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## Recycling bread waste into chemical building blocks using a circular biorefining approach

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Food waste is a global problem, causing significant environmental harm and resulting in substantial economic losses globally. Bread is the commonly wasted food item in the developed world and presents a severe problem for the majority of European nations. It is the second most wasted food item in the UK after potatoes, with an equivalent of 20 million slices of bread thrown away daily. Bread is a starchy material and a rich and clean source of easily extractable fermentable sugars – this is in direct contrast to lignocellulosic feedstocks where harsh physical, chemical and/or enzymatic pretreatment processes are required for release of fermentable sugars. Furthermore, these necessary lignocellulosic pretreatment methods often produce sugars contaminated with fermentation inhibitors. Therefore, bread waste presents a clear opportunity as a potential carbon source for novel commercial processes and, to this end, several alternative routes have been developed to utilize bread waste. Possibilities for direct recycling of bread waste within the food industry are limited due to the relatively short material lifetime, stringent process and hygiene requirements. Anaerobic digestion (AD) and incineration are commonly employed methods for the valorisation of bread waste, generating limited amounts of green energy but with little other environmental or economic benefits. Most food wastes and by-products in the UK including bakery waste are treated through AD processes that fail to harness the full potential of the these wastes. This short communication reviews the challenges of handling bread waste, with a focus on a specific UK scenario. The review will consider how bread waste is generated across the supply chain, current practices to deal with the waste and logistics challenges in waste collection. The presence of clean and high-quality fermentable sugars, proteins and other nutrients in bread make it an ideal substrate for generating chemicals, fuels, bioplastics, pharmaceuticals and other renewable products through microbial fermentations. We suggest potential applications for recycling bread waste into its chemical building blocks through a fermentative route where a circular biorefining approach could maximize resource recovery and environmental savings and eliminate waste to as close to zero as possible.

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## Bread wastage – a serious global problem

In nature, there are a number of iconic and irresistible fragrances such as scent from gasoline, a new car, a new notebook, the soil after fresh rainfall, and the sweet aroma from a bakery. When we pass a bakery where fresh bread is being

baked, we can sense the sweet aroma filling the air around the bakery. This sensation is lost with wrapped or packed bread, which is widely available in supermarkets. Bread is a universal staple across most income ranges, varying in cost from £0.30 to £20 for a loaf, based on the quality of ingredients and the marketing strategy of the baker. Bread is sold and consumed across the entire social and geographical spectrum. Since bread can be a relatively cheap or an expensive luxury depending on ingredients, the production process and marketing, hence consumption and therefore wastage are likely to be ubiquitous globally. Bread is a commonly wasted food in a majority of countries in the developed world and is a particularly serious problem in most European nations. The global annual production of bread is >100 million tons. According to global bread market split analysis, Europe dominates the market with a share of 53.6%, followed by the US (28.6%), Asia Pacific (10.9%) and Middle East and African countries (6.9%) [World

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transport conditions play an essential role in maintaining the bread in a healthy environment to ensure high quality and a good lifespan. Bread is a staple food produced for human consumption and considered waste if, due to any reasons, it is not consumed or becomes unfit for human consumption.<sup>7</sup> In the UK, a large amount of bread (32%) is wasted at the consumer level, and one of the primary reasons for this is its limited shelf life.<sup>8</sup> People's lack of awareness exacerbates this situation as they purchase more than they need and have insufficient knowledge on storage conditions and the shelf life. This scenario is not unique to the UK, and similar problems are observed in many European countries. Stensgård and Hanssen (2016) and Brancoli *et al.* (2019) identified bread as a significant waste generated in Norway and Sweden.<sup>7,9</sup> Bread waste generated at any stage of the supply chain causes enormous loss of potential nutrients and significantly impacts the carbon footprint of the process. Furthermore, such wastage has a knock-on effect in terms of wastage of energy resources invested in wheat production, post-harvesting, manufacturing of bread, transport, and storage. For example, one-fifth of greenhouse gas (GHG) emissions in the UK associated with food and drinks are generated during their production and distribution, so any wastage in these industries has clear negative environmental and societal impacts (Our waste, our resources: a strategy for England (<http://publishing.service.gov.uk>)). A service scheme take-back agreement (TBA), implemented in most European countries, makes the bakery responsible for any unsold products. Therefore, they must arrange collection and treatment by reversing the supply chain. Bakeries under the TBA are financially accountable for unpurchased products, and their collection and treatment. Hence, the bakers must forecast the amount to be ordered by the retailers and manage the product shelf-life to reduce waste.<sup>7,10</sup> Process improvements and technological advancements can minimize the amount of waste generated.

