Bread waste – a potential feedstock for sustainable circular biorefineries

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Review

Bread waste – A potential feedstock for sustainable circular biorefineries

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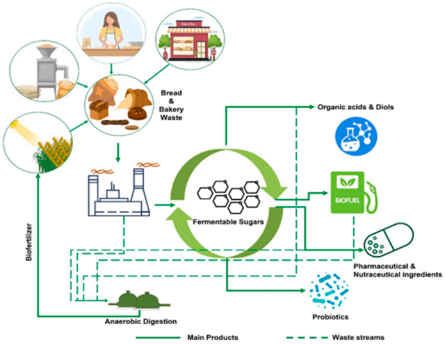
HIGHLIGHTS

- Bread waste (BW) is a potential feedstock for sustainable biorefineries.
- Being rich source of clean sugars, BW can be valorised into high value products.
- High level production of platform chemicals has been achieved using BW.
- Recycling of BW creates low carbon, circular economy pathway for clean production.

GRAPHICAL ABSTRACT



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ABSTRACT

The management of staggering volume of food waste generated (∼1.3 billion tons) is a serious challenge. The readily available untapped food waste can be promising feedstock for setting up biorefineries and one good example is bread waste (BW). The current review emphasis on capability of BW as feedstock for sustainable production of platform and commercially important chemicals. It describes the availability of BW (>100 million tons) to serve as a feedstock for sustainable biorefineries followed by examples of platform chemicals which have been produced using BW including ethanol, lactic acid, succinic acid and 2,3-butanediol through biological route. The BW-based production of these metabolites is compared against 1G and 2G (lignocellulosic biomass) feedstocks. The review also discusses logistic and supply chain challenges associated with use of BW as feedstock. Towards the end, it is concluded with a discussion on life cycle analysis of BW-based production and comparison with other feedstocks.

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1. Introduction

The rapid depletion of non-renewable fossil fuels and their adverse environmental impacts due to the emission of harmful greenhouse gases and toxic materials have resulted in a search for alternative sustainable resources as feedstock replacements. At present time, modern society is dependent on fossil fuels for ~ 80 % synthesis of fuels and ~ 90 % production of chemicals of the global requirement (Takkellapati et al. 2018). The world is embracing a transition from a fossil- to bio-based economy. The use of finite fossil-based substrates is becoming increasingly contentious, and they will need to be swapped with renewable and sustainable resources in the near future. Significant progress has been made in manufacturing low carbon renewable sources of heat and power, while even today, the production of chemicals and polymers is largely dependent on fossil-based petrochemical routes. Biomass, a renewable feedstock, has been identified as potential alternative for sustainable production of chemical building blocks to overcome environmental problems caused by our substantial dependence on petrochemical sources with a clear and net greenhouse gas saving without negatively impacting on biodiversity and land use (Narisetty et al. 2021; Narisetty et al. 2022a; Mohd Hamzah et al., 2022). For this, biorefineries with an infrastructure to process biomass into variety of commercially viable chemicals, and feasibility of developing integrated processes for fuel and energy purposes, that are analogous to petrochemical refineries has been established. One of the major factors determining the feasibility of a biorefinery is continuous availability and economical supply chain of biomass along with cost-effective pretreatment and saccharification costs for the extraction of fermentable sugars (Wenger and Stern, 2019; Ubando et al. 2021). In the last two decades, significant attention has been paid to the bio-based production of chemical building blocks from renewable feedstocks. In 2004, US Department of Energy prepared a list of 12 platform chemicals obtainable from biomass (Bozell and Petersen, 2010). Similarly, in 2017, LBNet (BBSRC, UK) released list of top biochemicals having strong commercial market value in UK (E4 Tech, 2017). In 2017, a report entitled “Biorefining Potential for Scotland, Zero Waste Scotland” was published from Scotland. As per the report, 27 million tons of biowaste is produced per annum in Scotland, that can be valorized into value-added chemicals, fuels, and other precursors for polymer, textile, and many other industrial sectors (Pitcairn et al., 2017). In the last two decades, the market for bio-based products is continuously increasing, and it has been forecasted to reach USD 97.2 billion by 2023 with a compound annual growth rate of 10.47 % (Ko et al. 2020).

The key limitation for the biological procceses is the identification of the suitable and renewable feedstock which could provide cost competitiveness with petrochemical process and that do not intervene with food chain. (Castillo Martinez et al., 2013). To this end, biorefineries can be divided into different categories. The first generation (1G) biorefinery, generating biofuels and biochemicals from edible sources (starch, sugar, corn, animal fats and vegetable oil), is widely known, efficient and well established. The well-known products from 1G are bioethanol and biodiesel. The USA and Brazil are the largest producers of bioethanol in the world using edible feedstocks corn and sugarcane juice, respectively (Bušić et al., 2018). Simmilarly, the European Union (EU) is the leading biodiesel producer and manufacturing this biofuel which mainly stems from using vegetable oils. The use of edible feedstocks creates socio-economic problems due to a resulting food-versus-feed debate (Naik et al. 2010; Takkellapati et al. 2018; Wenger and Stern, 2019). To overcome this, it is essential to establish a sustainable chemical industry capable of manufacturing chemicals and materials from a variety of non-edible and waste biomass as feedstocks which are not competing with food/feed production for resources. Second generation (2G) biorefinery is a potential alternative, making use of non-edible feedstocks and resulting is no concurrent conflict with food industries. Most of the work in the 2G biorefinery approach has been focussed on lignocellulosic biomass (LCB). Despite much research, the product(s) from 2G biorefineries have not been commercialized, mainly stemming from the recalcitrant nature of LCB. Whilst third generation (3G) refineries refer to the use of algal biomass for sustainable bio-production, this technology is confined to the laboratory scale and has yet to be translated to the industrial scale (Aristizábal-Marulanda and Cardona Alzate, 2019; Ubando et al. 2021; De Buck et al. 2020). Overall, the biobased products produced from any type of biorefinery should be cost competitive for commercial viability. A potential enlargement of the biomass feedstock sector is the adoption of cost-effective waste materials rich in renewable and fermentable carbon. Therefore, it is instrumental to concentrate on waste streams with high sugar content where the extraction of fermentable sugars is convenient and low cost such as food, bakery, bread, fruit and beverage wastes and these have received significant attention in recent years (Seong et al. 2015; Liakou et al. 2018; Amraoui et al. 2022). These streams are produced in sufficient amounts, making them attractive carbon feedstocks for biorefineries but the use of such bio-derived ‘wastes’ for biorefineries has been underexplored.

The aim of this review is to demonstrate the potential of bread waste (BW) as feedstock for the fermentative production of chemical building blocks. It begins by assessing the availability of BW to serve as feedstock for sustainable biorefineries, followed by summarising several recent examples of platform chemicals which have been biomanufactured using BW including ethanol, lactic acid, succinic acid and 2,3-butanediol via microbial processes. Finally, the BW-based production of these metabolites via microbial routes is compared against 1G and 2G (LCB) feedstocks and for a consequential assessment, same organism has been preferred for each product. The review also discusses potential logistic and supply chain challenges associated with use of BW as a microbial feedstock. Towards the end, it is wrapped up with discussion on life cycle analysis of BW-based production and comparison with other feedstocks.

