fermentation

Review

The Role of Yeast in the Valorisation of Food Waste

Laura Murphy [1,2] and David J. O'Connell [1,2,*]

[1] School of Biomolecular & Biomedical Science, University College Dublin, Belfield, D04V1W8 Dublin, Ireland; laura.murphy1@ucdconnect.ie
[2] BiOrbic Bioeconomy Research Centre, University College Dublin, Belfield, D04V1W8 Dublin, Ireland
* Correspondence: david.oconnell@ucd.ie

Abstract: The implementation of the circular bioeconomy is now widely accepted as a critical step towards reducing the environmental burden of industrial waste and reducing the impact of this waste on climate change. The valorisation of waste using microorganisms is an attractive and fast-developing strategy capable of achieving meaningful improvements in the sustainability of the biotechnology industry. Yeasts are a powerful chassis for developing valorisation strategies and key opportunities. Thus, this study examines how waste from the food sector can be effectively targeted for valorisation by yeast. Yeasts themselves are critically important elements in the production of food and brewing, and thus, the valorisation of waste from these processes is further reviewed. Policy and regulatory challenges that may impact the feasibility of industrial applications of yeast systems in the valorisation of food waste streams are also discussed.

Keywords: yeast; valorisation; circular bioeconomy; waste

Citation: Murphy, L.; O'Connell, D.J. The Role of Yeast in the Valorisation of Food Waste. *Fermentation* **2024**, *10*, 583. https://doi.org/10.3390/fermentation10110583

Academic Editor: Diomi Mamma

Received: 24 October 2024
Revised: 8 November 2024
Accepted: 11 November 2024
Published: 13 November 2024

1. Introduction

1.1. Circular Bioeconomy and Waste Valorisation

The circular bioeconomy and its implementations are now at the forefront of sustainable practise in the scientific sphere. The circular bioeconomy aims to steer activities away from linear strategies currently employed across many industries, which involve processing raw materials into products which are disposed of after use [1]. Instead, the circular bioeconomy proposes to incorporate a 'loop' in which materials and by-products are reused, remanufactured, and/or recycled into other processes [2]. While a prominent goal in sustainability practise is to reduce the volume of waste produced by industries and processes, the scale of waste production demands new approaches [3–5]. Therefore, plans to make use of this waste in the most environmentally conscious and efficient way possible is a central aim of the circular bioeconomy.

The feasibility and applicability of the circular bioeconomy is an issue that is hotly debated [6]. It is not enough to declare the use of waste products in a process as a 'sustainable circular bioeconomy process'; there must be evidence that the strategy employed to use this waste does not contribute to the emission of greenhouse gases or exceed recommended energy consumption levels. The overall environmental net impact of the waste material used must be positive and, therefore, worth pursuing [6]. For example, using a waste stream from food industry processes to feed a bioprocess producing a valuable protein may fit the concept of the circular bioeconomy well; however, if waste first requires an extensive pretreatment with harsh chemicals, and the final yield of the product from the secondary process is below a sustainable threshold, then the overall value or circularity remains unclear. Rigorous guidelines must be followed to ensure that the bioeconomy and, indeed, the circular bioeconomy are pursued in an efficient manner. The use of a life cycle analysis/assessment (LCA) can help overcome this hurdle. An LCA aims to determine the environmental impacts of production at each stage, beginning with the extraction of raw materials to the final disposal [7]. LCAs have a positive record in the sustainability field, where they have informed policy at the governmental level, helping to shape process developments in the industry while being a part of globally recognised standards (ISO 14040:2006) [8]. In this review, it is shown that an LCA is useful, as it can identify bottlenecks in the practicality of new processes, and identify where future optimisation is needed [9]. In tandem with LCAs, life cycle costing (LCC) can be utilised to determine the economic viability of a process. Here, consideration is given to the aspects of a process, including taxes/fees, fuel related to waste collection, and technology costs [10]. This establishes a comprehensive view of key aspects of waste management and valorisation practises, as well as the costs to companies, users, and society. Similarly, useful technological developments, which inform how we interpret and improve the circular bioeconomy, include digitalisation in the world of microbiology [11] and the use of machine learning [12]. These approaches can enable the discovery and utilisation of microbial diversity for more efficient ends and improve the modelling of biorefineries, which aid in the understanding of the complex nature of the circular bioeconomy.

1.2. Yeast as a Chassis for the Valorisation of Waste

Microorganisms are routinely utilised for the synthesis of materials and, indeed, in the world of waste valorisation [13]. Anarobic digestion is one avenue of bioremediation that is performed by microbes, resulting in biogas becoming the valorised product. However, due to low yields and other limitations, new approaches to valorisation have been sought [14]. Bacteria boast the ability to degrade certain plastics, such as polyethylene and polyvinyl chloride, and are often the primary microorganism of choice for this type of waste degradation and its subsequent valorisation [15]. Recent work has shown the potential of archaea in metal leaching to produce methane, an area which had previously been dominated by bacteria and fungi [16]. It is clear from these examples that a variety of attributes are required by microorganisms to valorise the vast range of global waste that is available.

When discussing waste from food and drink, yeasts offer some unique advantages over other microorganisms. There are over 1500 strains of yeast currently recognised [17], and the variety shown between these strains cannot be overstated. Yeasts do not form a single phylogenetic grouping [18]. However, common vernacular treats “yeast” as a synonym for perhaps the most popularly used and researched strain of yeast, *Saccharomyces cerevisiae*. However, there are several strains which are employed in the bioeconomy, including *Komagataella phaffii* that has been shown to both produce renewable chemicals [19] and generate waste that can be valorised [20]. As there are now over 70 products on the market which are being produced by *K. phaffii* [21–26], there is a wealth of waste that can be valorised from those processes. In this review, there are 14 different strains of yeast discussed. They range from oleaginous yeasts like *Rhodosporidium toruloides*, which naturally accumulates useful products, such as carotenoids and lipids [27], to non-conventional yeasts, such as *Yarrowia lipolytica*, that can grow on alternative carbon sources, such as hydrocarbons [28]. In addition, due to the diversity shown between yeast strains, there is potential for them to take waste from a variety of sources and create value-added products. Here, we focus on understanding the current standard of food waste valorisation research using yeast systems. Research across a number of continents is highlighted, reflecting the broad global interest in advancing the field of sustainability, and the valorisation of a broad range of food waste sources is described (Figure 1).

Waste from agricultural processes including examples from the dairy industry, and fruit and vegetable waste is valorised using a variety of yeasts and processes. These produce value added products such as lipids, biodiesel and carotenoids. Wastewater from these processes are also bioremediated by yeast.

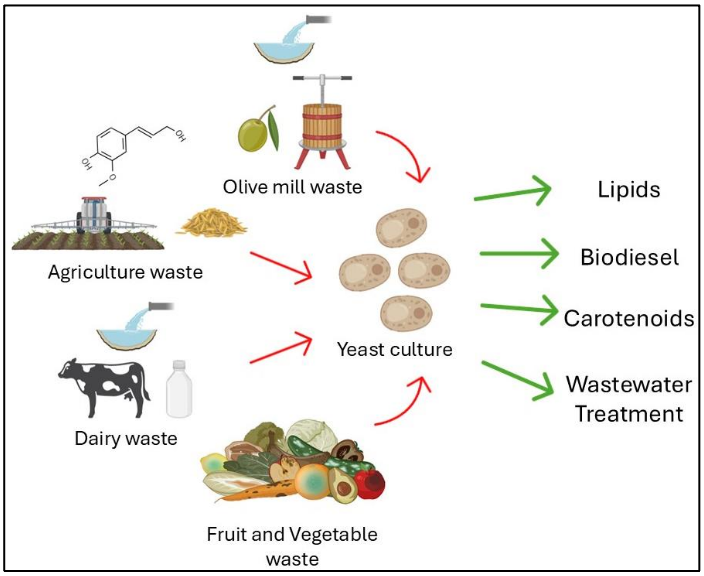

Figure 1. Valorisation of food waste, including that generated during the production process.

2. Yeast as a Chassis for Valorisation of Food Waste

2.1. Valorisation of Olive Mill Wastewater

Wastewater is a significant component of food waste and an important target for valorisation. There are approximately 380 billion cubic litres of wastewater generated globally each year [29], which can contain toxins and that is costly and energy-intensive to clean. Yeast presents an opportunity to provide a dual impact in relation to wastewater valorisation through (i) the removal of toxins and contaminating pollutants and (ii) the production of new value-added products. Olive mill wastewaters (OMW) have been actively investigated because of the difficulty in disposal due to antimicrobial and ecotoxic properties. They contain a variety of carbon sources which have the potential for upcycling [30]. Per 100 kg of olives produced, volumes of wastewater generated can reach 150 L [31]. Biosynthesis of single-cell protein by yeast isolated from OMW sources has been reported with a concomitant reduction in the pollution load of the waste [30]. Polyphenols, a component of OMW contributing to its pollution charge, have been effectively used for the biosynthesis of magnesium oxide nanoparticles by *Y. lipolytica*, where after phenol extraction, the yeast reduced the ecotoxic chemical oxygen demand (COD) value by 73%, highlighting the potential as a treatment option for harmful wastewaters [32]. Multiple yeast strains have shown this dual restorative and synthetic capability, including oleaginous *R. toruloides*, which simultaneously degraded phenols present in OMW and produced lipids that can act as a feedstock in biodiesel production [33]. D'Annibale et al. demonstrated that *Candida cylindracea* was capable of producing significant levels of lipases from OMW samples with varying COD, phenol, fat, and sugar content [34], highlighting both the versatility of this yeast strain, and the lack of a pre-treatment requirement for this waste stream for lipase production. Other studies have attempted to include additional waste items, such as crude glycerol (which is produced as a by-product of the biodiesel industry), as a diluent of OMW to produce citric acid by *Y. lipolytica* [35]. These studies have shown that OMW is tractable for valorisation by yeast, producing value-added products and reducing the environmental harm that this waste causes (Table 1).