## Manufacturer to the customer: process of waste generation

## Standard practices of bread waste management

The accurate forecasting of demand is a complex task as it is influenced by multiple factors. In addition, consumers always prefer to buy fresh bread with a long shelf-life (3–5 days); therefore, bread with a short expiry date (1–2 days) is more likely

AD is associated with low environmental savings and is not the most suitable technology to harness the full potential of surplus bread, a rich source of food-grade glucose. Recently, some innovative work to valorise bread waste has been started. For example, some breweries in the UK have started using bread waste to substitute malted barley to act as a source of sugar for fermentation in beer manufacturing. In 2017, Greencore

## Holistic approaches for bread waste valorisation *via* bioconversion

First-generation biorefineries using edible feedstocks such as corn, sugarcane, vegetable oils *etc.* for fuels and chemicals through fermentative routes have been quite successful and generate a billion litres of biofuels every year. However, the primary concern with an exponentially growing human population is that if edible raw materials are utilized to produce fuels & chemicals, then there may be a shortage of food commodities to fulfil the demand of the global population.<sup>23,24</sup> To avoid the food *versus* fuel/resource debate, the focus of biorefining studies has generally been diverted towards non-edible feedstocks. However, most non-edible feedstocks require energy-intensive harsh pre-treatments and are associated with impurities and inhibitors such as organic acids,

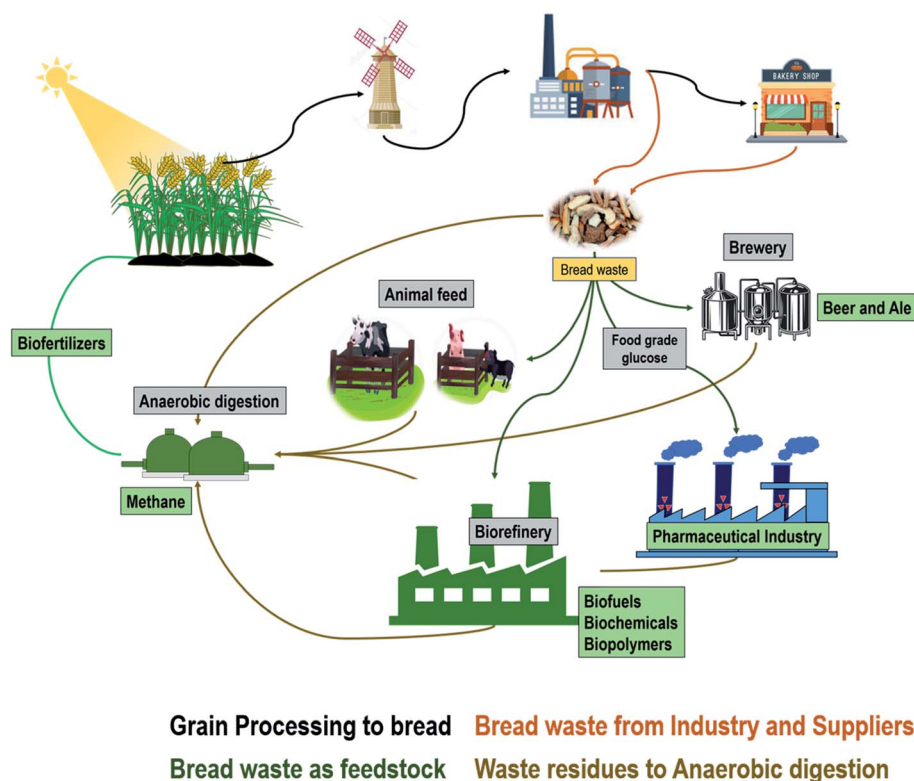


Fig. 1 Multiple routes for recycling of bread waste.

furan, and lignin derivatives. As an alternative, bread waste is a starchy material and a clean source of fermentable sugars and proteins. Typically 100 g of bread contains around 50–70 g carbohydrate, 8–10 g protein, 1–5 g fat and traces of phosphorus.<sup>25</sup> Sugars and amino acids can be obtained from bread *via* enzymatic hydrolysis, which has several outstanding advantages including mild reaction conditions, avoidance of toxic chemical usage and minimal/no risks of generation of fermentation inhibitors.<sup>26</sup> Furthermore, the composition of bread/bakery waste is consistent and homogeneous and the obtained sugars are as good as pure sugars. All of these reasons make bread waste an attractive potential feedstock for microbial fermentative production of a broad range of products, including industrially essential chemicals and fuels with high market values (Fig. 1).<sup>27</sup> Sugar hydrolysates from bread waste are generally devoid of growth inhibitors and can be a suitable medium for the growth of the majority of microbial chassis strains with commercial potential to produce high value-added chemicals and fuels such as 2-keto-D-gluconic acid,<sup>28</sup> lactic acid,<sup>29</sup> succinic acid,<sup>26</sup> pigments,<sup>30</sup> aromatic compounds,<sup>31</sup> and ethanol.<sup>32</sup> Currently, most of these chemicals are manufactured through a petrochemical-based route and are therefore associated with adverse environmental performance. On the other hand, if bread waste-based sugar was employed for fermentative production of chemical building blocks, it will result in an economical process and contribute towards a more sustainable environment.