2. Availability of bread waste as feedstock

Waste mangamement is a global challenge and if the vast amount of waste generated worldwide could be valorised intelligently via a biorefinery route, it can simmiltaneously lead to reduced waste and carbon neutral society. Food waste is a global problem. Recent studies estimate that 14 % of food produced is lost before it reaches to the retail shops (Santos et al., 2022) while 17 % of the available food is wasted at the marketing and consumer levels (UNEP, 2021). Approximately, 1.3 billion tons of food is wasted every year resulting in a loss of ~ USD 750 billion to the global economy (UNEP, 2013). For example, in UK alone £20 billion food and drink are wasted every year. Bread is a staple food in several parts of world including Europe and North America (HM Government, 2018; Kumar and Longhurst, 2018). Globally > 100 million tons of bread is manufactured every year and bread consumption in 2016 was 129 million tons (Jung et al., 2022). Due to short shelf-life and overproduction, ~10 % (900,000 tons) of bread is wasted during the supply chain from manufacturer to consumer consumption. The wastage of bread across the various stages of supply chain is a serious problem. Bread waste (BW) is major part of the global food waste (Fig. 1) and a big challenge in Europe where market share (53.6 %) is maximum (Narisetty et al. 2021). Bread is a product with one of the highest waste generation in several parts of the supply chain. In many countries around the world, BW is one of the major components of food waste. The BW constitute 13, 22, 23, 27, 7.9, 18.7, 2.2 and 12–17 % of food waste in Finland, Netherland, New Zealand, Norway, Portugal, Saudi Arabia, South Korea and Sweden, respectively (Jung et al., 2022). Bread although staple food in the UK households, it is the 2nd most wasted food product, totalling 20 million slices of bread per day (WRAP, 2021), while in Norway, bakery products constitutes 27 % of the edible household food waste (Hanssen et al., 2016). In Sweden, 29,870 tons/year of bread is wasted in domestic households, and 80,410 tons are wasted yearly in the whole suppy chain (Brancoli et al., 2019).

Furthermore, Stensgård and Hanssen (2016) identified bread as the product group with the highest waste levels in Norwegian retailers, similar to the results found by Lebersorger and Schneider (2014), Brancoli et al. (2017), van Dooren et al. (2019), and Katajajuuri et al. (2014) in Austria, Sweden, Netherlands, and Finland, respectively. The staggering volumes of BW does not only reflect just product loss, but also the loss of various natural resources like water, land, and energy use during the production and use of raw materials, transportation, and manufacturing of the final product (Narisetty et al. 2021). In addition to the loss of revenue and bioresources, BW like any other food waste causes massive harm to the wider environment through global warming, acidification and eutrophication (Brancoli et al. 2020). Thus, the reduction/recycling/valorisation of food waste has the potential to save global economic values i.e. billions of pounds/dollars/euros, invaluable bioresources and prevent millions of tons of GHG from entering the atmosphere.

3. Bread waste composition and saccharification process

Compositionally, BW contains 50–70 % starch which is a homopolysaccharide consisting of two components amylose and amylopectin. Amylose is a linear polymer of glucose-subunits linked by 1,4′-O-(α-glycopyranoside) or α-(1 – 4) glycosidic bonds. The amylopectin is a branching chain polymer containing 95 % glucose connected by α-(1 – 4) linkages while remaining 5 % via α-(1 – 6) glycosidic bonds. The conversion of starch into individual glucose units involves the hydrolysis of these α-(1 – 4) and α-(1 – 6) linkages, which can be made possible by the action of acid (H_2SO_4/HCl) or enzymes (α-amylase and glucoamylase) (Bello-Perez et al., 2020; Kapar Yilmaz et al., 2021). To unravel the potential of BW as the sustainable feedstock, it should be subjected to pretreatment or hydrolysis for the breakdown of starch into monomeric fermentable sugars.

3.1. *Dilute acid pretreatment of bread waste*

Traditionally acid hydrolysis has been used for production of soluble starch from the insoluble starch granules, where the starch is treated with high concentrations of acid at room temperature for longer duration (Ai and Jane, 2015; Höfer, 2015; Hoover, 2000). It was understood that the acids (HCl and H_2SO_4) cause breakage of glucosidic linkages and alter the physical and chemical properties of native starch. Although most of the studies in the literature on acid hydrolysis of starch is towards understanding the alteration in solubility, gelation, and other properties, however the process modified with lower concentrations of acids (dilute acids) and higher temperatures can be used for the production of fermentable sugars like glucose. Yadav and Majumder (2017) extracted starch from rotten potatoes via steeping and obtained an average of 82.2 g starch from 100 g of potatoes. The starch was subjected to dilute acid pretreatment (DAP) or hydrolysis using (0.1 – 0.2 M) H_2SO_4 and further, incubating the suspension at 60 – 100 °C for 4 h resulted in 40.5 g of glucose from 50 g of starch with conversion yield of 0.81. There have been only few reports making use of acid-based hydrolysis of starchy feedstock for production of biochemicals. Recently, there are few reports where acid hydrolysis of starch rich wastes have been integrated with fermentative production of chemicals (Torabi et al., 2020; Cox et al., 2022; Narisetty et al., 2022b). DAP of starchy feedstocks or BW is cost-effective, scalable, and commercially viable; however, limitations persist in either the upstream process, such as maintaining high temperatures and preventing equipment corrosion, or in the downstream process, such as neutralisation of the hydrolysate for further applications and the release of inhibitors toxic to microorganism growth, such as furfural, HMF, etc (Noureddini and Byun, 2010).

3.2. *Enzymatic saccharification of bread waste*

The processing of starch through enzymatic hydrolysis involves sequential steps gelatinization, liquefaction, and saccharification in the presence of α-amylase and glucoamylases (Yadav and Majumder, 2017).

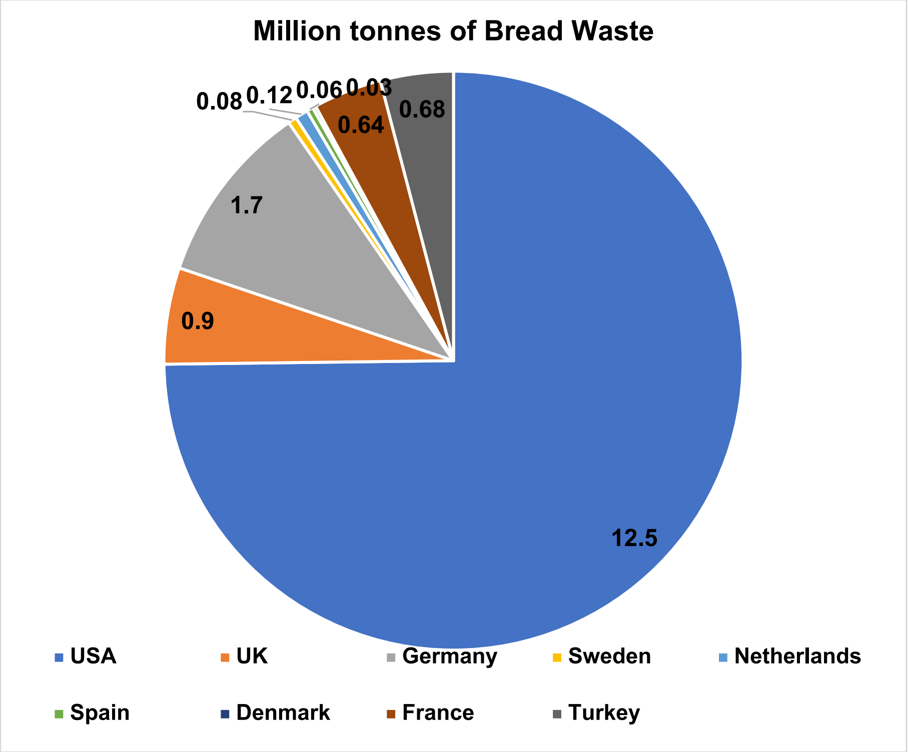

Fig. 1. Statistical representation of bread waste availability in different countries.