Table 1. Summary of process valorisation, the yeast strain involved, and the final product.

Waste Valorised	Yeast Strain Used	Product	Citation
Olive mill wastewater	OMW yeasts	single-cell protein	[30]
	Yarrowia lipolytica	magnesium oxide nanoparticles	[32]
	Rhodosporidium toruloides	biodiesel feedstock	[33]
	Candida cylindracea	lipases	[34]
		citric acid	[35]
Agricultural industry waste (Lignin, Camelina meal, biomass)	*Rhodosporidium toruloides*	triacetic acid lactone	[36]
	Rhodosporidium toruloides	carotenoids	[37]
	Candida tropicalis	ethanol	[38]
	S. cerevisiae	2-phenylethanol	[39]
	Candida utilis	β-glucans	[40]
	Rhodosporidium toruloides	lipase enzymes	[41]
	Candida utilis	mycotoxin absorption	[42]
Dairy industry waste (Whey; wastewater)	*Kluyveromyces marxianus*	ethanol; ethyl lactate	[43]
	S. cerevisiae	ethanol	[44]
	Kluyveromyces marxianus	cheese production	[45]
	non-Saccharomyces	alcoholic beverages	[46]
	S. cerevisiae	wastewater treatment; energy	[47]
Fruit and vegetable waste	*Rhodosporidium paludigenum*	biomass and lipids	[48]
	S. cerevisiae	bioethanol and vinegar	[49]
	Yarrowia lipolytica	recombinant protein	[50]
	S. cerevisiae	ethanol	[51]
	S. cerevisiae	onion vinegar	[52]
	S. cerevisiae, Pichia stipitis	ethanol	[53]
	Rhodosporidiobolus azoricus, Cutaneotrichosporon oleaginosum	biodiesel	[54]
	S. cerevisiae	sugars, ethanol	[55]
	Rhodosporidium toruloides	carotenoids	[56]
	Yarrowia lipolytica	laccase	[57]
Oils (sunflower, olive, palm)	*Yarrowia lipolytica*	lipase	[58]
	S. cerevisiae	ethanol	[59]
	Rhodotorula babjevae	mannitol, carotenoids, glycolipid	[60]

2.2. Valorisation of Agricultural Waste Streams

Residual biomass from a variety of agricultural processes has been investigated for valorisation by yeast, with particular interest in lignin/lignocellulose biomass, as lignin is the most prevalent aromatic biopolymer [61]. Current means of valorising lignin involve a combinatorial approach of thermochemical and enzymatic treatments [62]. As lignin is complex in structure, depolymerisation methods are employed to produce monomers and oligomers, which can then be used as substrates to produce biofuels and fine chemicals [61]. Sources of lignocellulose include hardwoods and softwoods, coffee grounds, and newspapers [61], with the nature of these sources highlighting the huge quantity of waste for potential valorisation. Research into utilising microorganisms for lignocellulose valorisation has been ongoing in recent years, with yeast strain development a focus area. One particular strain of yeast that holds promise for lignin valorisation is *R. toruloides* [36]. *R. toruloides* can utilise mixed carbon sources found in these waste streams and is capable of supporting a consolidated bioprocess, thereby reducing the number of stages of production and reducing costs. One study highlights a 'one-pot' approach for lignocellulose valorisation through the production of triacetic acid lactone (TAL) using an engineered strain of *R. toruloides*. In a bioreactor scale-up experiment, up to 3.9 g/L of TAL was produced in a means that was cost-effective and industry-applicable [36].

Other sources of biomass have similarly shown promise as feedstocks for the production of value-added products by a wide range of yeasts. *Camelina* meal is the primary by-product from *Camelina sativa* seed oil extraction. These seeds are commonly used as a supplement in livestock diets in the agricultural industry [37]. This waste stream can be valorised in two ways—the production of alternate products and increasing the nutritional value of the *Camelina* meal—which can be used as a food source for livestock. Bertacchi et al. took waste *Camelina* meal and developed a process for *R. toruloides* to produce carotenoids, a pigment that is found in animal feed and in dietary supplements [37]. With an estimated 2020 global market value of $2 billion [63], there is a significant incentive to produce this product in an inexpensive way. Titres of 16 mg/L were achieved in this study, despite exposure to the cultures to water-insoluble solids, which often detrimentally impact microbial growth and production in an industry setting [37]. This study provides a foundation for translation into industrial valorisation of this agricultural waste source in the future. Residual biomass from a variety of food and plant cultivations has proven to be a reliable source for the generation of new products. For example, one study examined the common agricultural waste biomass sugarcane bagasse and rice straw for the production of bioethanol and the valuable enzyme pyruvate decarboxylase, respectively [38]. Multiple strains of yeast were investigated, with *Candida tropicalis* fermentation using rice straw as a substrate demonstrating the highest levels of ethanol production at approximately 12.7 g/L. This work also highlighted the capacity of these yeasts to diminish waste disposal problems associated with ethanol production [38]. Tobacco waste has been exploited as a substrate for the production of useful products, specifically 2-phenylethanol (2-PE), which is used in the cosmetics and food industries [39]. 2-PE is a high-cost product, and this study aimed to produce it in purifiable quantities using tobacco waste as a substrate and, in parallel, treat the tobacco waste to reduce its negative environmental impact. *S. cerevisiae* was capable of achieving this with 1.65 g/L titres achieved, with the authors stating this can be improved in the future [39].

One avenue to effectively valorising agricultural waste is in the production of α-glucans, which are often used in medical applications due to their activation of the innate immune system, and β-glucans, which can lower blood cholesterol levels [64]. Microorganisms are routinely used for glucan extraction as they contain glucans in their cell walls; however, the production of glucans is often costly, with unsatisfactory yields to meet the global glucan demand, and is, therefore, underutilised [65]. Multiple agricultural wastes can be used for production, including starch-rich biomass like potato juice wastewater supporting *Candida utilis* growth and biosynthesis of β-glucan yields of up to 82% [40]. Flour-rich wastes, such as those arising as by-products from bread manufacture and other wheat milling by-products are rich substrates for the production of useful enzymes by the yeast *Rhodosporidium toruloides* [66]. These enzymes were produced using solid-state fermentation, and were produced at a rate of 0.32 g/L/h, where they were utilised to treat yeast cells, releasing approximately 80% of lipids and producing a hydrolysate that could be used as a substitute for yeast extract [66].

Mycotoxins are present in food and animal feed across the globe, and present a significant safety risk in the feed and food supply chains [41]. As such, new methods of reducing mycotoxin incorporation into these processes are under investigation, with adsorption being a potentially viable solution. Yeasts offer a specific benefit over other microorganisms in terms of adsorption due to the polymer structure of their cell wall and local humoral cellular response, where both factors are strain-dependent [41] and altered by growth conditions [42,67]. The capacity of isolated *Candida utilis* cell walls, and glucans isolated from *C. utilis* cultivation on low-cost substrates to adsorb several mycotoxins have been reported [41]. The efficiency of adsorption varies, and the most successful approach was shown with the capture of non-polar mycotoxins [41].

Together, these examples demonstrate the variety of waste sources that can be valorised and highlight the prospective application of yeast to utilise agricultural waste to reduce the levels of an environmental toxin, approaches that can prove a highly economical route toward the circular bioeconomy.

2.3. Yeast Valorisation of Waste from the Food, Wine, and Dairy Industries

2.3.1. Dairy (Whey)

The volume of dairy products is rapidly increasing across the globe with population growth and greater intensity of herd management, with European production expected to reach 162 million tonnes annually by 2031 [68]. Considering this volume of product, there is a significant waste stream to consider from this industry, with solid waste and effluents reaching up to 11 million tonnes globally [69]. There is mounting interest in exploiting yeast as host systems to capitalise on this opportunity for valorisation and reducing the global waste burden. Whey is produced as a by-product during cheese manufacture [70]. Whey proteins include immunoglobulins and bovine serum albumin, which are of high nutritional value [70]. The specific concentrations of these proteins are dependent on several factors, such as milk source, time of processing, and processing quality [71]. As a result of the high lactose content of whey, there is a high oxygen demand of whey and, therefore, a negative environmental impact [43]. Thus, valorising whey would be beneficial in producing value-added products and reducing environmental damage. Several species of yeast, for example, *Kluyveromyces marxianus* [43], have shown promise in fermentation in the difficult conditions provided by waste whey—using lactose as a carbon source and the low pH of acid whey. *Brettanomyces claussenii* is another strain which is studied for its potential ability to use whey to produce fermented health drinks such as kombucha [72].