Table 1 summarises the fermentative production of high-value products, including fuels, chemicals, enzymes and edible materials from bread waste in the last 5–10 years. Leung and associates (2012) used bread waste for fermentative production of succinic acid (SA), a top platform chemical, and observed an accumulation of 47.3 g L<sup>-1</sup> SA with a yield of 0.55 g SA per g bread.<sup>26</sup> This was followed by the work of Gadkari *et al.*, who carried out a LCA of the bioprocess and found a better environmental profile and significantly lower NREU (non-renewable energy units) in comparison to fossil-based SA production.<sup>33</sup> Sadaf and associates employed different modes of fermentation using bread waste containing 598 mg g<sup>-1</sup> reducing sugars for lactic acid (LA) production by several lactic acid bacteria. Like SA, LA is another platform chemical as per the revised list by the US Department of Energy. The three different strains of *Lactobacillus paracasei* SKL-9, SKL-11 and SKL-21 could produce 26.4, 28, and 27 g L<sup>-1</sup> LA *via* simultaneous saccharification and fermentation with conversion yields of 53, 56, and 54 mg LA per g bread waste, respectively. In the case of solid state fermentation, LA accumulated by SKL-9, SKL-11 and SKL-21 was 212, 223, and 250 mg LA per g bread waste respectively.<sup>29</sup> The latest published work by Maina *et al.* (2021) demonstrates the production of 2,3-butanediol (BDO) and acetoin, two commercially important chemicals with huge significant market potential, from bread waste hydrolysate by *Bacillus amyloliquefaciens*. The fed-batch culture with bread hydrolysate at a  $k_{La}$  (volumetric oxygen transfer coefficient) of 110 h<sup>-1</sup> resulted in a mixture of acetoin and of meso- and D-isomers of BDO with