Gelatinization involves the heating of starch in the presence of water at higher temperatures (~100 °C) where insoluble or crystalline starch are transformed into amorphous state. The suspension after gelatinization is subjected to liquefaction using α-amylases, where the starch polymers are hydrolysed into smaller dextrins (or Oligosaccharides) (Gupta et al., 2003; Ai and Jane, 2015). Further saccharification using glucoamylase results in conversion of dextrins to glucose monomers (Okafor et al., 2018). Demirci and associates studied the enzymatic hydrolysis of BW at the liquefaction and saccharfication stages with various BW loadings, achieving a maximum glucose conversion yield of 86 %, which is 99 % of the theoretical maximum at optimal values of 0.05 g/g substrate loading, 0.03 KNU/g -amylase, and 3.6 AGU/g glucoamylase (Sükrü Demirci et al., 2017). With the increased applications of starchy feedstocks in food, chemical, and pharma industries, various amylolytic cocktail enzymes are made commercially available that could reduce the complications and unit procedures in saccharification. In a recent study bread flour was hydrolysed to fermentable sugars using an alternative method to traditional sequential liquefaction and saccharification. A simulatenous liquefaction and saccharifcation was carried out under optimal pH (4.51) and temperature (64.7 °C) resulting in 146.8 g/L glucose with 25 % solid loading. Whereas with the classical sequential liquefaction and saccharification the maximum glucose concentrations of 126.9 g/L was obtained with 25 % solid loading (Sigüenza-Andrés et al., 2022). Furthermore enzymatic hydrolysis can be carried out under lower temperatures in comparison to acid hydrolysis and does not involve any harsh chemicals and release of toxic molecules like acid hydrolysis. Although commercialization of the enzymatic process is feasible, the enzymes involved are not cost-effective, however, this limitation can be addressed by developing in-house enzymes resulting in cutting-down the process costs.

4. Biorefinery approach for valorization of bread waste

Current food waste management options including landfill, incineration and anaerobic digestion (AD) could trigger diverse environmental and economic burdens (Jung et al. 2022). However, in recent years, global nations have committed to reversing the environmental impacts of such waste disposal processes through the transition towards Net-Zero industrial manufacturing. For example, the EU aims to be climate neutral and achieve the goal of zero carbon emissions by 2050. For this reason, the majority of food/bread waste is disposed by anaerobic digestion (AD); this process of course eliminates food waste, but has several disadvantages. During AD substantial amounts of carbon are lost by microbial metabolic activities such as respiration, cell growth etc, and through the production of CO_2 (Ward et al. 2008; Jung et al. 2022). AD also produce methane as a major end-product which is a low value product. Furthermore, recent studies have indicated that, for certain conditions (e.g. feedstock sourcing, greography and techonology), AD presents lower environmental savings when compared to other microbial valorisation pathways such as the production of animal feed, beer and ethanol (Brancoli et al. 2020). Therefore, it is important and imperative to design an environmentally benign disposal technology platform, whilst maximizing economic viability through the valorisation of BW into high value products.

5. Spectrum of products from bread waste (BW)

As explained above, BW is a rich source of high-quality fermentable food grade sugars in addition to other nutrients making food/bread waste as an attractive substrate for biorefineries. The sugars from BW are clean as they are devoid of inhibitors. Furthermore, the recovery of sugars from BW is facile and convenient unlike other crude renewable sources that require harsh pretreatment processes such as LCB (Narisetty et al. 2022a). The varying feedstock characteristics of biowaste streams such as MSW, sewage sludge, can also be a challenge for biorefinery application. But homogenous and consistent composition of BW provide advantage over other feedstocks. The use of BW as feedstock for biorefineries will therefore have multiple advantages, including financial and economonic benefits to industries generating BW. The low cost of BW will also deliver financial benefits to biorefinery plants through the decreased costs associated with the use of a waste resource as a microbial feedstock. Together, these financial incentives across this section of the chemical value-chain makes chemical production via this route through biorefineries an attractive industrial venture. For biological production of chemicals and fuels, microbes often used as biocatalyst are ethically sound and offers an environmentally attractive approach that can be performed safely, under aqueous conditions and at mild temperatures and pH in closed bioreactors. The following section outlines examples of industrially important products manufactured through fermentation routes using BW as a feedstock.

Considering DAP and enzymatic hydrolysis of BW, the recovery of sugars from BW is easy and convenient unlike other crude renewable sources requiring harsh pretreatments such as LCB. The use of BW as feedstock for biorefineries will have multiple advantages. The use of low-cost BW will help to ensure competitively priced products. Further, it will generate additional revenue for industries generating them such as bakeries, sandwich manufacturers and enhance their economic viability. Moreover, they don't need to pay waste disposal. The work will lead to manufacturing of green and environmentally friendly products at low cost as price of feedstock is one of the main cost contributors to the bioprocess. So, if we make a low-cost product, it can easily compete with chemical method which is the dominant route for production of chemicals and eventually replace it. For biological production of chemicals and fuels, microbes often used as biocatalyst are either generally regarded as safe (GRAS) or found in fermented foods that prove its safety, and culture purity can be maintained by cultivation in a closed tank bioreactors. Below the examples of some commercially important chemicals manufactured through fermentative route using BW as substrate are discussed (Fig. 2).

5.1. *Succinic acid (SA)*

SA, a C4 dicarboxylic acid, is an important platform chemical with multiple applications, resulting in a global market value of USD 175.7 million in 2017 that is forcasted to reach USD 900 million by 2026 (Li et al., 2021). Currently, significant fraction of the SA in the global market is made available through bio-based processes and international companies like BioAmber, Reverdia, Myriant and Succinity are current stakeholders. Despite the potential, the commercial biobased SA production has been declining in recent years due to the increased cost (USD 2.94/kg) compared to combined fossil and biobased route (USD 2.50/kg), further process development involving BW as an alternative feedstock could improve the biobased process economics (Pateraki et al. 2016; Stylianou et al. 2020; Prabhu et al. 2020). Currently, there are few reports in the literature that utilise BW for fermentative SA production, which need to be tested in pilot scales to understand its technical feasibility and commercial viability. Biochemically, SA is an intermediate of TCA (tricarboxylic acid) cycle and microorganisms produce SA via both oxidative and reductive pathways (Narisetty et al., 2022c; Oreoluwa Jokodola et al., 2022). Leung et al. (2012) extracted sugars and amino acids from BW using glucoamylase and protease from fungal strains, *Aspergillus awamori* and *Aspergillus oryzae*, respectively. The two fungi for this purpose were cultured via solid state fermentation and the resultant hydrolysate was used for SA accumulation by *Actinobacillus succinogenes*. In *A. succinogenes*, SA is synthesized from the reductive branch of the TCA cycle. The bacterial fermentation on BW hydrolysate in batch mode resulted in SA titers, yields and productivities of 47.3 g/L, 1.16 g/g glucose and 1.12 g/L. h, respectively. A SA yield of 0.55 g/g BW indicates that 550 g of SA can be obtained from 1 kg of BW feedstock. Table 1 compares SA production from BW with pure glucose and other waste streams by *A. succinogenes*. The comparison shows that the results achieved with BW is improved compared to many 2G or 3G feedstocks.

