-scale production, it's harder to implement changes. One case study focused on stakeholder dialogue—bringing all the big players to the table. But conflicts can arise, and that's why mutual understanding is important."

"In small artisanal bakeries, stakeholder dialogues were also useful. One key finding was that for the first time, bakeries were quantifying how much Altbrot they generated. Then, they developed measures—ideally through participatory processes that involved both researchers and practitioners to create implementable solutions."

"Some bakeries said that although it's good that supermarkets return unsold goods, it also puts the burden back on them. Supermarkets shift the responsibility, even though they are better equipped, financially and infrastructure-wise, to manage surplus. But this isn't happening."

"A major driver of overproduction is that supermarkets want to guarantee full shelves until closing time. This pressure on constant availability leads to waste. In one ministry, employees were allowed to take leftover bread home at the end of the day, which was a great idea. But people started baking fresh bread just before closing to take it home, which increased the amount of leftover bread. So the initiative had to be reversed."

"There's still a lot of room for raising awareness, especially around what bread means, and why its waste matters. For example, how many bread losses occur in households? It's one of the largest figures. In the ministry's data, avoidable food waste is still significantly high."

7. From your experience, where do you see the greatest potential for creating regional synergies between rural areas and a city like Vienna to further reduce bread waste?

"If it's thrown away in Vienna, it's usually incinerated. We also talked about the comparison between Scandinavian countries and Italy. In Austria, you have urban areas like Vienna and more rural ones like Lower Austria or Burgenland. Could we create synergies so rural surplus can help urban demand? Probably yes, but that would require high transport costs, so it's a tricky trade-off."

8. When reused, what resources could old bread replace? Consider ecological, economic, and social criteria.

"Some products for reuse are widely accepted socially and even generate new jobs. They can also be healthy and locally produced. But others depend on imported additives, like soy. And we always have to think about overall awareness of bread's value and what happens when it's reused.

Energy demands for reprocessing and transport costs also factor in. And economically, infrastructure and market integration are essential—animal feed is already well integrated, but other ideas are still in early stages.

Strict privacy laws also prevent searching through household waste. Many people don't want their trash examined. In a pilot study, they asked participants to collect their waste for six weeks and then reassessed it, but finding willing households was hard."

Interview with international food production company:

1. What reuse or recycling pathways for surplus bread are you familiar with or currently apply within your institution?
   "Currently, no surplus bread is used in our biorefinery located in xy. Although earlier pilot projects were conducted in collaboration with the xy company to explore such utilization, they were never implemented on a larger scale. A significant obstacle was the difficulty of producing a mash free from animal-derived components using surplus bread."

„At present, feed products are produced from other residual materials. The biorefinery primarily operates a large-scale industrial ethanol fermentation process, which predominantly relies on by-products from wheat starch production sourced both from the site itself and from low-grade grain, specifically "Kleinkorn", a type of small-kernel grain classified as feed grain due to its low baking quality."

„Fermentation processes at the facility are already sustained by up to 50% residual materials. These residues typically follow a multi-stage cascade use pathway, maximizing resource efficiency. The wheat residues used stem from harvests that are unsuitable for bread production, largely due to the high proportion of small kernels."

2. Approximately how much bread waste does your institution generate on a weekly basis? In your opinion, how significant is the amount of unreported bread waste across the sector?

   "Not relevant for our instution because we work on a different stage of the food chain."

3. Why do you think restaurants and cafés are not legally required to disclose the amount of food they waste? What potential opportunities for reuse or valorization do you believe are lost due to this lack of transparency?

   „There is certainly still considerable potential. A new project may be launched in the future, provided that the proportion of animal-derived components in the feed can be eliminated. Logistics also present a significant challenge; however, transparency is essential for advancing a circular economy. „

4. Have you come across any innovative bread waste valorization methods that were not mentioned in our discussion but that you've heard of or experienced yourself?

   „A traditional example is beer brewing, though the extent to which it is considered innovative remains debatable. In this context, fermentation and ethanol production are employed differently. Additionally, biogas production is known, though it is generally regarded as less innovative. Some other bakeries also produce high-percentage alcohol, such as gin."

5. In your view, what are the main barriers to implementing a more circular food system? Based on your expertise, what concrete steps could individuals or institutions take to help overcome these challenges?

“A more differentiated approach to regulatory barriers is needed, regulations should be designed to enable the fulfillment of all overarching goals. For instance, feed mash should not be required to be entirely free of animal-derived components; a certain permissible percentage that does not pose negative impacts should be allowed. Adjusted regulations that maintain overall safety and efficacy could facilitate such processes.”