Koutinas et al. successfully developed a hybrid system in which *K. marxianus* produced ethanol from waste whey lactose, and the ethanol produced was then used as a substrate in esterification reactions to produce the chemical ethyl lactate [43]. Whey permeate has been investigated as a co-substrate or to replace a portion of process water and was successful in supporting *S. cerevisiae* fermentation to produce ethanol for use as a biofuel [44]. The efficiency of ethanol production reached approximately 86% of the existing process when 15% of the water in the fermentation was replaced with hydrolysed whey permeate. The reduction in the required volume of water for the production of this bioethanol would lead to improved economics if applied to industry, in addition to utilising agricultural waste [44]. Interestingly, whey can be used as a substrate for yeast to create useful starter cultures for applications in cheese ripening [45]. Here, *K. marxianus* and kefir yeasts were tested for their efficiency in fermenting lactose and milk whey, where the biomass moved on to become a starter culture for cheese production. Moreover, the presence of harmful bacteria, such as staphylococci and enterobacteria, was reduced when the kefir starter culture was used [45]. Alcoholic beverages with varying aroma profiles and alcohol content can also be produced by yeasts fermented in whey, specifically tofu/soy whey [46]. Five non-*Saccharomyces* strains were tested in these experiments, with some demonstrating superiority in terms of ethanol production (reaching 6–7%), and each strain producing a unique volatile metabolite profile which directly correlates to the aromas of the beverages [46].

The concept of yeasts performing the dual action of diminishing the environmental burden of toxic wastewater and reducing the energy needed to treat it, while also producing a valuable product, is a big positive for the dairy industry. Real dairy wastewater as a substrate for *Saccharomyces cerevisiae* fermentation was studied for the reduction in chemical oxygen demand [47]. A removal percentage of 92% was achieved, and in addition, current and voltage were generated through a microbial fuel cell, 28 µA and 850 mV, respectively. This work highlights an exciting capacity for yeast to treat dairy wastewater while also producing environmentally friendly wastewater [47].

2.3.2. Fruit and Vegetable Waste

Sustainability in the food sphere is one of the most readily adopted mindsets in society today. Consumers participate in composting, recycling, and reduction in plastic waste from food and drink products, and reuse of food containers, bottles, coffee cups, etc. [73]. This certainly makes a difference both environmentally and economically, with predictions showing that an increase in composting practises in the United States would reduce carbon emissions by 30 million tons a year, in addition to reducing waste management costs by 16 billion USD [74]. In an industrial setting, there is a wealth of opportunity for the valorisation of the waste produced from food manufacture/processing, as it is estimated that up to 40% of total food waste occurs at the manufacturing stage [75].

Extensive research has been performed in relation to valorising fruit and vegetable waste. These studies range from the production of biomass and lipids from waste like corncob hydrolysate [48], to bioethanol and vinegar production from dates [49], to recombinant protein production from papaya fruit waste [50]. This variety of products and waste sources speaks to the adaptability of yeasts as a highly suitable chassis for the valorisation of food waste. Many fruits and vegetables are rich in lignocellulose; pineapple leaves, for example, have a high lignocellulose content, and production of bioethanol through saccharification and fermentation using *S. cerevisiae* has been demonstrated [51]. There was a fermentation efficiency of 91% reported over the existing process, and up to 9 g/L of ethanol was produced. In addition, hydrothermal pre-treatment of the pineapple leaves was employed, over the more environmentally damaging acid or base catalyst in the existing procedure [51]. Another interesting approach in using food waste to produce bioethanol involved waste onions [52]. Here, onion juice was transformed into onion liquor via *S. cerevisiae* fermentation, which eventually became onion vinegar [52]. Near-infrared spectroscopy was performed in this study to enable complex monitoring of this reaction, and along with some multivariate analysis, allowed the prediction of sugars, ethanol, and biomass concentrations [52], which is an interesting addition to a valorisation experiment, and gives a thought for how monitoring of these processes could be applied in an industrial scale. Co-cultures of yeasts have been evaluated on their ability to produce bioethanol from kitchen waste, namely a combination of *S. cerevisiae* and *Pichia stipitis* [53]. In this experiment, kitchen waste was gathered from municipality sources in Greece and were combined into a homogenous biomass, which was then used as a carbon source during fermentation of the *S. cerevisiae* and *P. stipitis* co-culture. The co-culture outperformed both individual yeast cultures, and achieved approximately 14 g/L of ethanol after 35 h [53]. Another route for producing biodiesel using yeasts is via lipid accumulation, where yeast lipids replace vegetable oils and animal fats in the biodiesel manufacturing process. Donzella et al. demonstrated the capacity for the oleaginous yeasts *Rhodosporidiobolus azoricus* and *Cutaneotrichosporon oleaginosum* to use pumpkin peel as a sole feedstock to produce a highest biomass yield of 45 g/L, with 55% of this being lipids [54]. Sugars produced from waste vegetables such as potato, sweet potato, and yam waste were then valorised into bioethanol in one study [55]. Enzymatic saccharification produced sugars from these waste sources, and the sugars were used during *S. cerevisiae* fermentation to produce bioethanol. Sweet potato waste provided the highest ethanol yield of 251 mg/g, indicating that this abundant waste source can be readily valorised [55].

Applications of valorising food waste go beyond bioethanol production, with some interesting products being produced from a variety of waste sources. For example, carotenoids, which can function as dietary supplements/antioxidants, pigments, and feeds, have been generated from cinnamon waste material [56]. Cinnamon had previously been excluded as a potential source of waste for valorisation due to the presence of several antimicrobial components, such as cinnamaldehyde [76]. However, this work shows that *R. toruloides* is capable of producing up to 2 mg/L of carotenoids with waste cinnamon bark hydrolysate as the sole carbon and nitrogen source, with suggestions of a second nitrogen source from a residual origin being able to increase this titre further, in a sustainable manner [56]. Laccases are other valuable enzymes which can be produced from food waste, having applications in waste detoxification and degradation of xenobiotics [57]. The yeast *Y. lipolytica*, carrying a laccase gene from a fungus, used beet molasses as a waste source for growth. Optimisations for laccase production were performed, and it was found that larger-scale bioreactor experiments yielded a significantly higher productivity of 0.0937 U/h of laccase [57].

2.3.3. Oils

Vegetable oils, including sunflower and olive oils, when heated to the high temperatures that occur when frying foods, are modified in a number of ways, with toxic compounds being produced [77]. This can lead to problems relating to both human and environmental health. The large volume of waste oils makes them difficult to dispose of, with frequent contamination of wastewater occurring, in addition to blockages of drains and sewers [77]. A primary focus of implementing a circular handling to this waste source is valorisation into biofuels; however, other avenues have been investigated, such as the manufacture of soap [78] and polyvinyl chloride (PVC) [79] production. This has sparked strong interest in using microorganisms for the conversion of this waste source into useful and valuable products.

Waste palm oil was investigated as a feedstock for the yeast *Y. lipolytica* to produce the enzyme lipase [58]. In the study, the highest lipase activity was seen with commercial waste palm oil obtained from a fast-food restaurant, with 4.9 U/mL achieved. The lipase product was tested as a biocatalyst and resulted in a hydrolysis yield of 13.1%, with a capability to be reused up to 3 times [58], highlighting the circular and sustainable nature of this approach to waste valorisation. Olive pomace from olive oil production is a significant by-product of this industry [80]. This residue contains sugars, proteins, fatty acids, and polyphenols and polyalcohols. Studies have shown that it can be valorised into bioethanol, where in one experiment, *S. cerevisiae* was capable of producing 0.46 g/g of ethanol [59]. Other waste pomace, including wine grape pomace, has been utilised to extract sugars, namely glucose and fructose to prepare growth media. Yeast *Rhodotorula babjevae* grew well in this newly created media, and produced multiple valuable compounds such as mannitol, carotenoids, and a rare glycolipid that has applications in the food and pharmaceutical industry [60].

3. Valorisation of Food Related Waste Produced by Yeast

Yeast themselves have been used for thousands of years in wine making, baking and brewing [81]. Significant research activity has sought to determine the potential for valorisation of yeast waste. Spent yeast, commonly referred to as brewers spent yeast (BSY), is the remainder of the fermentation process following the extraction of bioactive compounds, and it is traditionally viewed as waste [82]. The brewing industry was estimated to have produced up to 418,000 tonnes of spent yeast in the year 2020 [83], highlighting the wealth of material that could be valorised. This spent yeast is primarily comprised of proteins (including essential amino acids), along with polysaccharides and glycoproteins [84], all of which hold biotechnological value.

A significant focus in the area of BSY valorisation is on the production/extraction of β-glucan [85]. BSY itself contains a considerable percentage of β-glucan (up to 60% of cell dry weight) [86], however recovery is challenging due to the yeast cell wall. Robust cellular disruption methods have been developed by a number of groups in an attempt to liberate β-glucan from spent yeast and utilise it as a food ingredient. Crucially, the β-glucans that are liberated from yeasts are considered generally recognised as safe (GRAS) [87], highlighting the feasibility of use of these projects. A number of approaches have been described to valorise the food related waste produced by yeast (Table 2). Alkaline extraction is a popular method that is employed to disrupt the yeast membrane, with one experiment achieving 66% yield of β-glucans from yeast following optimisation of alkaline conditions [88]. Furthermore, the extracted β-glucan demonstrated antioxidant activity, and encouraging anti-cholesterol effects [88]. Varelas et al. used winery spent yeast as their source of biomass for β-glucan production [89]. In this waste the spent yeast is found in a by-product called wine lees, which are produced mainly during the early stages of wine production (e.g., fermentation and filtration) [90]. In addition, the sludge following alcoholic fermentation of wine also contains a large amount of spent yeast to extract β-glucans from [89]. This study performed yeast autolysis and hot alkali methods to obtain up to 43% β-glucan concentration from winery yeast waste biomass, demonstrating a novel way to obtain this valuable product from an abundant waste source [89].

