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Review

Production of Value-Added Products as Food Ingredients via Microbial Fermentation

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Abstract: Humankind has been unknowingly utilizing food fermentations since the first creation of bread, cheese, and other basic foods. Since the beginning of the last century, microbial fermentation has been extensively utilized for production of commodity chemicals. It has also gained substantial interest in recent decades due to its underlying applications in the preparation of natural and safe food ingredients including enzymes, antimicrobial agents, vitamins, organic acids, sweeteners, stabilizers, emulsifiers, oligosaccharides, amino acids, and thickening agents. In addition, some novel food ingredients that were conventionally made from some other sources such as plant tissue cultures or animals are now being introduced in the industry as 'fermentation products.' Some examples of such novel fermentation food ingredients include flavonoids, cultured meat products, food colorants, antioxidants, lipids, and fatty acids. This review summarizes some of the most prominent food ingredients and novel fermentation food products currently being produced via microbial fermentation as well as the strategies to enhance such fermentation processes. Additionally, economical feedstocks are discussed with their potential to be converted into value-added products with the help of microbial fermentations.

Keywords: enzymes; food ingredients; microbial fermentation; value-added products; vitamins

Citation: Iram, A.; Ozcan, A.; Turhan, I.; Demirci, A. Production of Value-Added Products as Food Ingredients via Microbial Fermentation. *Processes* **2023**, *11*, 1715. https://doi.org/10.3390/pr11061715

Academic Editor: Francesca Raganati

Received: 3 May 2023
Revised: 26 May 2023
Accepted: 31 May 2023
Published: 3 June 2023

1. Introduction

Fermentation is used for foods to provide flavor, preservation, enriching, and improving textural quality by humans over thousands of years. Although it has appeared as a production method of fermented foods, fermentation has also become an important process for the food industry with the development of bioprocess technologies and biotechnology. Furthermore, consumers worry about unsafe chemical food additives, and they tend to consume natural foods or natural additives as far as possible. Therefore, natural food ingredients, obtained by fermentation processes, are becoming preferable option [1].

Food ingredients, which are produced by fermentation such as enzymes, sweeteners, vitamins, organic acids, stabilizers, thickening agents, and amino acids, interest many manufacturers and researchers for the improvement of food quality. In addition, another of the main reasons to produce these ingredients by fermentation is to reduce costs and improve sustainability. For example, enzymes are widely used in different processes in the food industry, such as cheesemaking, baking, brewing, etc. Moreover, the market size of the enzyme industry reached more than USD 6.1 billion annually [2]. Industrial-scale fermentation processes have become increasingly important to meet the growing demand for enzymes. Similarly, microbial fermentation processes are essential to increase the production of valuable organic acids, especially lactic acid and citric acid. On the other hand, some ingredients, such as vitamins, can be produced by the chemical process, which can cause toxic impact for environment. However, microbial fermentation could be an environmentally friendly alternative to the traditional production of vitamins by means

of green "cell factories" [3]. Moreover, due to the preference for microbial fermentation, different types of wastes, such as agricultural and food wastes, can be evaluated in the production of food ingredients. Therefore, improvement in the fermentation process can contribute to overcoming many environmental problems.

However, there are some challenges for the production of these ingredients including high production costs, increasing energy consumption, low productivity, and sustainability of feedstocks. There is extensive research in the literature to overcome these challenges to the production of value-added food products by improving fermentation strategies. Various ingredients are basically produced by submerged batch fermentation. Nevertheless, fed-batch or continuous fermentation modes are frequently used by researchers to enhance production yield [4]. On the other hand, solid-state fermentation can be preferred to produce some food ingredients, especially those obtained from fungi. This can be explained by features of solid-state fermentation such as low-energy requirement, less wastewater generation, and environment friendliness [5]. In addition, regardless of submerged or solid-state fermentation, studies about optimization of fermentation conditions should be carried out to improve efficiency [6]. Other strategies studied by researchers include various approaches related to microorganisms. The most used microorganisms in food industry can be mentioned as *Aspergillus*, *Penicillum*, *Kluyveromyces*, *Rhizopus*, etc. (fungi); *Saccharomyces*, *Pichia*, *Candida*, *Yarrowia*, etc. (yeast); *Lactobacillus*, *Bacillus*, recombinant *Escherichia coli*, etc. (bacteria) (Table 1). Although food ingredients can be produced by almost of all type of microorganisms, some studies, such as the utilization of genetically engineered microorganisms [7], co-cultured processes [8], and cultivation with newly isolated microorganisms [9], may be required.