“Regarding surplus bread, many small businesses are involved. However, for larger enterprises dealing with significant volumes, small-scale collaborations are often impractical. Therefore, a more efficient system for the exchange and distribution of residual materials is needed—one that includes improved data collection on surplus quantities. Enhanced monitoring of bread waste generation would significantly support the implementation of circular economy projects by providing reliable information on the availability and timing of surplus materials.”

6. Do you believe there are already enough alternatives and solutions available on the market for food waste reduction? Or do you feel that certain aspects of food rescue and reduction are still being overlooked?

„As long as waste is still being sent to biogas plants, it indicates that there are either not enough alternative valorization options available or that existing alternatives are not being sufficiently utilized. It is essential to make effective use of by-product streams. “

7. From your experience, where do you see the greatest potential for creating regional synergies between rural areas and a city like Vienna to further reduce bread waste?

„Especially in rural areas, challenges arise due to the wide geographic dispersion and small scale of producers. When waste collection is required, the associated costs often exceed the value gained from its utilization. Regulatory measures could be introduced that mandate bakeries to collect surplus bread rather than dispose of it, allowing for centralized collection. However, this would place additional logistical and financial burdens on bakeries, necessitating political intervention and support. “

„Decentralized biogas plants, with smaller catchment areas and lower biogas prices, offer a potential solution and driving force. There are also initiatives such as the new Renewable Gas Act. Although this perspective runs counter to my own business in ethanol production, I recognize the clear advantages of biogas plants. These facilities are more evenly distributed across Austria, providing a more accessible and locally adaptable infrastructure. “

8. When reused, what resources could old bread replace? Consider ecological, economic, and social criteria.

„From an ecological perspective, key considerations include CO_2 emissions, their reduction, and the closing of material loops. “

“Economically, it is essential to weigh the cost of disposal against the expenses associated with bread valorization. In general, the implementation of a structured system could help reduce incidental costs and thereby increase motivation to support a circular economy. Furthermore, the actual price of bread and the broader lack of appreciation for food contribute to inefficiencies in resource use.“

„On the social level, public education and knowledge dissemination are crucial. There is significant potential in private households, which can be tapped through awareness campaigns, for example by promoting practices such as freezing bread to prevent waste.“

Interview with Sarah Lechner, StartUp founder of Brüsli (all answers translated to English)

1. What reuse or recycling pathways for surplus bread are you familiar with or currently apply within your institution?

“I am aware of and have seen a range of valorization pathways for surplus bread. These include processing into animal feed, biogas, and breadcrumbs (“Brösel”), as well as more innovative applications like bread chips, muesli (e.g., Brüsli, where 1 kg of old bread becomes 1 kg of cereal), distilling gin, and rework in production processes. Some bread is also incinerated, particularly in urban centers like Vienna. However, the share that actually gets reused remains relatively small due to logistical and legal challenges.”

2. Approximately how much bread waste does your institution generate on a weekly basis? In your opinion, how significant is the amount of unreported bread waste across the sector?

“In large-scale bakery operations, around 5% of what is produced ends up as waste, while 10–20% of baked goods are returned from retailers. These returned products require special legal controls and quality assurance processes, adding to complexity. Given that many institutions don't publicly report or systematically track their waste the actual amount of unreported bread waste across the sector is likely substantial. The lack of standardized data makes sector-wide assessments difficult.”

3. Why do you think restaurants and cafés are not legally required to disclose the amount of food they waste? What potential opportunities for reuse or valorization do you believe are lost due to this lack of transparency?

“There’s currently little pressure on gastronomy businesses to report food waste, which avoids the responsibility that would come with transparency. If food waste figures were publicly known, it would likely prompt both consumer pressure and policy changes. Without these obligations, opportunities for reuse (e.g., donations, transformation into new products, or redistribution) and valorization (e.g., creating alternative products from surplus) remain largely untapped. In contrast, countries like France and Spain have introduced penalties for food waste, setting a precedent for more responsible handling."

4. Have you come across any innovative bread waste valorization methods that were not mentioned in our discussion but that you've heard of or experienced yourself?

„Yes, several innovative methods exist:

- Brüsli: Upcycled muesli made entirely from old bread, enhanced with fruits and oils.
- Bread chips: Typically use 10–20% old bread.
- Rework: Reintroduction of surplus dough or ingredients into the production cycle.
- Gin distillation: Using stale bread as a fermentation base.
- Insect feed: Bread serves as feedstock for larvae, which are later processed into insect meal or fertilizer.
- Combustion: Still a major end-of-life route in Vienna. "

5. In your view, what are the main barriers to implementing a more circular food system? Based on your expertise, what concrete steps could individuals or institutions take to help overcome these challenges?