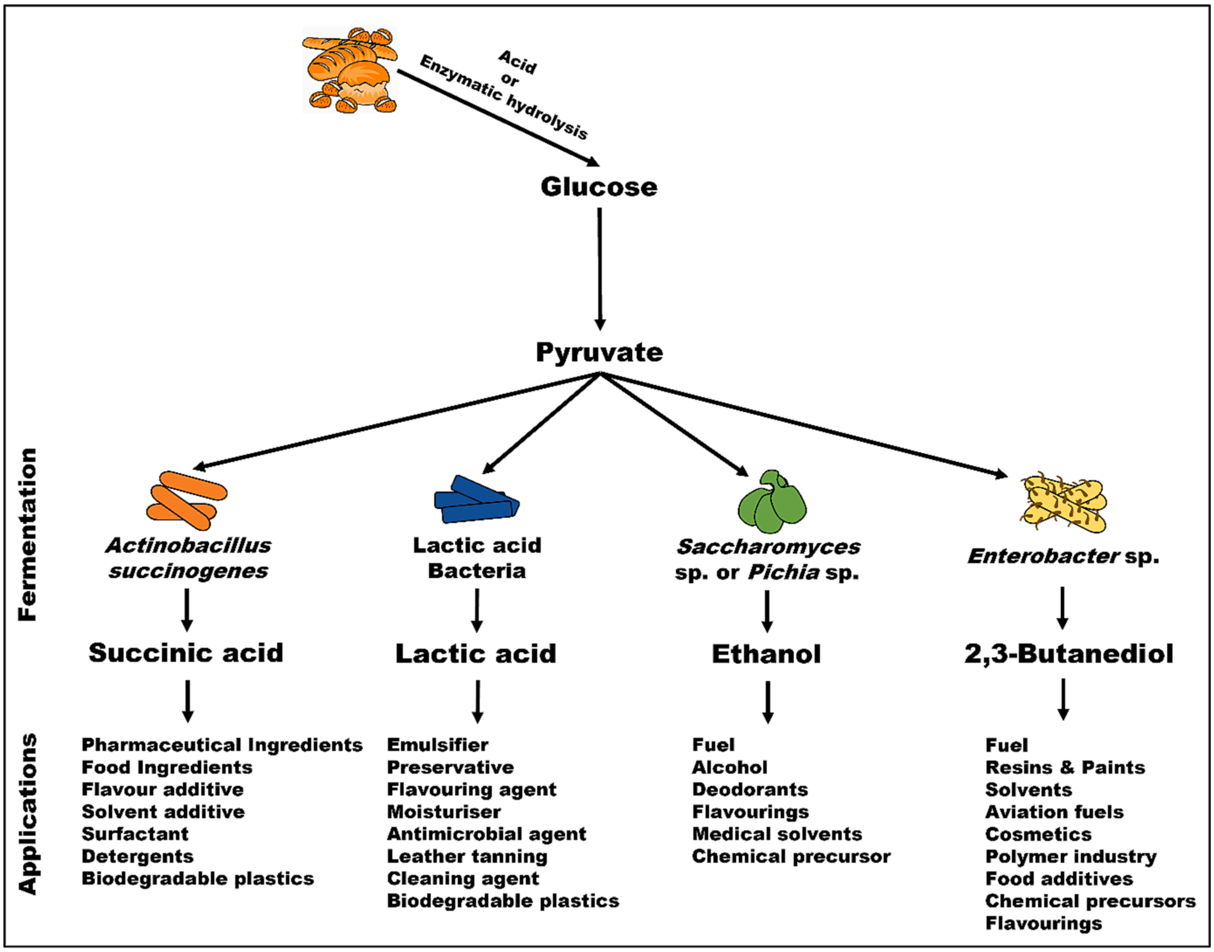

Fig. 2. The biochemicals obtained from bread waste and their industrial applications.

In comparison to other bakery wastes such as cake and pastry wastes, TYP (titer, yield and productivity) metrics are significantly higher which clearly indicates the potential of BW as feedstock for microbial bio-production. Surprisingly, despite so many positive features, there was no further work carried out in thie field by others on SA production using BW.

5.2. *Lactic acid (LA)*

Like SA, LA is a platform chemical and has been listed in the platform chemicals of 2009 among other chemical building blocks (Bozell and Petersen, 2010). LA is a C3 bifunctional molecule and being a platform chemical, LA has wide applications in food, pharmaceutical, cosmetics,

Table 1
Summary of SA production from BW and other 2G feedstock by *A. succinogenes.*

Feedstock	Feedstock treatment	Mode of Cultivation	SA Titer (g/L)	Yield (g/g feedstock)	Productivity (g/L.h)	Reference
BW	Enzymatic hydrolysis (55 °C, 300 rpm)	Batch	47.3	0.55	1.12	Leung et al., 2012
Cake waste	Enzymatic hydrolysis (55 °C, 300 rpm)	Batch	24.8	0.28	0.79	Zhang et al., 2013
Pastry waste	Enzymatic hydrolysis (55 °C, 300 rpm)	Batch	31.7	0.35	0.87	Zhang et al., 2013
Cassava roots	Liquefaction (90 ^{0}C, 2 h) and Saccharification (60 °C, 12 h)	Fed-Batch	151.4	1.51*	3.22	Thuy et al., 2017
Cane molasses	Anionic polyacrylamide (50 °C, 30 mins)	Fed-Batch	83.7	0.93	1.74	Wang et al., 2018
Corn stover	Dilute acid pretreatment (160 °C, 10 mins)	Batch	42.8	0.74*	0.40	Salvachúa et al., 2016
Fruit and vegetable waste	Enzymatic hydrolysis (55 °C, 500 rpm)	Batch	27.0	1.18*	1.28	Dessie et al., 2018
Duckweed	Liquefaction (85-90 °C, 1 h) and Saccharification (60 °C, 8 h)	Batch	75.5	0.42	1.35	Shen et al., 2018
Microalgae	Dilute acid pretreatment (155 °C, 15 mins)	Batch	30.5	0.12	1.10	Knoshaug et al., 2018

[*] Yield calculated based on total sugars.

food, speciality chemicals, textiles and leather. In 2016, the global LA market reached 1,220 kilotons, with a CAGR of 16.2 % (Cox et al. 2022). One important application of LA is in synthesis of polylactic acid (PLA), a biodegradable polymer and potential alternative to synthetic plastics derived from petrochemical routes, and presenting a viable solution to the global plastic crisis. Due to rising demand of PLA, it is anticipated that LA production would reach 1,960 kilotons by 2025, with a global market of USD 9.8 billion (Abedi and Hashemi 2020). Currently, a major fraction of LA is produced from fermentative routes that utilise edible 1G feedstocks. The widespread application of LA including PLA manufacture can also be achieved with a low-cost LA fermentation feedstock such as BW. There are few reports in the literature where bread or bakery waste has been employed for fermentative LA production. Alexandri et al. (2020) used the crust of bread waste (CBW) and lucerne green juice (LGJ) as carbon and nitrogen sources, respectively, for L (+)-LA production by *Bacillus coagulans*. The hydrolysis of CBW and LJG for this purpose was carried out using commercially sourced Novozyme lipase enzymes. The batch fermentation using CBW and LJG hydrolysate resulted in a LA accumulation of 62.2 g/L with conversion yield and productivity of 0.57 g/g CBW and 2.59 g/L. h, respectively. The continuous fermentation at a dilution rate of 0.2 h^{-1} equipped with a cell recycling system resulted in a LA titer of 55.0 g/L with productivity of 11.3 g/L. h and conversion yield of 0.35 g LA/g CBW. The recycling of cells resulted in linear increases in biomass concentration throughout the fermentation, reaching a DCW value of 42 g/L. In a more recent study by Olszewska-Widdrat et al. (2020), LA was manufactured from sugar bread (SB) by *B. coagulans*. The SB hydrolysate obtained after liquefaction and saccharification contained glucose (76.9 g/L), fructose (9.98 g/L) and disaccharides (38.5 g/L). The batch fermentation of SB hydrolysate by *B. coagulans* yielded 80.0 g/L LA titers after 30 h. The resulting yield and productivity were 0.85 g/g sugar and 2.67 g/L. h, respectively. Being a moderate thermophile, *B. coagulans* is grown at 50–55 ^{0}C which can allow the bioprocess to operate under non-sterile conditions and at reduced operational cost. In a recent report, Cox et al. (2022) made use of BW from a supermarket for LA production by *B. coagulans*. Unlike other reports, the sugars present in BW were released by acid catalyzed as well as enzymatic hydrolysis methods and subsequent LA fermentation was achieved simmialrly under non-sterile conditions. The batch fermentation using acid and enzymatic hydrolysate generated 102.4 and 129.4 g/L LA with a yield of 0.75 and 0.83 g/g glucose, respectively. The fed-batch fermentation using sugar-rich enzymatic hydrolysis feeds produced large LA titres of up to 155.4 g/L with a productivity of 1.30 g/L. h and a LA yield of 0.85 and 0.42 g/g on glucose and BW, respectively. The concentration of yeast extract used (2.0 g/L) in all the fermentation work was also far lower than is currently used in typical fermentation procedures. The waste residues generated during BW hydrolysis and LA fermentation were combined and subjected to AD to enhance the overall economical viability of the bioprocess but also to contribute to the development of a net-zero biorefinery process. Table 2 compares LA production from a variety of crude renewable carbohydrate sources by *B. coagulans*. The results achieved on BW clearly outcompetes analogous feedstocks in terms of LA titers, yields and productivity and creates a strong incentive to develop this approach further.