Table 2. Summary of valorisation of food related waste produced by yeast.

Type of Waste	Yeast Strain Producing Waste	Product/Output	References
Brewers spent yeast (BSY)	*S. cerevisiae*	β-glucans	[88]
Winery spent yeast	*S. cerevisiae*	β-glucans	[89]
BSY	*S. cerevisiae*	peptides	[83]
BSY	*S. cerevisiae*	silver phosphate nanocomposites	[91]
BSY	Unspecified	activated carbon	[92]
Fermentation waste	*S. cerevisiae*	peptides	[93]
Microbrewery waste	*S. cerevisiae*, *R. toruloides*	lipids/biodiesel	[94]
BSY	*S. cerevisiae*	wastewater treatment	[95]
BSY	*S. cerevisiae*	biogas, bioethanol, oils	[96]
BSY	*S. cerevisiae*	ethanol	[97]
Baijiu/Jiuzao	Variety of *Saccharomyces* and non-*Saccharomyces* strains	antioxidants biochar	[98,99]

Successful extraction of peptides from spent yeast has demonstrated antihypertensive and antioxidant properties in addition to a 71% reduction in HMG-CoA, suggesting a cholesterol-lowering capacity also [83]. Silver phosphate nanocomposites have been synthesised from spent brewers' waste [91]. In varying the synthesis temperature and time, the component ratios of the nanocomposites differed, producing a panel of candidates. The presence of yeast and the high nitrogen content is believed to contribute to the growth of silver phosphate. Multiple nanocomposites showed antibacterial activity against *E. coli*, and crucially, these nanocomposites were made in an environmentally friendly process [91]. Other products produced from spent yeast include activated carbon. Here, yeast residue originating from the ethanol industry was carbonised at 800 °C [92]. This was subsequently activated and used to remove the presence of the therapeutic dipyrone from aqueous effluent at an experimental sorption potential of approximately 88 mg/g [92]. The use of extracted peptides from *S. cerevisiae* waste as a skin health additive has been explored [93]. Along with being non-toxic at any concentration tested, the peptides achieved modulation of specific metabolites which have a positive effect on skin health [93]. Lipid production is also possible using BSY as a feedstock, where, in work by Patel et al. [94], waste from a microbrewery was pretreated with organosol to solubilise lignin and hemicellulose, and glucose and xylose were harvested. Glucose yields reached approximately 46%, and xylose was 25%. These were then used as a substrate for another yeast, *R. toruloides*, to produce lipids for use as a biodiesel [94]. There is an appealing circularity in using spent yeast to feed another yeast process for the production of a useful product.

Interestingly, spent yeast has been examined as a tool to remove toxic dyes from wastewaters. In the textile industry in particular, dyes in waste effluent is a major problem, due to their high concentration and the difficulty in their treatment [100]. Soh et al. used spent yeast from a local brewery plant as a biosorbent and aimed to remove Congo red dye from water samples [95]. The study showed that the BSY was comparable to other sorbents in the removal of Congo red [95], thereby highlighting an opportunity for reuse of this vast waste source in a meaningful way. In terms of mitigating negative environmental impact through the use/valorisation of BSY, an interesting approach established a brewers spent grain biorefinery process which involved the retrieval of biogas, bioethanol, and used oils from BSY [96]. While successful in demonstrating the capacity for up to 379 mL biogas/g, a 45% ethanol yield, and 70% oil extraction efficiency, the research team also hypothesise that BSY could be utilised for the green production of up to 7 million MJ per year is the European brewer's yeast is exploited to its fullest potential [96]. This is an interesting consideration and a welcome look at the feasibility to implementing a circular bioeconomy approach to BSY handling on a larger scale.

It is also possible to valorise BSG through producing ethanol [97]. Six different types of BSG were tested, as the varying composition of BSG can represent a hurdle in its valorisation. The BSG was pretreated by autohydrolysis, leading to high glucose yields of up to 85%. From here, the slurries were used as substrates for ethanol production via fermentation from two different *S. cerevisiae* strains. Ethanol yields of up to 94%, or 42.27 g/L, were achieved [97], indicating a real opportunity for a more sustainable production of ethanol.

Distilled drinks such as Baijiu are another great source of yeast waste for valorisation. Baijiu is the most popularly consumed beverage globally, and as a result of this demand, it produces over 20 million tonnes of agricultural waste every year [101]. The flavour type of the produced Baijiu is linked to the species of yeast used during the fermentation process, and yeasts used in its production include both saccharomyces and non-saccharomyces strains [102]. Jiuzao is the remainder following the solid-state fermentation and distillation of Baijiu and is the material that is most readily valorised due to its components like lignin, cellulose, and hemicellulose [101]. Several interesting applications for valorised Jiuzao have been investigated in recent years. For example, Jiang et al. demonstrated that a tetrapeptide isolated from Jiuzao hydrolysate had antioxidant potential in vivo [98]. Other applications include producing biochar, which can be used in water treatment and carbon sequestration [103]. One study utilised biochar made from Jiuzao to remove turbidity levels in Baijiu, highlighting the reusability of waste from Baijiu production within the Baijiu sector [99].

4. Current State of Yeast in the Food Waste Valorisation Sphere

This review has illustrated the potential of yeast systems in the biotechnology waste valorisation sphere, with a focus on food waste—both from the food production process, and the physical remainders from food preparation. The duality of yeast to both produce useful products from a wide range of waste sources, and to also generate waste that can be transformed into valuable outputs highlights the true wealth of success that could be found in this area of research. The global journey towards true sustainable circularity is ongoing, and while optimisations and advancements are still needed, the steps taken in recent years have been hugely impactful. It is well established that there is a pressing need for intervention in the current agricultural, dairy, and food-related sectors in relation to waste handling.

4.1. Regulatory Considerations

Some of the barriers, which reduce the impact of the works discussed in this review and limit their implementation, must be considered. Governmental support often poses the largest obstacle when it comes to altering standard practises in any industry. Regulations are set in place and are often longstanding. Convincing governments, stakeholders or regulatory authorities to allow waste materials to be syphoned off for valorisation elsewhere will prove challenging, as research suggests [104]. Processes may be patented and IP protected, and if anything is genetically modified, then there are many difficulties in handling and using all related wastes, and furthermore, it would involve an overhauling of established processes where new steps are introduced [105]. Stakeholders, in particular, may be very influential in the progression of the circular bioeconomy, as their backing and investment in these projects have shown to positively influence their implementation, along with increasing public support for such work [104].

The means and stage of production in which waste is generated is also an important factor when it comes to implementing change into an established process. There is a global inequality in when food waste is generated, for example. In developing countries, most food loss occurs post-harvest, whereas in more affluent areas, this loss happens post-consumer obtainment [106]. This would influence when an intervention would occur to make the process more sustainable through harvesting/collection of the food waste for valorisation using yeasts. Keeping with food waste, research has shown that there are five aspects which are critical for the use of circular economy biorefineries on a commercial level [106,107]· An efficient waste collection system is needed to generate a high volume of quality food waste. There is a vast range of sources of food waste, which may lead to difficulties in coordination. This would be a time-sensitive process due to the decaying nature of food waste and, therefore, careful thought must be put towards transport and storage processes. As mentioned, policy support for such processes is needed along with interest from society. And finally, the economic feasibility of the proposed processes must be debated. Here, LCAs and LCCs can be powerful tools in assessing the viability of a new venture and would be useful in tacking this issue.

4.2. Geographical Considerations

When discussing the circular bioeconomy, it is imperative that the geographical and socio-economic factors are considered carefully. Each region must be examined separately when reviewing progress and identifying barriers, as with any concept or technology, advancements are made at different rates throughout the world. As the second largest continent by surface area, Africa offers a wealth of agricultural and industrial processes, ones which generate varied by-products worth valorising. One particular output is lignocellulose biomasses that show promise as a starting material for the production of a range of products [108]. Crops, such as olives and potatoes, are produced in huge quantities, with the residues following cultivation being in the mega tonne range, estimated at 2.7 Mt in 2019, according to the FAO statistics [109]. To deal with this enormous 'waste' accumulation, research into valorisation in Africa has shown progress in recent years [108]. An important consideration is the "food vs fuel" dilemma, where certain crops are only suitable for producing bioethanol in large quantities, and would, therefore, require more land to grow, thereby sacrificing land on which crops for food could be grown. Other considerations include land governance, technological readiness, and acceptance by local communities, along with regulatory issues. Development in each of these areas is needed to begin implementing a circular bioeconomy in Africa.

Europe has often been at the forefront of sustainable policy development and implementation, particularly since 2016, when the *Paris Agreement* was introduced, along with the 2030 agenda for sustainable development plan [110]. It is estimated that the implementation of the circular bioeconomy could create over 180,000 direct jobs, and reduce the demand for raw materials by up to 40%, by the year 2030 [111]. Research has shown that across that many individual countries within Europe, the general trend in the evolution of the circular bioeconomy has been positive and progressive [112]. However, as mentioned, the circular bioeconomy is a complex issue and countries within Europe have developed their sustainable practises at varying rates over a 10 year period (2006–2016), with Slovakia, Poland, and Latvia developing quickly, for example [112]. However, it is suggested that this rapid development may be due to a catch-up effect, as these countries were far behind than the likes of Finland and the Netherlands. The latter countries have governmentally-implemented bioeconomy programmes and policy, and perhaps these strategies need longer for a greater growth to be observed and for an already well-established circular economy to improve further [112].