"Key barriers include:

- Logistics and reprocessing complexity: It's often cheaper to produce new goods than to process and repurpose old ones.
- Retail structure: Orders are often placed late (e.g., morning orders), while bakeries must estimate production earlier, leading to surplus.
- Lack of awareness: Especially at the household level, including poor planning and confusion about best-before dates.
- Legal hurdles and insufficient support systems: Regulations can make reprocessing returned goods difficult.

Concrete steps:

- Improve consumer education on food planning and MHD understanding.
- Adjust bakeries' evening offerings to reduce overproduction.
- Broaden the focus beyond bread—fruit, vegetables, and imports also contribute to systemic loss.
- Invest in local production loops, e.g., insect farms at household or farm scale.
- Promote policy change and targeted funding to support circular solutions. "

6. Do you believe there are already enough alternatives and solutions available on the market for food waste reduction? Or do you feel that certain aspects of food rescue and reduction are still being overlooked?

“There are many innovative solutions, but most are still not widely implemented or economically viable. Bread reuse, for instance, is often not competitive with fresh production due to high costs in logistics and processing. Moreover, current approaches tend to focus on specific categories (like bread), while other types of food loss,such as surplus produce from overseas shipments, are often overlooked. What’s needed is a more systemic approach that integrates solutions across all product types and scales.”

7. From your experience, where do you see the greatest potential for creating regional synergies between rural areas and a city like Vienna to further reduce bread waste?

“Rural areas often consist of smaller producers with less structural surplus. This opens potential for regional synergies where urban waste streams, such as bread waste from Vienna, could be transferred to rural micro-facilities for processing (e.g., insect larvae production, composting, or animal feed). Creating networks between rural innovators and urban suppliers,such as the example of the Swiss entrepreneur working on local valorization, can foster more balanced and circular flows between regions.”

9. When reused, what resources could old bread replace? Consider ecological, economic, and social criteria.

“Ecological: Reduction of CO_2 emissions caused by new production and disposal processes. Transport efforts also decrease if local processing is possible.

Economic: Savings on raw material procurement. At the same time, new costs arise from processing and logistics, which can only become economically viable through scaling and financial support.

Social: Raising awareness about the value of food can lead to more responsible consumer behavior. Additionally, new business models in the upcycling sector offer job opportunities and potential for innovation.“

Interview with bakery Aschauer:

1. What reuse or recycling pathways for surplus bread are you familiar with or currently apply within your institution?

“We make alcohol, beer and gin out of our leftover bread.”

2. Approximately how much bread waste does your institution generate on a weekly basis? In your opinion, how significant is the amount of unreported bread waste across the sector?

“Around 10–15% of products are returned. Availability is optimized using AI control in relation to demand. Within the company itself, the data is consistently recorded, although with a certain error rate.”

3. Why do you think restaurants and cafés are not legally required to disclose the amount of food they waste? What potential opportunities for reuse or valorization do you believe are lost due to this lack of transparency?

“Many restaurants and cafés bake goods based on demand, which helps reduce immediate waste. However, without legal requirements to disclose food waste, it's unclear how efficiently this is managed overall. The lack of transparency also obscures how ingredients (Wareneinsatz) are used and whether surplus food could be repurposed or donated. This limits opportunities for reuse, valorization, and broader sustainability efforts in the food sector.”

4. Have you come across any innovative bread waste valorization methods that were not mentioned in our discussion but that you’ve heard of or experienced yourself?

“One interesting aspect related to bread waste reduction starts at the household level, where better shopping planning can significantly reduce overbuying. Proper storage and awareness of best-before dates (MHD) also play a crucial role. On a larger scale, there has been a shift in the relationship between bakeries and supermarkets: previously, bakeries delivered on commission and accepted returns, but now many no longer take back unsold goods. This change is largely due to the bakeries' economic dependence on supermarkets. A noteworthy example in this context is Thereser Mölk’s collaboration with M-Preis, which may involve innovative approaches to managing or valorizing unsold bakery products.”

5. In your view, what are the main barriers to implementing a more circular food system? Based on your expertise, what concrete steps could individuals or institutions take to help overcome these challenges?

“One of the main barriers to implementing a more circular food system lies on the consumer side. Many people lack awareness about the true value of food, which leads to wasteful behaviors. This issue is deeply rooted in our education system, where sustainability and food literacy are often not emphasized enough. Additionally, the agricultural sector plays a crucial role—practices and policies in farming must align more closely with circular principles. To overcome these challenges, individuals can become more mindful consumers, valuing food and reducing waste, while institutions should integrate food education into curricula and support sustainable farming practices through policy and incentives.”