Table 1. Microbial products as value-added food ingredients.

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
Enzymes	Proteases	*Bacillus subtilis* B22	Submerged	334 ± 1.8 U/mL	40 °C with pH: 8 and Agricultural waste materials	[10]
	Proteases	*Rhodotorula mucilaginosa* CBMAI 1528	Submerged	280 ± 1.7 U/mL	20 °C and a culture medium containing both glucose and casein peptone (20 and 10 g/L, respectively)	[11]
	Proteases	*Geobacillus thermoglucosidasius* SKF4	Submerged	175 U/mL	60 to 65 °C, pH 7 to 8, >1% NaCl with casein and yeast extract	[12]
	Proteases	*Aspergillus sydowii* URM5774	Submerged	352.0 U/mL	pH 8.0 at 45 °C with coffee ground residues	[13]
	Proteases	*Bacillus mojavensis*	Submerged	78.7%	pH 9.08, temperature 39.74 °C with eggshells and membrane-based substrates	[14]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
	Lipase	*A. niger*	Submerged	1.55 U/mL	soluble starch 4%, $(NH_4)_2SO_4$ 0.1%, K_2HPO_4 0.1%, $MgSO_4 \cdot 7H_2O$ 0.05%, peptone 3%, olive oil 1.05%. pH 7. Temperature 30 °C, agitation 213 rpm	[15]
	Lipase	*Penicillium fellutanum*	Submerged	1038.86 U/gds	pH 5.0, incubation time 24 h, temperature 35 °C	[16]
	Glucoamylase	*Aspergillus niger van Tieghem*	Submerged	274.4 U/mL	51.82 g L^{-1} malt extract, 9.27 g L^{-1} $CaCl_2 \cdot 2H_2O$ and 0.50 g L^{-1} $FeSO_4.7H_2O$ 30 °C and 150 rpm	[17]
	α-amylase	*Aspergillus oryzae*	Solid-State	10,994.74 U/gds	edible oil cakes, temperature of 32.5 °C, pH of 4.5, moisture content of 64%	[18]
	Cellulase	*A. niger* (NRRL 330)	Submerged	0.54 ± 0.02 IU/mL	pH: 5, Temperature: 30 °C, Peptone: 5 g/L, Yeast extract: 16.5 g/L and Ammonium sulfate: 1.9 g/L	[19]
	Hemicellulase	*A. niger* (NRRL 330)	Submerged	48.71 ± 2.05 IU/mL	pH: 5, Temperature: 30 °C, Peptone: 5 g/L, Yeast extract: 16.5 g/L and Ammonium sulfate: 1.9 g/L	[19]
Antimicrobials	Nisin	*Lactococcus lactis*	Submerged	523.5 ± 256.7 IU/mL	D-glucose (80 g/L), peptone (10 g/L), YE (10 g/L), KH_2PO_4 (10 g/L), NaCl (2 g/L), and $MgSO_4 \cdot 7H_2O$ (0.2 g/L), at 32 °C	[20]
	lysozyme	*Kluyveromyces lactis* K7	Submerged	141 U/mL	25 °C, pH 4, no aeration	[21]
	lysozyme	*Kluyveromyces lactis* K7	Submerged	173 U/mL	16.3% lactose, 1.2% casamino acid, 0.8% yeast nitrogen, no pH control, 25 °C, 150 rpm, and no aeration	[22]
	lysozyme	*Pichia pastoris* GS115	Submerged	14,680 ± 300 U/mL	28 °C Temperature, 250 rpm agitation	[23]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
Vitamins	Vitamin B12	*Propionibacterium freudenreichii* DSM 20271 and *Levilactobacillus brevis*	Submerged	742 ng/g dw	200 rpm at 25 °C	[24]
	Vitamin K	*Bacillus subtilis* natto	Submerged	12.09 mg/L	temperature (35 °C), agitation (200 rpm) and pH (6.58)	[25]
	Vitamin K	*Bacillus subtilis* natto (NF1)	Submerged	28.7 ± 0.3 mg/L	aeration (1 vvm), agitation (200 rpm for glycerol and 234 rpm for glucose), pH (6.48 for glucose and 6.6 for glycerol), and temperatures (30 °C for glucose and 35 °C for glycerol)	[26]
Organic acids	Lactic acid	*Lactobacillus casei*	Submerged	59.27 g/L	yeast extract was 31.35 (g/L)	[27]
	Lactic acid	*Lactobacillus plantarum* 23	Submerged	14.2 g/L/h	pH 5.0 and 200 rpm agitation	[28]
	Propionic acid	Mixed bacterial culture	Submerged	26.5 g/L	pH 6, 30 °C	[29]