Latin America has demonstrated a growing interest in circular bioeconomy practises in recent years, with Brazil and countries containing similar scale agricultural industries putting more research into the implementation of the circular bioeconomy [113]. Due to the nature of the sectors within Latin America, such as forestry, livestock, and agriculture, there is a large volume of bio-based waste produced and, therefore, large potential for progress in terms of sustainability and circular waste handling [113]. This area of research is currently in its infancy in this region, with only a total of 64 publications related to the circular bioeconomy having been published by 2022 [113]. However, the themes from these papers match the global trends in waste valorisation, such as recovering value from agricultural waste and wastewater, and producing bioenergy from waste sources. Overcoming economic, political, and technological barriers in Latin America will allow research to advance and expand the opportunities for improving waste management practises.

4.3. Environmental Impact of Large-Scale Fermentations

It would be remiss to overlook the negative environmental impact of large-scale fermentations. As the fermentation industry grows in scale generally, and replaces some traditional chemical approaches, so too grows any associated harmful effects, albeit they are less than their chemical counterparts [114]. Furthermore, the popularity of fermented foods has risen in recent years [115]. Indeed, the methane and other greenhouse gases produced during fermentations contribute to global warming. While, generally, fermentation practises have a positive environmental impact when compared to other approaches, and utilises waste sources and promotes the circular bioeconomy [116] as outlined throughout this review, implementing a large-scale process also increases any waste from the fermentation itself. Water for the cultures, which becomes wastewater following the fermentation, and any energy costs and carbon emissions from the fermentation will increase as we scale-up. This is an important consideration when discussing the viability of some of the valorisation approaches outlined.

5. Conclusions

The future is bright for both the food waste circular bioeconomy and the role of yeasts in delivering the aims. There is a wealth of opportunity for meaningful intervention and the valorisation of a variety of agricultural and food wastes, which can be transformed into value-added products. Building upon the research highlighted in this review will open the door for discussions about policy change, and could lead to investment into valorisation processes at a larger scale, thereby aiding in the reduction in global waste through the implementation of the circular bioeconomy.

Funding: This research was funded by the Atoms-2-Products centre for doctoral training, which is supported by the Science Foundation Ireland (SFI) and the Engineering and Physical Sciences Research Council (EPSRC) under Grant No. 18/EPSRC-CDT/3582.

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

References

1. Brandão, A.S.; Gonçalves, A.; Santos, J.M.R.C.A. Circular bioeconomy strategies: From scientific research to commercially viable products. *J. Clean. Prod.* **2021**, *295*, 126407. [CrossRef]
2. Holden, N.M.; Neill, A.M.; Stout, J.C.; O'Brien, D.; Morris, M.A. Biocircularity: A Framework to Define Sustainable, Circular Bioeconomy. *Circ. Econ. Sustain.* **2023**, *3*, 77–91. [CrossRef] [PubMed]
3. Ali, A.; Alpaslan, B. Pro-industry Policies, Sustainability, and Industrial Growth. In *Industrial Policy and Sustainable Growth*; Yülek, M.A., Ed.; Springer: Singapore, 2018; pp. 27–49. [CrossRef]

4. Ma, N.; Shum, W.Y.; Han, T.; Cheong, T.S. Global Industrial Development: Insights From the Distribution Dynamics Approach for the Post COVID Era. *Front. Public Health* **2021**, *9*, 792947. [CrossRef]
5. Hosono, A. Industrial Development and Transformation: Insights from Outstanding Cases. In *SDGs, Transformation, and Quality Growth: Insights from International Cooperation*; Hosono, A., Ed.; Springer: Singapore, 2022; pp. 39–73. [CrossRef]
6. Tan, E.C.D.; Lamers, P. Circular Bioeconomy Concepts—A Perspective. *Front. Sustain.* **2021**, *2*, 701509. [CrossRef]
7. Ayres, R.U. Life cycle analysis: A critique. *Resour. Conserv. Recycl.* **1995**, *14*, 199–223. [CrossRef]
8. *ISO 14040:2006*; Environmental management: Life Cycle Assessment—Principles and Framework. ISO: Geneva, Switzerland, 2006.
9. Sevigné-Itoiz, E.; Mwabonje, O.; Panoutsou, C.; Woods, J. Life cycle assessment (LCA): Informing the development of a sustainable circular bioeconomy? *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2021**, *379*, 20200352. [CrossRef]
10. Martinez-Sanchez, V.; Kromann, M.A.; Astrup, T.F. Life cycle costing of waste management systems: Overview, calculation principles and case studies. *Waste Manag.* **2015**, *36*, 343–355. [CrossRef]
11. Krüger, A.; Schäfers, C.; Busch, P.; Antranikian, G. Digitalization in microbiology—Paving the path to sustainable circular bioeconomy. *New Biotechnol.* **2020**, *59*, 88–96. [CrossRef]
12. Tsui, T.H.; van Loosdrecht, M.C.M.; Dai, Y.; Tong, Y.W. Machine learning and circular bioeconomy: Building new resource efficiency from diverse waste streams. *Bioresour. Technol.* **2023**, *369*, 128445. [CrossRef]
13. Vaishnavi, J.; Jabez Osborne, W.; Samuel, J. Chapter 11—Microorganism in waste valorization and its impact on the environment and economy. In *Relationship Between Microbes and the Environment for Sustainable Ecosystem Services*; Samuel, J., Kumar, A., Singh, J., Eds.; Elsevier: Amsterdam, The Netherlands, 2023; pp. 191–205. [CrossRef]
14. Lad, B.C.; Coleman, S.M.; Alper, H.S. Microbial valorization of underutilized and nonconventional waste streams. *J. Ind. Microbiol. Biotechnol.* **2022**, *49*, kuab056. [CrossRef] [PubMed]
15. Ru, J.; Huo, Y.; Yang, Y. Microbial Degradation and Valorization of Plastic Wastes. *Front. Microbiol.* **2020**, *11*, 442. [CrossRef] [PubMed]
16. Abdel Azim, A.; Bellini, R.; Vizzarro, A.; Bassani, I.; Pirri, C.F.; Menin, B. Highlighting the Role of Archaea in Urban Mine Waste Exploitation and Valorisation. *Recycling* **2023**, *8*, 20. [CrossRef]
17. Kurtzman, C.P.; Fell, J.W. Yeast Systematics and Phylogeny—Implications of Molecular Identification Methods for Studies in Ecology. In *Biodiversity and Ecophysiology of Yeasts*; Péter, G., Rosa, C., Eds.; Springer: Berlin/Heidelberg, Germany, 2006; pp. 11–30. [CrossRef]
18. Kurtzman, C.P. Molecular taxonomy of the yeasts. *Yeast* **1994**, *10*, 1727–1740. [CrossRef] [PubMed]
19. Carneiro, C.V.; Serra, L.A.; Pacheco, T.F.; Ferreira, L.M.; Brandão, L.T.; Freitas, M.N.; Trichez, D.; Almeida, J.R. Advances in Komagataella phaffii Engineering for the Production of Renewable Chemicals and Proteins. *Fermentation* **2022**, *8*, 575. [CrossRef]
20. Murphy, L.; Lynch, C.D.; O'Connell, D.J. Valorisation of Spent Yeast Fermentation Media through Compositional-Analysis-Directed Supplementation. *Appl. Microbiol.* **2024**, *4*, 959–971. [CrossRef]
21. Pichia.com. Pichia Produced Products on the Market. Available online: https://pichia.com/science-center/commercialized-products/ (accessed on 30 May 2024).
22. Thuluva, S.; Paradkar, V.; Gunneri, S.; Yerroju, V.; Mogulla, R.; Suneetha, P.V.; Turaga, K.; Kyasani, M.; Manoharan, S.K.; Adabala, S.; et al. Immunogenicity and safety of Biological E's CORBEVAX vaccine compared to COVISHIELD (ChAdOx1 nCoV-19) vaccine studied in a phase-3, single blind, multicentre, randomized clinical trial. *Hum. Vaccin. Immunother.* **2023**, *19*, 2203632. [CrossRef]
23. Van Roy, M.; Ververken, C.; Beirnaert, E.; Hoefman, S.; Kolkman, J.; Vierboom, M.; Breedveld, E.; 't Hart, B.; Poelmans, S.; Bontinck, L.; et al. The preclinical pharmacology of the high affinity anti-IL-6R Nanobody(R) ALX-0061 supports its clinical development in rheumatoid arthritis. *Arthritis Res. Ther.* **2015**, *17*, 135. [CrossRef]
24. Baeshen, N.A.; Baeshen, M.N.; Sheikh, A.; Bora, R.S.; Ahmed, M.M.M.; Ramadan, H.A.I.; Saini, K.S.; Redwan, E.M. Cell factories for insulin production. *Microb. Cell Factories* **2014**, *13*, 141. [CrossRef]
25. Chance, R.E.; Frank, B.H. Research, development, production, and safety of biosynthetic human insulin. *Diabetes Care* **1993**, *16* (Suppl. S3), 133–142. [CrossRef]
26. Nielsen, J. Production of biopharmaceutical proteins by yeast: Advances through metabolic engineering. *Bioengineered* **2013**, *4*, 207–211. [CrossRef]
27. Park, Y.-K.; Nicaud, J.-M.; Ledesma-Amaro, R. The Engineering Potential of *Rhodosporidium toruloides* as a Workhorse for Biotechnological Applications. *Trends Biotechnol.* **2018**, *36*, 304–317. [CrossRef] [PubMed]
28. Flores, C.L.; Gancedo, C. mutants devoid of pyruvate carboxylase activity show an unusual growth phenotype. *Eukaryot. Cell* **2005**, *4*, 356–364. [CrossRef] [PubMed]
29. Bank, E.I. *Wastewater as a Resource*; European Investment Bank: Luxembourg, 2022. [CrossRef]
30. Arous, F.; Azabou, S.; Jaouani, A.; Zouari-Mechichi, H.; Nasri, M.; Mechichi, T. Biosynthesis of single-cell biomass from olive mill wastewater by newly isolated yeasts. *Environ. Sci. Pollut. Res.* **2016**, *23*, 6783–6792. [CrossRef] [PubMed]
31. Hachicha, S.; Chtourou, M.; Medhioub, K.; Ammar, E. Compost of poultry manure and olive mill wastes as an alternative fertilize. *Agron. Sustain. Dev.* **2006**, *26*, 135–142. [CrossRef]
32. Hamimed, S.; Jebli, N.; Sellami, H.; Landoulsi, A.; Chatti, A. Dual Valorization of Olive Mill Wastewater by Bio-Nanosynthesis of Magnesium Oxide and Yarrowia lipolytica Biomass Production. *Chem. Biodivers.* **2020**, *17*, e1900608. [CrossRef]