Interview with one of biggest retail chains in Austria:

1. What reuse or recycling pathways for surplus bread are you familiar with or currently apply within your institution?

"The bread is collected centrally and sent to an animal feed production facility. This project is called Reversio. But first, we focus on prevention measures. Each store is responsible for ordering just the right amount to avoid surplus. Of course, sometimes there's leftover bread—you want to make sure there's always enough available for customers.

Another strategy we use is selling products at a reduced price the next day, under a program called REttercycle. Items from the baking shop are offered at a discount. Anything that's still left after that is donated to social organizations."

2. Approximately how much bread waste does your institution generate on a weekly basis? In your opinion, how significant is the amount of unreported bread waste across the sector?

"After one year, around 2,000 tons of bread waste were collected and reused thanks to Reversio. Animal feed production is our last resort. Before that, we try to prevent waste and donate what we can. Only a very small amount actually ends up being disposed of—and that's usually baked goods that contain animal products, which we can't repurpose as easily."

3. Why do you think restaurants and cafés are not legally required to disclose the amount of food they waste? What potential opportunities for reuse or valorization do you believe are lost due to this lack of transparency?

"Studies have shown that supermarkets actually generate the least food waste proportionally, and the second-lowest is food service businesses like cafés and restaurants. So yes, it would make sense for them to publish their data as well. But realistically, the effort and resources required would be huge—so it's probably not feasible for many of them, even though it could make a real difference."

"With more transparency, there would be greater public pressure and possibly more regulation. But the added workload for each restaurant or café is definitely something to consider."

4. Have you come across any innovative bread waste valorization methods that were not mentioned in our discussion but that you've heard of or experienced yourself?

"Yes, like reworking old bread into food for human consumption—just like you'd do at home. You can use it for soups, as salad toppings, and so on. But once you're operating at a larger scale, it becomes much harder logistically and legally to comply with all the necessary regulations."

5. In your view, what are the main barriers to implementing a more circular food system? Based on your expertise, what concrete steps could individuals or institutions take to help overcome these challenges?

"A big challenge is the legal definition of food waste. If you want to reintroduce leftover food into the human food chain, it's often unclear whether it can still be legally considered food.

For smaller bakeries, it's easier—they can internally process leftovers or turn old bread into products like alcohol. But for bigger institutions, the regulations are stricter. You have to make absolutely sure that the leftovers are never classified as 'waste' and that there are no hygiene issues. The line between food and waste is very thin and unclear. Clearer definitions and communication from policymakers would help a lot."

"There was a case recently where food was taken from a disposal bin and reused, and it led to legal consequences. So as a retailer, you're responsible for making sure these products are either donated or reused before they're considered waste. Otherwise, if hygiene standards aren't met, especially with products containing meat, it can become a legal issue."

"Another challenge is logistics. Food needs to move quickly from A to B to stay safe, and maintaining the cold chain is a big part of that. Any break in that chain can cause problems."

6. Do you believe there are already enough alternatives and solutions available on the market for food waste reduction? Or do you feel that certain aspects of food rescue and reduction are still being overlooked?

"One thing that's often overlooked is the role of the consumer. Households actually generate the most food waste—not the upstream or downstream parts of the supply chain. Especially when it comes to bread, there are so many simple ways to avoid waste at home."

"Last September (2024), there was a public report released with MA48 that made this point very clear. They emphasized that individuals—not just retailers—need to take responsibility for reducing waste."

7. From your experience, where do you see the greatest potential for creating regional synergies between rural areas and a city like Vienna to further reduce bread waste?

"With Reversio, we've already established a system that connects all parts of Austria. We have seven central collection points where nearby stores bring their leftover bread. It doesn't matter which region—everything can be processed and reused. The collected bread is then sent to an animal feed facility in Lower Austria."

"In Vienna, there are a lot of social organizations that take donations, but that’s not always the case in rural areas. Supporting those kinds of initiatives financially could help balance the system more evenly across the country."

"Each market is responsible for organizing its own donation process, usually with local charities. But when it comes to larger initiatives like animal feed production, it depends more on regional infrastructure and capacity."

8. Related to the reuse of bread: Which social, economic and ecological aspects can you think of?

"Socially maybe not directly, but from a quality management point of view, it’s important to make sure the best-before date isn’t shortened and the product still meets market standards when reused."

"From a logistical and economic perspective, the more waste you generate, the higher your disposal costs. So if you can find ways to reuse that bread, it's a win for the company. But it also makes operations more complex—staff need to understand and manage multiple processes like donations, feed production, or upcycling. That requires extra time and resources."