Sweeteners	Arabitol	*Candida parapsilosis* SK26.002 Mutant A6	Submerged	32.92 g/L	30 °C, pH: 4.0, 4% initial inoculum and 200 rpm in shake flask with medium containing 200 g/L glucose and 30 g/L yeast extract	[30]
	Arabitol	*Yarrowia lipolytica* ARA9	Submerged	118.5 g/L	30 °C, pH: 5.0, 600 rpm agitation speed and 1.0 vvm aeration rate. Medium containing 200 g/L crude glycerol, 3.7 g/L $(NH_4)_2SO_4$ and 2 g/L yeast extract	[31]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
	Erythritol	*Yarrowia lipolytica* M53-S	solid state fermentation	190.5 mg/gds	30 °C, 70% initial moisture content, pH: 4.0, 7.5×10^4 cells/gds inoculum size and supplemented with 0.02 g/gds NaCl. Medium containing 60% peanut press cake and 40% sesame meal supplemented with 4% biochar and 20% concentrated enzymatic hydrolysate of the defatted Schizochytrium residue	[32]
	Erythritol	*Moniliella pollinis* MUCL 40570	Submerged	106.40 ± 0.42 g/L	30 °C, pH: 5.5, 3% (*v*/*v*) initial inoculum and 200 rpm in shake flask. Sugarcane molasses media: 300 g/L total sugar conc. and 5 g/L yeast extract. Beet molasses media: 200 g/L total sugar and 0.67 g/L yeast extract. Grape musts media: 200 g/L total sugar and 6.7 g/L yeast extract.	[33]
	Erythritol	*Moniliella pollinis* CBS 461.67	Submerged Fed-Batch	94 g/L	30 °C, inital pH: 6.5–6.8 (not controlled during fermentation), 150 rpm agitation speed and 1.0 vvm aeration rate. Sugarcane juice medium: 175 g/L total sugar and 1.63 g/L Moniliella culture lysate. Molasses medium: 219.8 g/L total sugar and 1.63 g/L Moniliella culture lysate	[34]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
	Mannitol	*Leuconostoc citreum* TR116	Submerged	61.6 g/L	30 °C, inital pH: 6.5, 1.0% (*v*/*v*) initial inoculum and 120 rpm agitation speed. MRS5 medium containing 100.0 g/L fructose and 50.0 g/L glucose. Apple juice medium supplemented with 2.0 g/L yeast extract	[35]
	Mannitol	*Lactobacillus intermedius* NRRL B-3693	Submerged	80 g/L	37 °C, inital pH: 6.0 and 100 rpm agitation speed. Red must medium containing 155.3 g/L sugar, 7.48 g/L yeast extract and 0.047 g/L $MnSO_4 \cdot H_2O$ and white must medium containing 175.7 g/L sugar, 7.54 g/L yeast extract and 0.088 g/L $MnSO_4 \cdot H_2O$	[36]
Oligosaccharides	Fructooligo-sagharides	*Aspergillus oryzae* DIA–MF	Solid state fermentation	7.64 g/L	30 °C, pH: 4.5, 70% initial moisture content and 2.0×10^7 spores/g substrat inoculum size. Different fermentation medium including sugarcane bagasse, coffee husk, pineapple peel, prickle pear peel and banana peel waste supplemented with aguamiel	[37]
	Fructooligo-sagharides	*Bacillus aryabhattai* GYC2-3	Submerged	26 g/L	30 °C, pH: 8.0, 5% (*v*/*v*) inoculum containing 1×10^6 CFU/mL and 150 rpm in shake flask with medium containing 250 g/L sucrose	[38]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
	Fructooligo-sagharides	*Mutant strain of Aspergillus oryzae* S719 (overexpressed FTase genes)	Submerged	586 ± 4.7 g/L	50 °C, pH: 6.0, 160 rpm agitation speed and 1.0 g/L mycelium as inoculum. Medium containing 900 g/L sucrose	[39]
	Mannooligo-sagharide	*recombinant Aspergillus sojae* AsT3	solid state fermentation	983.53 U/mg	30 °C, pH: 7.0, 1:3 (*w*/*v*) solid-to-liquid ratiot and 7.0% inoculum size. Different fermentation medium including 5 g of wheat bran, rye bran, oat husk, barley husk supplemented with 4 g/L yeast extract	[5]