5.3. *Ethanol*

Ethanol or bioethanol represent replacements to fossil technologies that currently manufacture ethanol for use in the transportation industry, wherein 84 % of ethanol is consumed. Here, bioethanol is mixed with gasoline in different ratios, where mixtures of 5 and 10 % by volume can be used without any engine modifications. In addition to use as a biofuel, ethanol is also used in the chemical synthesis of ethylene, which has a market demand of 140 million tons per year (Uçkun and Liu, 2015; Sydney et al. 2019). As such, the global market for ethanol has increased over the past two decades, reaching 100.2 billion litres in 2016 with a continued predicted increase to 134.5 billion litres by 2024 (Bušić et al. 2018). At the commercial scale, ethanol is produced from yeast (*Saccharomyces cerevisiae*) fermentations using edible feedstocks such as corn or sugarcane juice. Alternative feedstocks derived from LCB are currently under investigation as alternative replacements for bioethanol production by fermentation but this has yet to be applied at the commercial scale. To meet the exponentially increasing global demand for ethanol, more feedstocks are therefore required, and one good example could be bread & bakery waste from the food and drink sector to create a circular bioprocess.

To the end, the literature contains a number of examples where BW has been successfully valorised into bioethanol, including studies by Ebrahimi et al. (2008) using bread residues for ethanol accumulation via saccharification of BW using amylolytic enzymes. The enzymatic bread

Table 2
LA production from various crude renewable sources by *B. coagulans.*

Feedstock	Feedstock treatment	Mode of Cultivation	SA Titer (g/L)	Yield (g/g feedstock)	Productivity (g/L. h)	Reference
Kitchen waste	Enzymatic hydrolysis (55 °C, 60 rpm)	Open, non-sterile Batch	86.0	0.53	0.72	Sakai and Ezaki, 2006
Mixed food waste*	Enzymatic hydrolysis (55 °C, 400 rpm)	Batch	94.0	0.27	2.61	Kwan et al., 2016
Bakery waste*	Enzymatic hydrolysis (55 °C, 400 rpm)	Batch	82.6	0.23	2.50	Kwan et al., 2016
Corncob residues	Enzymatic hydrolysis (50 °C, 72 h, 200 rpm)	Fed-batch	79.1	0.76	0.94	Jiang et al., 2019
Tapioca starch hydrolysate	Liquefaction (85 °C, 2 h) and Saccharification (60 °C, 20 h)	Continuous cell-recycling	50.3	0.74	10.1	López-Gómez et al., 2019
Molasses	N/A	Continuous cell-recycling	59.6	0.85	5.9	López-Gómez et al., 2019
Defatted rice bran	Liquefaction (85 °C, 2 h, 500 rpm) and Saccharification (50 °C, 21 h)	Batch	75.9	0.38	2.70	Alexandri et al., 2019
Crust BW	Liquefaction (80 °C, 2 h) and Saccharification (52 °C, 22 h)	Batch	62.2	0.57	2.59	Alexandri et al., 2020
Sugar bread	Liquefaction (80 °C, 2 h) and Saccharification (52 °C, 25 h)	Batch	80.0	0.52	2.67	Olszewska-Widdrat et al. 2020
BW	Enzymatic hydrolysis (60 °C, 48 h)	Fed-batch	155.4	0.42	1.30	Cox et al. 2022
BW	Acid hydrolysis (121 °C, 15 mins)	Batch	102.4	0.26	1.42	Cox et al. 2022

* Lactic acid production by *Lactobacillus casei Shirota*.

hydrolysate with initial 250 g/L glucose concentration was inoculated using 20 g/L dry yeast cells (*S. cerevisiae*), 100 % utilization was observed in 10 h with ethanol titers of 100 g/L, with 0.40 g/g yield. Extrapolating the experimental values, an overall yield of 350 g ethanol can be produced from a kg of dry bread. Torabi et al. (2021) used waste wheat bread for ethanol production via fermentation. The BW was hydrolysed using amylolytic enzymes and dilute hydrochloric acid prior to innoculation. The authors employed statistical design for optimization of dilute acid and enzymatic (alpha amylase + glucoamylase) hydrolysis conditions to maximise the release of glucose. The overall resulting glucose yield obtained with enzymatic hydrolysis (93 %) was higher than dilute acid hydrolysis (69.8 %). The subsequent ethanol fermentation by *S. cerevisiae* using acidic and enzymatic hydrolysate resulted in 248 and 313 g ethanol per kilogram dry bread residues with a theoretical maximum yield of 86.9 % and 83.0 %. More recently, Narisetty et al. (2022b) performed a detailed study on BW hydrolysis and subsequent ethanol fermentation. The BW was saccharified via acidic and enzymatic hydrolysis and both routes were optimized in terms of solid and acid/enzyme loading to maximise productivity. The acidic and enzymatic hydrolysis of BW yielded maximum glucose release of 75.0 and 97.9 g/L at solid loading of 20 % w/v which is 73.5 and 95.9 % of the maximum theoretical yield, respectively, and the obtained hydrolysate was fermented into ethanol. The fed-batch fermentation using glucose-rich acidic and enzymatic hydrolysates resulted in ethanol titers of 106.9, and 114.9 g/L with a conversion yield and productivity of 0.47, and 0.49 g/g, and 3.0, and 3.2 g/L.h, respectively. The AD of residues from acidic/enzymatic hydrolysis of BW and spent microbial biomass yielded a biochemical methanation potential (BMP) of 345 and 379 mL CH_4/g VS respectively. Both the above reports confirm that acid hydrolysis is an effective method for the extraction of fermentable sugars from BW samples and being much cheaper in comparison to enzymatic methods could contribute to the design of a low cost process. The ethanol production from various biogenic residues including 1G/2G feedstocks and pure glucose has been summarised in Table 3. The BW-based ethanol production is very promising in terms of TYP metrics and compares favourably with pure glucose feeds, indicating that BW can be a viable feedstock for future ethanol bioprocesses. For example, the amount of BW generated in UK is sufficient enough to fulfil 15–20 % of annual national demand for bioethanol (Narisetty et al. 2021). This is similarly true in other countries and demonstrates how BW can be simultaneously remediated and upcycled into valuable industrial products using microbial biotechnology.

5.4. 2,3-Butanediol (BDO)

BDO is a C4 metabolite containing hydroxyl groups attached to second and third carbon atom, with applciations as a platform chemical in the cosmetics and pharmaceutical industries. The high heat value of BDO (27.2 kJ/g) is comparable to other biofuels such as *n*-butanol (33.1 kJ/g), methanol (22.1 kJ/g), ethanol (29.1 kJ/g) which makes it applicable as a drop-in fuel/fuel additive for aviation transportation. The presence of two hydroxyl groups in BDO enable its conversion into value-added derivatives, examples of which include the dehydration products methyl ethyl ketone and 1,3-butadiene. The former is an industrial solvent, and the latter is a precursor for synthetic rubber. Bio-based routes to methyl ethyl ketone and 1,3-butadiene from BDO via fermentation are imperative to enable transition away from current fossil-based manufacturing routes. There is also an economic incentive, as the total global production and resulting market value of BDO and its derivatives is ~ 32 million tons per year and USD 43 billion, respectively (Amraoui et al., 2022; Maina et al., 2021a; Narisetty et al., 2022d).

Fermenation routes to BDO from BW are less developed and there is only one two reports on BW-based production of BDO. Maina et al. (2021b) employed bakery waste (containing sweet bread, whole wheat bread, rye bread, pretzel and croissant) and BW (containing whole wheat, whole gran rye and five grain consisting of wheat, rye, barley, oats and maize breads) for fermentative production of acetoin/BDO by *Bacillus amyloliquefaciens*. The carbohydrates content in bakery and bread was depolymerized via enzymatic route using alpha-amylase and glucoamylase. The batch and fed-batch fermentation were performed in bioreactors at different volumetric mass transfer coefficients (k_La) to investigate the impact of aeration on portioning of carbon flux into acetoin and BDO biosynthesis. BDO was the main fermentation product at lower k_La (64 h^{-1}) while acetoin was obtained as major product at a higher k_La (200 h^{-1}). The bacterial culture resulted in a mixture of acetoin (~35 %) and BDO (~65 %) with a total production titre of 103.9 g/L during fed-batch cultivation at a k_La of 110 h^{-1} and a yield of 0.39 g/g and productivity of 0.87 g/L. h. In very recent work, Narisetty et al.