33. Singh, S.; Bharadwaj, T.; Verma, D.; Dutta, K. Valorization of phenol contaminated wastewater for lipid production by *Rhodosporidium toruloides* 9564T. *Chemosphere* **2022**, *308*, 136269. [CrossRef]
34. D'Annibale, A.; Sermanni, G.G.; Federici, F.; Petruccioli, M. Olive-mill wastewaters: A promising substrate for microbial lipase production. *Bioresour. Technol.* **2006**, *97*, 1828–1833. [CrossRef]
35. Sarris, D.; Rapti, A.; Papafotis, N.; Koutinas, A.A.; Papanikolaou, S. Production of Added-Value Chemical Compounds through Bioconversions of Olive-Mill Wastewaters Blended with Crude Glycerol by a Yarrowia lipolytica Strain. *Molecules* **2019**, *24*, 222. [CrossRef]
36. Otoupal, P.B.; Geiselman, G.M.; Oka, A.M.; Barcelos, C.A.; Choudhary, H.; Dinh, D.; Zhong, W.; Hwang, H.; Keasling, J.D.; Mukhopadhyay, A.; et al. Advanced one-pot deconstruction and valorization of lignocellulosic biomass into triacetic acid lactone using *Rhodosporidium toruloides*. *Microb. Cell Factories* **2022**, *21*, 254. [CrossRef]
37. Bertacchi, S.; Bettiga, M.; Porro, D.; Branduardi, P. Camelina sativa meal hydrolysate as sustainable biomass for the production of carotenoids by *Rhodosporidium toruloides*. *Biotechnol. Biofuels* **2020**, *13*, 47. [CrossRef]
38. Nunta, R.; Techapun, C.; Sommanee, S.; Mahakuntha, C.; Porninta, K.; Punyodom, W.; Phimolsiripol, Y.; Rachtanapun, P.; Wang, W.; Zhuang, X.; et al. Valorization of rice straw, sugarcane bagasse and sweet sorghum bagasse for the production of bioethanol and phenylacetylcarbinol. *Sci. Rep.* **2023**, *13*, 727. [CrossRef] [PubMed]
39. Ye, J.; Tian, S.; Lv, L.; Ding, Y.; Xu, J.; Zhang, J.; Li, L. Production and purification of 2-phenylethanol by *Saccharomyces cerevisiae* using tobacco waste extract as a substrate. *Lett. Appl. Microbiol.* **2021**, *73*, 800–806. [CrossRef] [PubMed]
40. Bzducha-Wróbel, A.; Koczoń, P.; Błażejak, S.; Kozera, J.; Kieliszek, M. Valorization of Deproteinated Potato Juice Water into β-Glucan Preparation of C. utilis Origin: Comparative Study of Preparations Obtained by Two Isolation Methods. *Waste Biomass Valorization* **2020**, *11*, 3257–3271. [CrossRef]
41. Bzducha-Wróbel, A.; Bryła, M.; Gientka, I.; Błażejak, S.; Janowicz, M. Candida utilis ATCC 9950 Cell Walls and β(1,3)/(1,6)-Glucan Preparations Produced Using Agro-Waste as a Mycotoxins Trap. *Toxins* **2019**, *11*, 192. [CrossRef]
42. Luo, Y.; Wang, J.; Liu, B.; Wang, Z.; Yuan, Y.; Yue, T. Effect of Yeast Cell Morphology, Cell Wall Physical Structure and Chemical Composition on Patulin Adsorption. *PLoS ONE* **2015**, *10*, e0136045. [CrossRef]
43. Koutinas, M.; Menelaou, M.; Nicolaou, E.N. Development of a hybrid fermentation–enzymatic bioprocess for the production of ethyl lactate from dairy waste. *Bioresour. Technol.* **2014**, *165*, 343–349. [CrossRef]
44. Parashar, A.; Jin, Y.; Mason, B.; Chae, M.; Bressler, D.C. Incorporation of whey permeate, a dairy effluent, in ethanol fermentation to provide a zero waste solution for the dairy industry. *J. Dairy Sci.* **2016**, *99*, 1859–1867. [CrossRef]
45. Koutinas, A.A.; Papapostolou, H.; Dimitrellou, D.; Kopsahelis, N.; Katechaki, E.; Bekatorou, A.; Bosnea, L.A. Whey valorisation: A complete and novel technology development for dairy industry starter culture production. *Bioresour. Technol.* **2009**, *100*, 3734–3739. [CrossRef]
46. Chua, J.-Y.; Lu, Y.; Liu, S.-Q. Evaluation of five commercial non-Saccharomyces yeasts in fermentation of soy (tofu) whey into an alcoholic beverage. *Food Microbiol.* **2018**, *76*, 533–542. [CrossRef]
47. Al-saned, A.J.O.; Kitafa, B.A.; Badday, A.S. Microbial fuel cells (MFC) in the treatment of dairy wastewater. *IOP Conf. Ser. Mater. Sci. Eng.* **2021**, *1067*, 012073. [CrossRef]
48. Chaiyaso, T.; Manowattana, A.; Techapun, C.; Watanabe, M. Efficient bioconversion of enzymatic corncob hydrolysate into biomass and lipids by oleaginous yeast Rhodosporidium paludigenum KM281510. *Prep. Biochem. Biotechnol.* **2019**, *49*, 545–556. [CrossRef] [PubMed]
49. Hamden, Z.; El-Ghoul, Y.; Alminderej, F.M.; Saleh, S.M.; Majdoub, H. High-Quality Bioethanol and Vinegar Production from Saudi Arabia Dates: Characterization and Evaluation of Their Value and Antioxidant Efficiency. *Antioxidants* **2022**, *11*, 1155. [CrossRef] [PubMed]
50. Han, Z.; Park, A.; Su, W.W. Valorization of papaya fruit waste through low-cost fractionation and microbial conversion of both juice and seed lipids. *RSC Adv.* **2018**, *8*, 27963–27972. [CrossRef] [PubMed]
51. Saini, R.; Chen, C.-W.; Patel, A.K.; Saini, J.K.; Dong, C.-D.; Singhania, R.R. Valorization of Pineapple Leaves Waste for the Production of Bioethanol. *Bioengineering* **2022**, *9*, 557. [CrossRef]
52. González-Sáiz, J.-M.; Esteban-Díez, I.; Rodríguez-Tecedor, S.; Pizarro, C. Valorization of onion waste and by-products: MCR-ALS applied to reveal the compositional profiles of alcoholic fermentations of onion juice monitored by near-infrared spectroscopy. *Biotechnol. Bioeng.* **2008**, *101*, 776–787. [CrossRef]
53. Ntaikou, I.; Menis, N.; Alexandropoulou, M.; Antonopoulou, G.; Lyberatos, G. Valorization of kitchen biowaste for ethanol production via simultaneous saccharification and fermentation using co-cultures of the yeasts *Saccharomyces cerevisiae* and *Pichia stipitis*. *Bioresour. Technol.* **2018**, *263*, 75–83. [CrossRef]
54. Donzella, S.; Serra, I.; Fumagalli, A.; Pellegrino, L.; Mosconi, G.; Lo Scalzo, R.; Compagno, C. Recycling industrial food wastes for lipid production by oleaginous yeasts Rhodosporidiobolus azoricus and Cutaneotrichosporon oleaginosum. *Biotechnol. Biofuels Bioprod.* **2022**, *15*, 51. [CrossRef]
55. Chatterjee, S.; Venkata Mohan, S. Refining of vegetable waste to renewable sugars for ethanol production: Depolymerization andfermentation optimization. *Bioresour. Technol.* **2021**, *340*, 125650. [CrossRef]
56. Bertacchi, S.; Pagliari, S.; Cantù, C.; Bruni, I.; Labra, M.; Branduardi, P. Enzymatic Hydrolysate of Cinnamon Waste Material as Feedstock for the Microbial Production of Carotenoids. *Int. J. Environ. Res. Public Health* **2021**, *18*, 1146. [CrossRef]