**Table 1** Microbial production of fuels, chemicals and enzymes using bread waste as a feedstock

| S. no. | Feedstock               | Microorganism                                                                                   | Product                | Fermentation mode                                                | Titer                   | Yield <sup>a</sup>                                                        | Productivity                            | Reference |
|--------|-------------------------|-------------------------------------------------------------------------------------------------|------------------------|------------------------------------------------------------------|-------------------------|---------------------------------------------------------------------------|-----------------------------------------|-----------|
| 1      | Waste bread hydrolysate | <i>Biohydrogenbacterium</i> R3                                                                  | Hydrogen               | Separate hydrolysis and fermentation (SHF)                       | 7482 mL                 | 103 mL g <sup>-1</sup>                                                    | 103.91 mL h <sup>-1</sup>               | 36        |
| 2      | Waste bread hydrolysate | <i>Saccharomyces cerevisiae</i>                                                                 | Ethanol                | SHF                                                              | 58 g L <sup>-1</sup>    | 0.35 g g <sup>-1</sup>                                                    | 1.21 g L <sup>-1</sup> h <sup>-1</sup>  | 32        |
| 3      | Waste bread hydrolysate | <i>Saccharomyces cerevisiae</i>                                                                 | Ethanol                | SHF                                                              | 33.9 g L <sup>-1</sup>  | 0.25 g g <sup>-1</sup>                                                    | 0.36 g L <sup>-1</sup> h <sup>-1</sup>  | 35        |
| 4      | Waste bread hydrolysate | <i>Saccharomyces cerevisiae</i>                                                                 | Ethanol                | SHF                                                              | 100 g L <sup>-1</sup>   | 0.35 g g <sup>-1</sup>                                                    | 10 g L <sup>-1</sup> h <sup>-1</sup>    | 45        |
| 5      | Waste bread             | <i>Lactobacillus paracasei</i>                                                                  | Lactic acid            | Simultaneous saccharification and SSF (solid-state fermentation) | 28 g L <sup>-1</sup>    | 0.056 g g <sup>-1</sup>                                                   | 0.58 g L <sup>-1</sup> h <sup>-1</sup>  | 29        |
| 6      | Waste bread hydrolysate | <i>Actinobacillus succinogenes</i>                                                              | Succinic acid          | SHF                                                              | 47.3 g L <sup>-1</sup>  | 0.55 g g <sup>-1</sup>                                                    | 1.12 g L <sup>-1</sup> h <sup>-1</sup>  | 26        |
| 7      | Bread crumbs            | <i>Thraustochytrium</i> sp. AH-2                                                                | Lipids                 | Submerged fermentation                                           | 390 mg L <sup>-1</sup>  | 0.03 g g <sup>-1</sup>                                                    | 2.32 mg L <sup>-1</sup> h <sup>-1</sup> | 46        |
| 8      | Waste bread hydrolysate | <i>Bacillus amyloliquefaciens</i>                                                               | BDO + acetoin          | SHF                                                              | 103.9 g L <sup>-1</sup> | 0.39 <sup>b</sup> g g <sup>-1</sup>                                       | 0.87 g L <sup>-1</sup> h <sup>-1</sup>  | 34        |
| 9      | Waste bread             | <i>Rhizopus oryzae</i>                                                                          | $\alpha$ -Amylase      | SSF                                                              | —                       | 100 units per g                                                           | —                                       | 38        |
| 10     | Waste bread             | <i>Rhizopus oryzae</i>                                                                          | Protease               | SSF                                                              | —                       | 2400 units per g                                                          | —                                       | 38        |
| 11     | Waste bread             | <i>Aspergillus awamori</i> 2B.361 U2/1                                                          | Glucosylase            | SSF                                                              | —                       | 114 units per g                                                           | —                                       | 27        |
| 12     | Waste bread             | <i>Aspergillus awamori</i> 2B.361 U2/1                                                          | Protease               | SSF                                                              | —                       | 83.2 units per g                                                          | —                                       | 27        |
| 13     | Waste bread             | Enzymatic hydrolysis ( $\alpha$ -amylase + glucosylase) + biotransformation (glucose isomerase) | Glucose-fructose syrup | Sequential hydrolysis and enzymatic biotransformation            | —                       | 0.45 g g <sup>-1</sup><br>(glucose) + 0.4 g g <sup>-1</sup><br>(fructose) | —                                       | 47        |
| 14     | Waste bread hydrolysate | <i>Aspergillus</i> sp.                                                                          | Protease               | Submerged fermentation                                           | —                       | 117 units per g                                                           | —                                       | 39        |
| 15     | Waste bread hydrolysate | <i>Aspergillus</i> sp.                                                                          | Glucosylase            | Submerged fermentation                                           | —                       | 8 units per g                                                             | —                                       | 39        |

<sup>a</sup> Yield: calculated per gram of waste bread saccharified for glucose production. <sup>b</sup> Yield calculated per gram glucose.

Ethanol has several interesting properties as a biofuel and offers a number of advantages, such as a high-octane number, high heat vaporization, and combustion efficiency. In addition, bioethanol is less toxic and readily biodegradable and contains negligible amounts of sulphur.<sup>40</sup> Currently, it is blended with petrol at up to 10% levels in many countries, including the UK. The demand for ethanol has also increased during the current COVID19 pandemic due to its application as a sanitiser and disinfectant. Recently, the UK Government has decided to ban all new petrol and diesel-based cars from 2030 to cut down carbon emission to meet the zero-emission goal by 2050. Bioethanol production uses energy from only renewable sources and contributes towards a carbon-neutral environment. It is anticipated that the demand will go further up in future because bioethanol is a low carbon fuel and can play a key role in decarbonisation of the transport sector. Therefore, it can make a significant contribution to achieving the renewable energy requirements and zero emission targets of the UK by 2050. However, ethanol production is currently not promising in the UK. Bioethanol production started in 2007 in the UK and

Currently, diverse microorganisms like bacteria (*Actinobacillus succinogenes*),<sup>26</sup> yeast (*Saccharomyces cerevisiae*),<sup>32,35</sup> and fungi (*Aspergillus terreus*)<sup>44</sup> have been employed as microbial cell factories for bioconversion of starchy feedstocks like food, bakery and bread wastes into valuable products such as succinic acid, ethanol, and itaconic acid. Further, rational and process intensification approaches can be implemented to sustain the economic feasibility. Understanding the efficiency of bread waste as a sustainable feedstock, Dr Vinod Kumar's group at the School of Water, Energy and Environment, Cranfield University, United Kingdom, is developing a circular bioeconomy approach towards valorising waste bread for the production of high value-added chemicals and fuels.