Table 3
Bioproduction of ethanol from different feedstocks by *S. cerevisiae.*

Feedstock	Feedstock treatment	Mode of Cultivation	Ethanol Titer (g/L)	Yield (g/g feedstock)	Productivity (g/L. h)	Reference
Bread residues	Liquefaction (85 °C, 3 h) and Saccharification (60 °C, 72 h)	Batch	100.0	0.35	10.0	Ebrahimi et al. 2008
Cassava starch	Liquefaction (95 °C, 3 h) and Saccharification (32 °C, 66 h)	SSF	89.1	0.48*	2.10	Choi et al., 2010
Corn stover	Steeping (10 % ammonia, 24 h) Dilute acid pretreatment (108 °C, 6 h)	Batch	31.1	0.41*	0.43	Zhao and Xia, 2010
Wood cellulose	Dilute acid pretreatment (120 °C, 1 h) and Enzymatic hydrolysis (50 °C, 28 h)	Batch	18.5	0.49*	1.16	Gupta et al., 2009
Wheat-rye bread	Liquefaction (85 °C, 1 h) and Saccharification (35 °C, 96 h)	SSF	128.0	0.42	2.70	Pietrzak and Kawa-Rygielska, 2015
Potato waste	Fungal and yeast co-cultivation (35 °C, 72 h)	SSF	37.9	0.41*	0.53	Izmirlioglu and Demirci, 2017
Waste cake	Enzymatic hydrolysis (95 °C, 80 mins, 200 rpm)	Batch	46.6	1.12	1.17	Han et al., 2019
Waste wheat bread	Dilute acid pretreatment (121 °C, 20 mins)	Batch	35.2	0.25	0.36	Torabi et al., 2020
Waste wheat bread	Liquefaction (50 °C, 1 h, 600 rpm) and Saccharification (60 °C, 56 h, 600 rpm)	Batch	42.3	0.31	0.44	Torabi et al., 2020
BW	Dilute acid pretreatment (121 °C, 15 mins)	Fed-batch	106.9	0.18	2.97	Narisetty et al. 2022b
BW	Enzymatic hydrolysis (60 °C, 48 h)	Fed-batch	114.9	0.24	3.19	Narisetty et al. 2022b
Pure glucose	N/A	Fed-batch	111.3	0.48*	3.10	Narisetty et al. 2022b

[*] Yield calculated based on total sugars; **SSF: Simultaneous Saccharification and Fermentation.

(2022d) investigated the biosynthesis of BDO from BW by *Enterobacter ludwigii*. Analogous to their previous work, BW was hydrolysed using acid and enzymatic routes to obtain glucose rich solution with a yield of 330–530 g/kg BW for BDO fermentation. BDO titres of 135.4, and 138.8 g/L were amassed after 96 h fed-batch fermentations using a glucose rich solution obtained from acid and enzymatic hydrolysis with conversion yield of 0.42 and 0.48 g/g yield, respectively. The results were comparable to TYP (144.5 g/L, 0.47 g/g, 1.51 g/L. h) metrics achieved using a pure glucose feed. Again, these results prove BW as highly promising substrate for generating a variety of high value products and can be a viable future feedstock for sustainable biorefineries. The BDO production from various feedstocks and pure glucose has been summarised in Table 4.

5.5. Other products

Recently, two more reports have been published on the biovalorisation of BW. Sigüenza-Andrés and associates (2022) hydrolysed BW to obtain high glucose slurry via liquefaction and saccharification steps using α-amylase and glucoamylase, respectively. These methods were compared with traditional sequential hydrolysis protocols. The simultaneous enzymatic hydrolysis resulted in a glucose concentration of 112.1 g/L in 2 h compared to 126.9 g/L achieved in 4 h using the traditional two-step method. When the simultaneous process was prolonged for 4 h, 146.8 g/L glucose was accumulated (Sigüenza-Andrés et al., 2022). This simultaneous approach could result in a reduction of time, labour, energy and equipment costs for BW pre-processing and thus, the overall cost for glucose extraction from BW for fermentation. Jung et al. (2022) also developed a zero-waste strategy for the valorisation of BW sugars. Here, the BW was enzymatically depolymerized to obtain glucose and used as the carbon substrate in heterotrophic cultivation of *Euglena gracilis*, which is known to accumulate paramyon (conglomerate of β-1,3-glucan) for use in the medical and cosmetics sectors. The biomass and paramylon productivity achieved after 3 d in this system were 3.04 and 1.93 g/L. d, respectively. Further, the residues derived from enzymatic hydrolysis of BW were subjected to pyrolysis to obtain syngas. The process of pyrolysis is performed under an inert atmosphere using CO_2 for a greener pyrolysis platform, leading to the oxidation of volatile organic matter from BW residues and enhanced CO formation. The pyrolysis in the presence of 5 wt% Ni/SiO_2 catalyst improved the molar concentrations of H_2 and CO pyrolysis products in the presence of CO_2 by 2- and 6-fold, respectively, when compared to pyrolysis conducted in the absence of catalyst under N_2. This work indicates that CO_2, a greenhouse gas, can be used to improve the efficiency of such bio-processes to create syngas from BW residues for use in the chemical industry.

6. Logistics and supply chain challenges with bread waste as feedstock for valorisation pathways

One of the most relevant challenges in the valorisation of BW is the segregated collection of the feedstock itself, since the majority of fermentation technologies require that the substrate should not be contaminated with other materials. Although households are the part of the supply chain with the highest BW generation levels (Brancoli et al., 2019), segregated collection is most likely not feasible, due to the high complexity and cost of adding an extra waste fraction in the domestic collection scheme. Bakeries are convenient places for sourcing surplus bread, due to the homogeneous flow of material in the form of flour, dough or defective products. Further, bakeries collect a relative large amount of material at very few physical locations (Brancoli et al., 2017). Nevertheless, the amounts of surplus bread generated at this early stage in the supply chain are limited. Brancoli et al. (2019) calculated that bakeries are responsible for 15 % of the total bread surplus in the Swedish supply chain, which is equivalent to 5 % of the total national bread production and similar to the results found in Beretta et al. (2013) when investigating the Swiss supply chain. Therefore, it might be necessary to source surplus bread from other parts of the supply chain when considering an overally viable industrial bioprocess (Fig. 3). Retailers are also relevant candidates for the supply of surplus bread for biorefineries, due to the generation of large amounts of BW in, again, relatively few physical localities. For instance, in Sweden, retailers are responsible for 35 % of the total surplus bread generated in the supply chain, the equivalent of 28,200 tons per year or 2.9 kg per capita per year (Brancoli et al., 2019). Nevertheless, contrary to bakeries, sourcing bread waste from retailers has a higher risk of contamination from other products sold on site. Nevertheless, there are some characteristics of the distribution of bread to retailers that are advantageous for a segregated bread collection.

Bakeries have very short lead times, meaning that the time between the placement of an order and the delivery is limited due to consumers' requirement for fresh products (Ismatov, 2015, Stenmarck et al., 2011). Therefore, it is relatively common that bread suppliers deliver directly to the supermarkets. In that way, bakeries are able to deliver the products as quick as possible. This configuration opens the possibility for bakeries to operate a reverse supply chain, wherein they also collect the unsold

Table 4
BDO accumulation from various crude renewable sources by *E. ludwigii*.