Polysaccharides	Glucan	*Lasiodiplodia theobromae* CCT 3966	Submerged	0.047 g/g	28 °C, pH: 7.0, 105 CFU/m inoculum and 200 rpm in shake flask. Fermentation medium including Sugarcane straw hydrolysate (40 g/L glucose concentration)	[40]
	Glucan	*Candida utilis* ATCC 9950	Submerged	82%	28 °C, 10.0% (*v*/*v*) inoculum, 200 rev/min agitation and 2.5 vvm aeration. Medium containing Deproteinated Potato Juice Water (pH 5.0 ± 0.2) supplemented with 10% of glycerol	[41]
	Glucan	*Lasiodiplodia theobromae* MMPI	Submerged	1.06 g/L	28 °C, pH: 5.5, 10.0 mL inoculum and 150 rpm in shake flask. Medium including soybean molasses (20 g/L total sugar)	[42]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
	Glucan	*T-DNA* − based mutant *Aureobasidium pullulans* CGMCC 19650	Submerged	78.6%	30 °C, pH: 3.8, 10.0% (*v*/*v*) inoculum, 400 rpm agitation speed and 1.0 vvm aeration rate. Medium containing 50 g/L glucose, 3.0 g/L yeast extract	[43]
	Pullulan	*Aureobasidium pullulans* MTCC 2013	Submerged	24.77 ± 1.06 g/L	28 °C, pH: 6.5, 5.0% of 1×10^8 cells inoculum and 150 rpm in shake flask. Medium including hydrolyzed kitchen waste supplemented with 0.25% peptone and yeast extract	[44]
	Pullulan	*Aureobasidium pullulans* CCTCC M 2012259	Submerged	50 g/L	30 °C, pH: 3.8, 10.0% (*v*/*v*) inoculum, 400 rpm agitation speed and 1.0 vvm aeration rate. M1 containing 51.59 g/L cassava starch and 4.40 g/L corn steep liquor powder. M2 containing 51.75 g/L cassava starch and 9.47 mL/L soybean meal hydrolysate	[45]
	Pullulan	*Aerobasidiom pullulans* KY 767024	Submerged	19.45 ± 0.40 g/L	28 °C, pH: 5.5, 10.0% inoculum in shake flask. Medium including corn bran hydrolysates 20% (*w*/*v*) yeast extract 0.2% (*w*/*v*)	[46]
	Pullulan	*Aureobasidium pullulans* FB-1	Submerged	4.8%, *w*/*v*	30 °C, pH: 6.5 5.0% (*v*/*v*) inoculum, 300 rpm agitation and 0.75 vvm aeration. Medium containing 50 g/L sucrose, 2.0 g/L yeast extract	[47]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
Amino Acids	Glutamic acid	*Corynebacterium glutamicum* NCIM 2168	Submerged	16.49 g/L	30 °C, 5.0% (*v*/*v*) inoculum and 200 rpm in shake flask. Medium containing 50 g/L glucose, 10 g/L urea and 19.24% of salt solution	[48]
	Glutamic acid	*Corynebacterium glutamicum* PTCC 1532	Submerged	19.84 mg/mL	30 °C, pH: 7.0, 10 mL of the overnight culture inoculum, 180 rpm in shake flask. Medium containing 90 g/L glucose, 9 µg/L biotin and 3 g/L urea	[49]
	methionine	Genetically engineered *Escherichia coli* W3110-BL	Submerged	1.48 g/L	37 °C, 5.0% (*v*/*v*) inoculum, 1.4 vvm aeration rate and agitation controlled DO 20%. Medium containing 120 g/L glucose, 50 mg/L L-lysine, 100 mg/mL Amp, and 0.1 mmol/L isopropyl b-d-1-thiogalactopyranoside	[7]
	methionine	Recombinant *Escherichia coli*	Submerged (Fed-Batch)	3.22 g/L	30 °C, pH: 7.0, 10 mL of the overnight culture inoculum, 180 rpm in shake flask. Medium containing 20 g/L glucose, 2 g/L yeast extract, 0.01 g/L L-lysine and 1.0 mL/L salt solutiın	[50]
	tryptophan	Genetically engineered *Escherichia coli* TS-10	Submerged	1.710 g/L	Tryptophan fermentation was carried out in shake flask with lysogeny broth medium for 48 h	[51]