57. Darvishi, F.; Moradi, M.; Madzak, C.; Jolivalt, C. Production of Laccase by Recombinant Yarrowia lipolytica from Molasses: Bioprocess Development Using Statistical Modeling and Increase Productivity in Shake-Flask and Bioreactor Cultures. *Appl. Biochem. Biotechnol.* **2017**, *181*, 1228–1239. [CrossRef]
58. Fraga, J.L.; Souza, C.P.L.; Pereira, A.d.S.; Aguieiras, E.C.G.; de Silva, L.O.; Torres, A.G.; Freire, D.G.; Amaral, P.F.F. Palm oil wastes as feedstock for lipase production by Yarrowia lipolytica and biocatalyst application/reuse. *3 Biotech.* **2021**, *11*, 191. [CrossRef] [PubMed]
59. Fernandes, M.C.; Torrado, I.; Carvalheiro, F.; Dores, V.; Guerra, V.; Lourenço, P.M.L.; Duarte, L.C. Bioethanol production from extracted olive pomace: Dilute acid hydrolysis. *Bioethanol* **2016**, *2*, 103–111. [CrossRef]
60. Pedras, B.M.; Gonçalves, C.; Figueira, D.R.; Simões, P.; Gonçalves, P.; Paiva, A.; Barreiros, S.; Salema-Oom, M. White wine grape pomace as a suitable carbon source for lipid and carotenoid production by fructophilic Rhodorotula babjevae. *J. Appl. Microbiol.* **2022**, *133*, 656–664. [CrossRef] [PubMed]
61. Putra, F.J.; Kahar, P.; Kondo, A.; Ogino, C. Valorization of Lignin and Its Derivatives Using Yeast. *Processes* **2022**, *10*, 2004. [CrossRef]
62. Nguyen, L.T.; Phan, D.-P.; Sarwar, A.; Tran, M.H.; Lee, O.K.; Lee, E.Y. Valorization of industrial lignin to value-added chemicals by chemical depolymerization and biological conversion. *Ind. Crops Prod.* **2021**, *161*, 113219. [CrossRef]
63. Martínez-Cámara, S.; Ibañez, A.; Rubio, S.; Barreiro, C.; Barredo, J.-L. Main Carotenoids Produced by Microorganisms. *Encyclopedia* **2021**, *1*, 1223–1245. [CrossRef]
64. Abdeshahian, P.; Ascencio, J.J.; Philippini, R.R.; Antunes, F.A.F.; de Carvalho, A.S.; Abdeshahian, M.; dos Santos, J.C.; da Silva, S.S. Valorization of Lignocellulosic Biomass and Agri-food Processing Wastes for Production of Glucan Polymer. *Waste Biomass Valorization* **2021**, *12*, 2915–2931. [CrossRef]
65. Driscoll, M.; Hansen, R.; Ding, C.; Cramer, D.; Yan, J. Therapeutic potential of various β-glucan sources in conjunction with anti-tumor monoclonal antibody in cancer therapy. *Cancer Biol. Ther.* **2009**, *8*, 218–225. [CrossRef]
66. Tsakona, S.; Skiadaresis, A.G.; Kopsahelis, N.; Chatzifragkou, A.; Papanikolaou, S.; Kookos, I.K.; Koutinas, A.A. Valorisation of side streams from wheat milling and confectionery industries for consolidated production and extraction of microbial lipids. *Food Chem.* **2016**, *198*, 85–92. [CrossRef]
67. Pereyra, C.M.; Gil, S.; Cristofolini, A.; Bonci, M.; Makita, M.; Monge, M.P.; Montenegro, M.A.; Cavaglieri, L.R. The production of yeast cell wall using an agroindustrial waste influences the wall thickness and is implicated on the aflatoxin B1 adsorption process. *Food Res. Int.* **2018**, *111*, 306–313. [CrossRef]
68. Bhat, R.; Di Pasquale, J.; Bánkuti, F.I.; Siqueira, T.T.; Shine, P.; Murphy, M.D. Global Dairy Sector: Trends, Prospects, and Challenges. *Sustainability* **2022**, *14*, 4193. [CrossRef]
69. Usmani, Z.; Sharma, M.; Gaffey, J.; Sharma, M.; Dewhurst, R.J.; Moreau, B.; Newbold, J.; Clark, W.; Thakur, V.K.; Gupta, V.K. Valorization of dairy waste and by-products through microbial bioprocesses. *Bioresour. Technol.* **2022**, *346*, 126444. [CrossRef]
70. Madureira, A.R.; Pereira, C.I.; Gomes, A.M.P.; Pintado, M.E.; Malcata, F.X. Bovine whey proteins—Overview on their main biological properties. *Food Res. Int.* **2007**, *40*, 1197–1211. [CrossRef]
71. Pintado, M.E.; Macedo, A.C.; Malcata, F.X. Review: Technology, Chemistry and Microbiology of Whey Cheeses. *Food Sci. Technol. Int.* **2001**, *7*, 105–116. [CrossRef]
72. Lawton, M.R.; deRiancho, D.L.; Alcaine, S.D. Lactose utilization by Brettanomyces claussenii expands potential for valorization of dairy by-products to functional beverages through fermentation. *Curr. Opin. Food Sci.* **2021**, *42*, 93–101. [CrossRef]
73. Reynolds, C.; Goucher, L.; Quested, T.; Bromley, S.; Gillick, S.; Wells, V.K.; Evans, D.; Koh, L.; Carlsson Kanyama, A.; Katzeff, C.; et al. Review: Consumption-stage food waste reduction interventions—What works and how to design better interventions. *Food Policy* **2019**, *83*, 7–27. [CrossRef]
74. Farhidi, F.; Madani, K.; Crichton, R. How the US Economy and Environment can Both Benefit From Composting Management. *Environ. Health Insights* **2022**, *16*, 11786302221128454. [CrossRef]
75. Garcia-Garcia, G.; Woolley, E.; Rahimifard, S. Optimising Industrial Food Waste Management. *Procedia Manuf.* **2017**, *8*, 432–439. [CrossRef]
76. OuYang, Q.; Duan, X.; Li, L.; Tao, N. Cinnamaldehyde Exerts Its Antifungal Activity by Disrupting the Cell Wall Integrity of Geotrichum citri-aurantii. *Front. Microbiol.* **2019**, *10*, 55. [CrossRef]
77. Lopes, M.; Miranda, S.M.; Belo, I. Microbial valorization of waste cooking oils for valuable compounds production—A review. *Crit. Rev. Environ. Sci. Technol.* **2020**, *50*, 2583–2616. [CrossRef]
78. Félix, S.; Araújo, J.; Pires, A.M.; Sousa, A.C. Soap production: A green prospective. *Waste Manag.* **2017**, *66*, 190–195. [CrossRef] [PubMed]
79. Suzuki, A.H.; Botelho, B.G.; Oliveira, L.S.; Franca, A.S. Sustainable synthesis of epoxidized waste cooking oil and its application as a plasticizer for polyvinyl chloride films. *Eur. Polym. J.* **2018**, *99*, 142–149. [CrossRef]
80. Mateo, J.J.; Maicas, S. Valorization of winery and oil mill wastes by microbial technologies. *Food Res. Int.* **2015**, *73*, 13–25. [CrossRef]
81. Iorizzo, M.; Coppola, F.; Letizia, F.; Testa, B.; Sorrentino, E. Role of Yeasts in the Brewing Process: Tradition and Innovation. *Processes* **2021**, *9*, 839. [CrossRef]
82. Jaeger, A.; Arendt, E.K.; Zannini, E.; Sahin, A.W. Brewer's Spent Yeast (BSY), an Underutilized Brewing By-Product. *Fermentation* **2020**, *6*, 123. [CrossRef]