Feedstock	Feedstock treatment	Mode of Cultivation	Ethanol Titer (g/L)	Yield (g/g feedstock)	Productivity (g/L. h)	Reference
Fruit extract	Dilute acid Pretreatment (121 °C, 30 mins)	Fed-batch	50.0	0.40*	0.41	Liakou et al. 2018
VHP cane sugar**	N/A	Fed-batch with synthetic medium	108.8	0.38*	1.15	Maina et al. 2019
Sugarcane molasses	N/A	Fed-batch	50.6	0.31*	2.66	Psaki et al. 2019
Xylose rich hydrolysate from sugarcane bagasse	Hydrothermal pretreatment	Fed-batch	63.5	0.36*	0.84	Amraoui et al., 2021
Glucose rich hydrolysate from brewer's spent grain	Microwave assisted alkali pretreatment (400 W, 60 *sec*) and Enzymatic hydrolysis (50 °C, 96 h, 150 rpm)	Fed-batch	118.5	0.43*	1.65	Amraoui et al. 2022
BW	Liquefaction (80 °C, 2 h) and Saccharification (52 °C, 22 h)	Fed-batch	103.9[a]	0.39*	0.87	Maina et al. 2021a
BW	Dilute acid Pretreatment (121 °C, 15 mins)	Fed-batch	135.4	0.15	1.41	Narisetty et al. 2022d
BW	Enzymatic hydrolysis (45 °C, 48 h)	Fed-batch	138.8	0.19	1.45	Narisetty et al. 2022d
Pure glucose	N/A	Fed-batch	144.5	0.47*	1.51	Narisetty et al. 2022d

[*] Yield calculated based on total sugars; **VHP: Very High Purity; [a]Combined production of acetoin and BDO by *Bacillus amyloliquefaciens*.

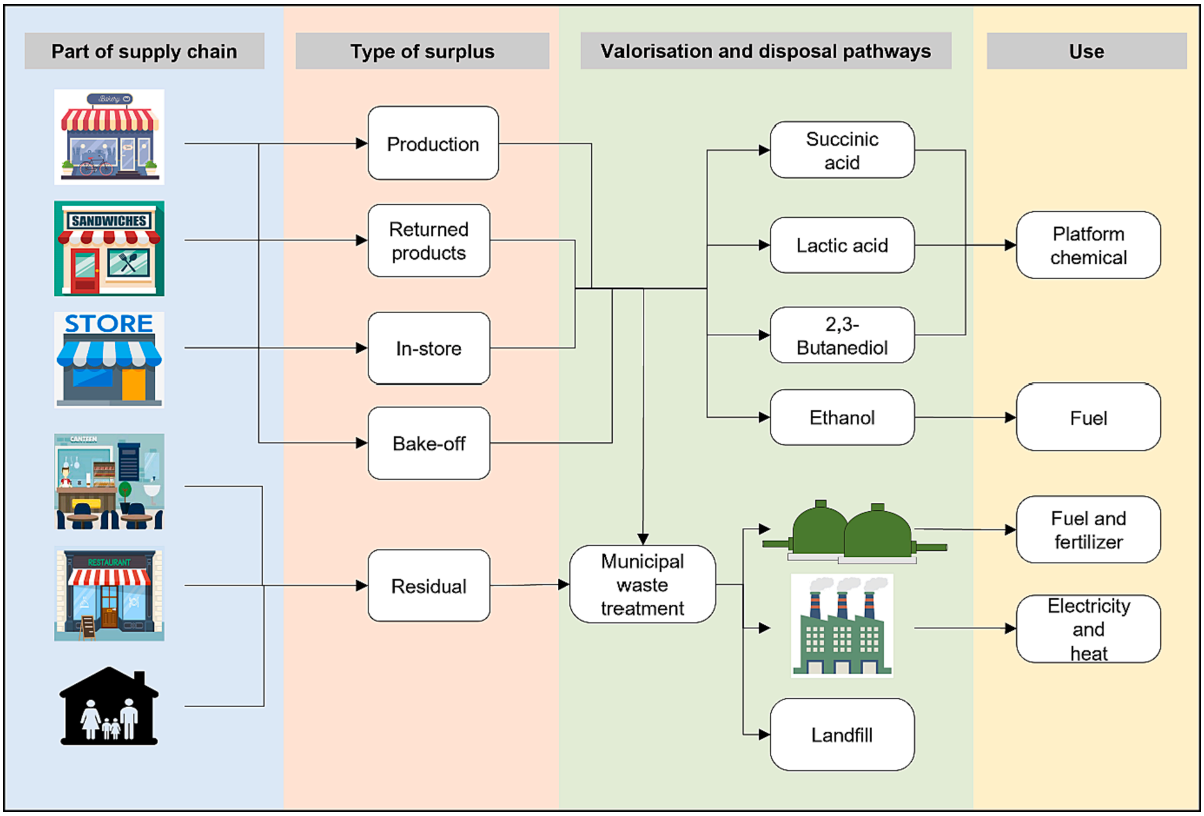

Fig. 3. Illustration defining the bread waste (BW) generation in different parts of supply chain, and valorisation strategies to high value products along with their applications.

bread from retailers and enabling the segregation of BW products. Substantiating this fact, it is also common in some European countries that bread is sold under a take-back agreement clause (TBA). In this case, the manufacturer or the supplier is monetarily accountable for unsold goods and the collection and treatment of restored goods. The occurrence of returned bread has been documented recently in countries such as Germany (Brosowski et al., 2016), Norway (Stensgård and Hanssen, 2016), Austria (Lebersorger and Schneider, 2014), the Netherlands (Weegels, 2010), and Italy (Matteo, 2011). A mechanism or a technique need to be implemented in collection of surplus bread alone, which brings an oppurtunit to implement cradle-to-cradle rather than cradle-to-grave measures by valorizing BW through biological routes, which is not possible if its collected along with the mixed food waste fractions. The reverse supply chain operated by bakeries might also be used to collect not only their own products but also the bread that is baked within supermarkets' in-store bakeries, increasing the material to be valorised downstream. However, greater collaboration between retailers and bakeries is required to allow such fractions to be transported collectively in a unified manner. Conversely, it is relevant to also mention that several publications have established a correlation between TBA and high BW generation, indicating the presence of environmental trade-offs between the benefits of segregated collection and the increase in waste generation (Brancoli et al., 2019; Eriksson et al., 2017; Ghosh and Eriksson, 2019).

The collection and transportation of segregated bread waste also impacts the sustainability of the valorisation pathways, particularly when compared with traditional waste management practices. The different valorisation or waste management processes require different infrastructures, e.g., facilities for manufacturing chemicals, AD, and incineration. The availability differs in different geographical locations. The infrastructures for waste management alternatives, e.g. AD and incineration, are likely to be present in a higher number of regions in a country, while the number of plants that valorise bread waste into chemicals or fuels is lower and located in specific regions. For instance, in Sweden there are>280 biogas plants (Klackenberg, 2021), in constrast to a single ethanol plant. For this reason, the transportation distances for traditional waste management alternatives are expected to be lower than those for biorefineries for chemical production. Brancoli et al., (2020) found that the environmental benefits of valorising BW in higher stages of the waste hierarchy, e.g. into chemicals, to the detriment of standard waste management practices, are constrained by the transportation distance.

7. Sustainability assessment of bread waste valorization

Using BW as a feedstock to create high-value products is a potential way to achieve a circular economy. Nevertheless, such technologies must be assessed in relation to the three dimensions of sustainability, namely social, economic, and environmental. These aspects are assessed using different methodologies. The environmental impacts are often calculated using life cycle assessment. The economic analysis, which includes the costs of procuring, operating, and disposing a technology is performed using life cycle costing. Finally, social aspects, including indicators such as human rights and working conditions, are evaluated using social life cycle assessment (Lin et al., 2020; Aghbashlo et al., 2022). There are limited studies on the economic performance of bread waste valorisation technologies. Lam et al. (2014) performed a techno economic analysis of succinic acid production and for this a production facility for the treatment of 1 ton BW generated every day in Hong Kong was considered. The total annual revenue estimated from the sale of high purity SA (25,388 kg), solid waste biomass (270,108 kg) from process and BW waste treatment was USD 374,041 with a total production cost of USD 230,750 per year. The annual profit of USD 143,559 resulted in a return on investment and IRR (internal rate of return) of 12.8 % and 15.3 % respectively, for a payback period of 7.2 years.