As described in the previous section, utilisation of bread waste as an economical feedstock is a viable option that can drive costs down for the production of green chemicals. Many different renewable feedstocks have been investigated against their pure counterparts in the production of materials but what hasn't been covered in as much detail is the logistical and environmental impact of using waste. The concise useable life

of materials such as bread waste makes the redistribution challenging. Waste materials must be quickly transported to the site of fermentation, ready for pre-processing and eventual fermentation. When considering the quantities required, especially at a commercial scale, this can result in tonnes of waste needing to be delivered and processed within a short period. If this is left unprocessed or the supply exceeds the production demand, then there is a possibility of food decaying and beginning to create an environmental health hazard to the workers, attracting rodents as well as degrading the material to such an extent that it is no longer suitable for use as a feedstock. Regulation of the quality of waste material and transportation timings must be carefully controlled to enable swift utilisation of the waste. There are many bread waste locations such as bakeries, supermarkets and domestic waste collection sites, where the distribution or supply chain remains an unsolved issue. In the TBA, a reverse flow of logistics flow enables the clean flow of bread waste, which is not possible at the domestic level where it is a part of the municipal solid waste. This contamination with other food wastes is the major obstacle for domestic bread waste as a resource, presenting challenges for separation. In addition, lack of control of timescales means that domestic bread waste, even if properly separated, may have begun to degrade to an unusable state before collection, resulting in issues in processing. Domestic collection would therefore likely require separated food waste bins requiring individual collections at short time intervals – a major feasibility challenge both from the perspective of household acceptability, and increased resource load on local councils. An alternative may be the provision of segregated single collections for domestic food waste to households, for example cotton bags/small bins for bread waste, which could form a part of pre-existing domestic food waste collection with separation taking place at biowaste collection plants. However this would not overcome timescale and degradation challenges, so supermarkets and bakeries still remain more viable options, although these have logistical issues too. Collection of bread waste from each bakery or supermarket would have to be introduced. Many supermarkets, for example, Tesco, already use their bread waste in-house for items such as sourdough and many others are signed up to agreements to return any unused waste to the manufacturer. Others already ship them to specific companies to deal with in a collective food waste process rather than focus on separation. It would require close partnership with the company's bakeries and supermarkets to implement a regular collection service solely for bread waste.

One final word of caution when using bread waste as the feedstock would be to consider the balance of GHG emissions through a complete life cycle analysis (LCA). Whilst it is the case that the use of waste as a feedstock diminishes the waste deposition at landfill sites and therefore, a reduction in amount the GHG emissions. But accepting the TBA agreement results in additional transportation for the collection of bread waste which may further contribute to increased GHG emissions. Of course, regardless of the disposal route, bread waste must likely be transported, but careful attention must be paid to the levels of transportation required for different processing routes. The

use of bread waste for fermentation must be carefully monitored, and since specific processes such as ethanol fermentation produce carbon dioxide as a by-product, care must be taken to not add to the process carbon footprint though this CO<sub>2</sub> production. Although fermentative CO<sub>2</sub> is relatively pure, however, it could be relatively quickly contained and captured from the process. Throughout the world, various research groups in academia and industry are investigating technologies that can absorb CO<sub>2</sub> from the atmosphere and either store it long term, use it directly in products such as carbonated beverages or convert it to long-chain alcohols and alkenes, which constitutes synthetic fuels. Hence bread waste can be a suitable and sustainable feedstock to produce value-added chemicals, biofuels, and synthetic fuels.

## Conclusions

Bread waste is potentially one of the major bioresources in the UK and, whilst wastage should be minimised, eliminating wastage completely from the bread supply chain is an unrealistic goal. Bread waste represents a substantial untapped rich source of clean and fermentable sugars and, to a lesser extent, proteins. It can be converted into high-value chemicals, biofuels, bioplastics and other biorenewable products with applications across many industries. Currently, the majority of bread waste goes for anaerobic digestion, but the potential exists for much higher value uses, and the scope of opportunity is enormous. The full potential of bread waste needs to be unleashed through using it as a feedstock for biomanufacturing of food and non-food products through fermentative routes. As discussed, Europe has greater opportunity and need for assessing the valorisation of bread waste as business case followed by US, and Asia Pacific countries. Based on the availability, and valorisation options, a business plan considering the bread waste as raw material for high value-added chemicals, biofuels, pharmaceutical products, beer and/or pet food ingredients can be materialized. We believe that this article provides an insight into the potential of bread waste and will encourage more researchers to contribute towards the goal of bread/bakery waste based biorefineries with the associated multiple benefits of minimizing/eliminating the enormous amount of this waste generated globally and creating wealth out of it.

## Availability of data and materials

Data sharing is not applicable to this article as no new data was created or analysed in this study.

## Conflicts of interest

There are no conflicts to declare.

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