83. Oliveira, A.S.; Pereira, J.O.; Ferreira, C.; Faustino, M.; Durão, J.; Pintado, M.E.; Carvalho, A.P. Peptide-rich extracts from spent yeast waste streams as a source of bioactive compounds for the nutraceutical market. *Innov. Food Sci. Emerg. Technol.* **2022**, *81*, 103148. [CrossRef]
84. Feldmann, H. Yeast Cell Architecture and Functions. In *Yeast: Molecular and Cell Biology*; Wiley-VCH: Weinheim, Germany, 2012; pp. 5–24. [CrossRef]
85. Gautério, G.V.; Silvério, S.I.D.C.; Egea, M.B.; Lemes, A.C. β-glucan from brewer's spent yeast as a techno-functional food ingredient. *Front. Food Sci. Technol.* **2022**, *2*, 1074505. [CrossRef]
86. Yang, W.; Huang, G. Extraction methods and activities of natural glucans. *Trends Food Sci. Technol.* **2021**, *112*, 50–57. [CrossRef]
87. Krpan, V.; Vlatka, P.-T.; Krbavčić, I.; Slobodan, G.; Katarina, B. Potential Application of Yeast β-Glucans in Food Industry. *Agric. Conspec. Sci.* **2009**, *74*, 277–282.
88. Bacha, U.; Nasir, M.A.-O.; Iqbal, S.; Anjum, A.A. Nutraceutical, Anti-Inflammatory, and Immune Modulatory Effects of β-Glucan Isolated from Yeast. *Biomed. Res. Int.* **2017**, *2017*, 8972678. [CrossRef]
89. Varelas, V.; Tataridis, P.; Liouni, M.; Nerantzis, E.T. Valorization of Winery Spent Yeast Waste Biomass as a New Source for the Production of β-Glucan. *Waste Biomass Valorization* **2016**, *7*, 807–817. [CrossRef]
90. Pérez-Serradilla, J.A.; de Castro, M.D.L. Role of lees in wine production: A review. *Food Chem.* **2008**, *111*, 447–456. [CrossRef] [PubMed]
91. Sudagar, A.J.; Rangam, N.V.; Ruszczak, A.; Borowicz, P.; Tóth, J.; Kövér, L.; Michałowska, D.; Roszko, M.Ł.; Noworyta, K.R.; Lesiak, B. Valorization of Brewery Wastes for the Synthesis of Silver Nanocomposites Containing Orthophosphate. *Nanomaterials* **2021**, *11*, 2659. [CrossRef]
92. Modesto, H.R.; Lemos, S.G.; dos Santos, M.S.; Komatsu, J.S.; Gonçalves, M.; Carvalho, W.A.; Carrilho, E.N.V.M.; Labuto, G. Activated carbon production from industrial yeast residue to boost up circular bioeconomy. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24694–24705. [CrossRef]
93. Costa, E.M.; Oliveira, A.S.; Silva, S.; Ribeiro, A.B.; Pereira, C.F.; Ferreira, C.; Casanova, F.; Pereira, J.O.; Freixo, R.; Pintado, M.E.; et al. Spent Yeast Waste Streams as a Sustainable Source of Bioactive Peptides for Skin Applications. *Int. J. Mol. Sci.* **2023**, *24*, 2253. [CrossRef] [PubMed]
94. Patel, A.; Mikes, F.; Buhler, S.; Matsakas, L. Valorization of Brewers' Spent Grain for the Production of Lipids by Oleaginous Yeast. *Molecules* **2018**, *23*, 3052. [CrossRef]
95. Soh, E.Y.S.; Lim, S.S.; Chew, K.W.; Phuang, X.W.; Ho, V.M.V.; Chu, K.Y.H.; Wong, R.R.; Lee, L.Y.; Tiong, T.J. Valorization of spent brewery yeast biosorbent with sonication-assisted adsorption for dye removal in wastewater treatment. *Environ. Res.* **2022**, *204*, 112385. [CrossRef]
96. Kavalopoulos, M.; Stoumpou, V.; Christofi, A.; Mai, S.; Barampouti, E.M.; Moustakas, K.; Malamis, D.; Loizidou, M. Sustainable valorisation pathways mitigating environmental pollution from brewers' spent grains. *Environ. Pollut.* **2021**, *270*, 116069. [CrossRef] [PubMed]
97. Pinheiro, T.; Coelho, E.; Romaní, A.; Domingues, L. Intensifying ethanol production from brewer's spent grain waste: Use of whole slurry at high solid loadings. *New Biotechnol.* **2019**, *53*, 1–8. [CrossRef]
98. Jiang, Y.; Wang, R.; Yin, Z.; Sun, J.; Wang, B.; Zhao, D.; Zeng, X.A.; Li, H.; Huang, M.; Sun, B. Optimization of Jiuzao protein hydrolysis conditions and antioxidant activity in vivo of Jiuzao tetrapeptide Asp-Arg-Glu-Leu by elevating the Nrf2/Keap1-p38/PI3K-MafK signaling pathway. *Food Funct.* **2021**, *12*, 4808–4824. [CrossRef]
99. Xu, X.; Feng, W.; Guo, L.; Huang, X.; Shi, B. Controlled synthesis of distiller's grains biochar for turbidity removal in Baijiu. *Sci. Total Environ.* **2023**, *867*, 161382. [CrossRef] [PubMed]
100. Chequer, F.D.; de Oliveira, G.A.R.; Ferraz, E.A.; Cardoso, J.C.; Zanoni, M.B.; de Oliveira, D.P. Textile Dyes: Dyeing Process and Environmental Impact. In *Eco-Friendly Textile Dyeing and Finishing*; Melih, G., Ed.; IntechOpen: Rijeka, Croatia, 2013.
101. Stewart, K.; Willoughby, N.; Zhuang, S. Research Trends on Valorisation of Agricultural Waste Discharged from Production of Distilled Beverages and Their Implications for a "Three-Level Valorisation System". *Sustainability* **2024**, *16*, 6847. [CrossRef]
102. Yan, C.; Zhang, Q.; Wang, J.; Chang, X.; Yao, L.; Chen, X.; Li, X. Characteristics of four yeasts and the effects of yeast diversity on the fermentation of baijiu. *Food Biosci.* **2023**, *56*, 103094. [CrossRef]
103. Khedulkar, A.P.; Dang, V.D.; Thamilselvan, A.; Doong, R.-a.; Pandit, B. Sustainable high-energy supercapacitors: Metal oxide-agricultural waste biochar composites paving the way for a greener future. *J. Energy Storage* **2024**, *77*, 109723. [CrossRef]
104. Morone, P.; Imbert, E. Food waste and social acceptance of a circular bioeconomy: The role of stakeholders. *Curr. Opin. Green. Sustain. Chem.* **2020**, *23*, 55–60. [CrossRef]
105. Pender, A.; Kelleher, L.; O'Neill, E. Regulation of the bioeconomy: Barriers, drivers and potential for innovation in the case of Ireland. *Clean. Circ. Bioeconomy* **2024**, *7*, 100070. [CrossRef]
106. Mak, T.M.W.; Xiong, X.; Tsang, D.C.W.; Yu, I.K.M.; Poon, C.S. Sustainable food waste management towards circular bioeconomy: Policy review, limitations and opportunities. *Bioresour. Technol.* **2020**, *297*, 122497. [CrossRef]
107. Lin, C.S.K.; Pfaltzgraff, L.A.; Herrero-Davila, L.; Mubofu, E.B.; Abderrahim, S.; Clark, J.H.; Koutinas, A.A.; Kopsahelis, N.; Stamatelatou, K.; Dickson, F.; et al. Food waste as a valuable resource for the production of chemicals, materials and fuels. Current situation and global perspective. *Energy Environ. Sci.* **2013**, *6*, 426–464. [CrossRef]

108. Fertahi, S.; Elalami, D.; Tayibi, S.; Taarji, N.; Lyamlouli, K.; Bargaz, A.; Oukarroum, A.; Zeroual, Y.; El Bouhssini, M.; Barakat, A. The current status and challenges of biomass biorefineries in Africa: A critical review and future perspectives for bioeconomy development. *Sci. Total Environ.* **2023**, *870*, 162001. [CrossRef]
109. FAOSTAT Crop Residues Statistics. Food and Agriculture Organization of the United Nations. Available online: https://www.fao.org/faostat/en/#data/GT (accessed on 10 November 2024).
110. Negi, S.; Hu, A.; Kumar, S. 24—Circular Bioeconomy: Countries' Case Studies. In *Biomass, Biofuels, Biochemicals*; Pandey, A., Tyagi, R.D., Varjani, S., Eds.; Elsevier: Amsterdam, The Netherlands, 2021; pp. 721–748. [CrossRef]
111. Deselnicu, D.; Militaru, G.; Deselnicu, V.; ZĂInescu, G.; Albu, L. Towards a Circular Economy—A Zero Waste Programme for Europe. In Proceedings of the ICAMS 2018—7th International Conference on Advanced Materials and Systems, Bucharest, Romania, 18–20 October 2018; pp. 563–568. [CrossRef]
112. Kardung, M.; Drabik, D. Full speed ahead or floating around? Dynamics of selected circular bioeconomies in Europe. *Ecol. Econ.* **2021**, *188*, 107146. [CrossRef]
113. Salvador, R.; Pereira, R.B.; Sales, G.F.; de Oliveira, V.C.V.; Halog, A.; De Francisco, A.C. Current Panorama, Practice Gaps, and Recommendations to Accelerate the Transition to a Circular Bioeconomy in Latin America and the Caribbean. *Circ. Econ. Sustain.* **2022**, *2*, 281–312. [CrossRef]
114. Agrawal, D.; Awani, K.; Nabavi, S.A.; Balan, V.; Jin, M.; Aminabhavi, T.M.; Dubey, K.K.; Kumar, V. Carbon emissions and decarbonisation: The role and relevance of fermentation industry in chemical sector. *Chem. Eng. J.* **2023**, *475*, 146308. [CrossRef]
115. Siddiqui, S.A.; Erol, Z.; Rugji, J.; Taşçı, F.; Kahraman, H.A.; Toppi, V.; Musa, L.; Di Giacinto, G.; Bahmid, N.A.; Mehdizadeh, M.; et al. An overview of fermentation in the food industry—Looking back from a new perspective. *Bioresour. Bioprocess.* **2023**, *10*, 85. [CrossRef] [PubMed]
116. Sarkale, P.S.; Ghewari, P.G.; Sarkale, P.S. Emerging Trends in Fermentation Technology: Implications for Food Security and Environmental Sustainability. *Nat. Camp.* **2024**, *28*, 252–260.