The majority of the studies focus on the environmental aspects of bread waste valorisation. In EU Waste Framework Directive (European Commission, 2008), a hierarchy was defined for food waste that aims to reduce the environmental impacts caused by the production and disposal of waste. It defines the food waste as the potential feedstock for the manufacturing of high value added chemicals and fuels, and ranks it as the preferred option after its prevention and use as animal feed. The European Commission considers the transition to a bio-based economy as a promising avenue for generating industrial revenues, decreasing environmental impacts and promoting job creation (European Commission, 2015). To this end, the use of waste as feedstock has the potential to avoid the extraction of raw materials and displace existing waste disposal pathways of higher environmental impact. Although the waste hierarchy is an appropriate guideline for food waste valorisation and management, there are situations where the environmental performance of a technology might deviate from it (Manfredi et al., 2011). This may happen because of different reasons, such as waste composition, sorting efficiency, waste collection system, energy matrix and the technology used in the system. Deviations from waste hierarchies are permitted as long as they are scientifically supported, which often comes from the use of Life cycle assessment (LCA) methodology.

The literature on the assessment of environmental impacts of valorisation pathways for BW is limited. This could be explained by two main reasons. First, by the fact that such valorisation technologies might not be feasible in regions where the segregated collection of BW is not implemented, e.g. countries without takeback agreements. Secondly, the lack of data on the amounts of BW may well regarded it an extraneous waste flow and precise actions were not considered (Brancoli et al., 2020). Early studies on BW end-of-life focused on the lower stages of the waste hierarchy. Eriksson et al. (2015) compared six waste management options (landfill, incineration, composting, AD, animal feed and donations) for different food fractions and concluded that BW has the highest potential for greenhouse gas emission reduction. Vandermeersch et al. (2014) compared the diversion of BW from AD to animal feed production and concluded that a reduction of 30 % of the environmental impacts could be achieved. Almeida et al. (2018) compared the production of standard craft beer with a process using bread surplus and found that the latter could reduce the environmental impacts by 20 % comparatively, due to the lower requirement for barley and the use of the spent grain as animal feed.

Literature on LCA of valorisation of bread into chemicals and fuels is limited to a few publications. Overall, the technologies that valorise BW into chemicals and fuels are novel and have a low technology readiness level (TRL). Brancoli et al. (2020) assessed different management and valorisation pathways for BW, including the production of ethanol. The results indicated that prevention was the pathway with the highest environmental savings, but the valorisation into ethanol performed better than common waste management practices such as AD and incineration. A large share of the total environmental impacts of conventional ethanol comes from the crop used as a feedstock. The main benefit of ethanol production using BW is the avoided production of wheat, as bread was modelled as waste and therefore entered the system burden-free. Furthermore, the use of DDGS, a co-product in ethanol production, as animal feed, further contributed to the environmental savings. A policy brief from the EU (Martin and Jorrit, 2015) states that the production of ethanol from waste feedstocks can reduce the competition between energy and food crops.

Gadkari et al. (2021) investigated the production of SA from BW via fermentation in relation to greenhouse gas (GHG) emissions and non-renewable energy use (NREU). The results indicated steam consumption and the usage of other ancillary materials, such as heating oil as hotspots in the system, i.e. processes that contribute significantly to the total environmental impact of the technology. The fermentative production of SA was found to have a lower environmental impact than its fossil counterpart. The GHG emission and NREU for fermentative SA production from BW were significantly lower by 33 % (1.30 vs 1.94 kg CO_2 eq) and 46 % (31.6 vs 59.2 MJ/kg SA), respectively, than the analogous fossil route. It is relevant to note that the study used mass allocation, and due to the high mass of the remaining biomass after fermentation, 90 % of the burdens were allocated to it, considering its use as fish feed. As described above that Narisetty et al. (2022b) accumulated ethanol using BW, they also performed the AD of waste generated during the process to impose a zero-waste strategy and LCA of ethanol production from BW. The system considered the fermentative production of ethanol and AD of the residues coming from ethanol fermentation and the hydrolysis of BW. About 85 % of total ethanol produced globally comes alone from Brazil and USA using sugarcane juice and corn, respectively. The GWP (global warming potential) of BW-based ethanol (1.267 kg CO_2 eq) has been found to be comparable to ethanol production from sugarcane, Brazil (1.06 kg CO_2 eq) and maize grain, USA (1.05 kg CO_2 eq) and emissions are lower than wheat, France (1.5 kg CO_2 eq), switchgrass, Uruguay (2.43 kg CO_2 eq), sweet Potato (1.87 kg CO_2 eq) or wheat Straw (4.2 kg CO_2 eq). Nevertheless, the direct comparison of LCA results must be done with caution, as the results are often sensitive to methodological choices, such as the allocation key used, TRL, and other parameters. For instance, Narisetty et al. (2022b) did not include a co-product analysis of the ethanol production, namely DDGS, nor the methane produced during AD process. The inclusion of such co-products could potentially increase the environmental benefits of the technology. Overall, the electricity consumption, particularly at the fermentation stage, had the largest contribution to the environmental impacts of the technology. Similarly, Lam et al. (2018) investigated different scenarios for the production of hydroxymethylfurfural from BW and identified the energy consumption and the choice of catalyst as hotspots in the system. The majority of the technologies proposing the valorisation of BW, or food waste in general, into chemical and other value-added products are still in the early stages of development and need to be optimized in order to be comparable to or better than the reference products (Albizzati et al., 2021). Furthermore, such low TRLs are correlated with greater ambiguities in relation to their environmental impacts and economic performance and ultimately their industrial uptake.

8. Challenges and future directions

It has been demonstrated in may reports described above that at lab scale production of biochemicals using BW is as good as pure carbon sources. The main challenge arises for the production at a commercial scale to ensure that the TYP metrics obtained at laboratory scale can be maintained at large scale (pilot, commercial). To this end, research is needed to evaluate the influence of hydrolysed BW as opposed to 1G feedstocks on the fermentation characteristics; key parameters include the feedstock physicochemical properties (e.g., viscosity, solid content) and their mixing characteristics within large scale bioreactors (stirred tanks, airlift). Future research should also investigate the cost analysis of BW-based production taking into account all the parameters impacting the price and compare it with commercial production using pure carbon and sources and petrochemical route wherever applicable. In case of waste as feedstock, correct logistics and an efficient supply chain also plays crucial role for the commercial viability of the process. For example, in case of BW, collection from several points such as bakeries, supermarkets, sandwich manufacturing companies, households etc, transport to plant locations before its start degrading or get contaminated and associated cost are important parameters in predicting the process economics. Finally, the separation of the products from the fermentation broth cultured on crude renewable source like BW, a topic that was not covered in this review, is an area that requires extensive investigation, including research on the impact of BW hydrolysate properties on established downstream processes. In relation to assessing the sustainability of different pathways for BW valorisation, there is a lack of studies particularly on the economic and social aspects. The assessment of the beneifts of the different valorisation routes is crucial to support the choice of the most sustainable pathway.

9. Conclusions

The successful transition to circular bioeconomy relies on the efficient use of readily available bioresources. Developing the pathways to transform food/bread waste into chemical building blocks would provide an immediate solution to the increasing volumes of food waste associated with growing global population and create a sustainable, secure and stable source of fuels and chemicals and result in a reduced waste and carbon neutral society while addressing the problem of disposing this food waste. Further, process optimization and intensification will continue to drive cost reductions and process efficiency to match the industrial requirements and catalyze uptake at the commercial scale.

CRediT authorship contribution statement

Vinod Kumar: Conceptualization, Writing – original draft, Writing – review & editing, Project management. **Pedro Brancoli:** Conceptualization, Writing – original draft, Writing – review & editing. **Vivek Narisetty:** Conceptualization, Writing – original draft, Writing – review & editing. **Stephen Wallace:** Conceptualization, Writing – original draft, Writing – review & editing. **Dimitris Charalampopoulos:** Conceptualization, Writing – original draft, Writing – review & editing. **Brajesh Kumar Dubey:** Writing – review & editing. **Gopalakrishnan Kumar:** Writing – review & editing. **Amit Bhatnagar:** Writing – review & editing. **Shashi Kant Bhatia:** Writing – review & editing. **Mohammad J.Taherzadeh:** Writing – review & editing.

Declaration of Competing Interest

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

Data availability

No data was used for the research described in the article.

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