Table 1. *Cont.*

Category	Product	Microorganisms	Fermentation Mode	Productivity	Fermentation Conditions	Refs.
	tryptophan	*Pediococcus acidilactici* TP-6	Submerged	68.05 mg/L	30 °C, 10.0% (*v*/*v*) inoculum in shake flask. Medium containing 14.06 g/L molasses, 23.68 g/L meat extract, 5.56 g/L urea 0.024 g/L and $FeSO_4$	[52]
	tryptophan	Genetically modified *Escherichia coli* CCTCC M20211388	Submerged	52.1 g/L	35 °C, pH: 7.0, 20 mL (OD600: 1.0) inoculum, aeration rate and agitation controlled DO 20–30%. Medium containing 20 g/L glucose, 1 g/L yeast extract and 2 g/L sodium citrate	[53]
	Lysine	Metanolic engineered *C. glutamicum*	Submerged (Fed-Batch)	221.3 ± 17.6 g/L	fermentation was carried out in bioreactor with 10% (*v*/*v*) inoculum. Medium containing 80 g/L glucose, 40 g/L beet	[54]

This review focusses on the production of food ingredients produced via microbial fermentations by utilizing novel approaches as well as low-cost feedstocks. Furthermore, the utilized microbial strains, fermentation conditions, alternative substrates, and the properties of each ingredient were also discussed.

2. Food Ingredients as the Fermentation Products

Food ingredients are significant factors for human health and lifestyle and could be produced through different ways. Fermentation is one of production methods, and it has some advantages such as sustainability, flexibility, and productivity. Therefore, using fermentation to produce food ingredients has become a significant option for researchers and manufacturers. In this section of review, critical points of fermentative production of food ingredients are summarized.

2.1. Enzymes

Enzymes are the biological catalysts that can accelerate the corresponding reactions [55]. Since their discovery, enzymes have become a crucial part of many industrial sectors due to their accelerated mode of action under operable conditions such as temperature and pH [55]. Based on one estimate, the enzyme industry comprised more than USD 6.1 billion annually, which is expected to increase to at least USD 8.5 billion [2]. For the food industry, proteases, lipases, and carbohydrases are some of the enzymes that can be expanded into many different applications based on their mode of action and market size along with their novel fermentation strategies in the food industry. While most of these enzymes are produced with the help of microbial fermentations at industrial scales, the new and innovative technologies such as biofilm reactors, cell-immobilization techniques,

and the use of economical feedstock are also continuously evaluated to enhance the overall enzyme production process (Tables 1 and 2).

Among a broad spectrum of microbial enzymes in the food industry, proteases can be considered as one of the most prominent ones as they approximately represent more than 60% of the hydrolytic enzyme production in the world [56]. There are many applications of proteases in the food industry, specifically in the coagulation of milk to produce cheese, meat tenderization, brewing, and baking processes (Table 3). All such applications require specific operating conditions especially related to the optimum pH, and proteases can be categorized according to their optimum pH into acidic, neutral, and alkaline proteases [56]. The mechanism of action of proteases can be generalized according to their catalytic types based on the types of amino acids present at their active sites. Proteases can be divided into aspartate proteases, serine proteases, cysteine proteases, and metalloproteases [57]. Aspartate proteases cleave a peptide bond between two hydrophobic amino acid residues [57]. Cysteine proteases have a thiol group which upon activation by binding to the substrate attacks the peptide bond as a nucleophile. Serine proteases act in a similar way with the nucleophilic serine at the active site. On the other hand, metalloproteases use the nucleophilic action of water as the steps for peptide bond hydrolysis. On the other hand, protease can also operate under a wide temperature range (20 to 65 °C). The production of protease, therefore, has been a topic of interest for the past few decades because of their chemical nature and culture conditions as shown in Table 1. Owing to their wide range of functional parameters, they have been found in many food processing applications. For example, in case of cheesemaking, their function to digest casein through peptide hydrolysis is imperative for operating at the required pH [58].

Numerous studies are showing the potential of many microbial strains that can be used to produce proteases under different cultural conditions. Among various microbial species for enzyme production, fungal strains represent more than 60% of the total enzyme productions, while other species such as bacteria (24%), Streptomyces (4%), and yeast (4%) are also prominent [55]. Table 1 also shows that most of the new research is happening to replace the current solid-state fermentations process by submerged fermentations which are more easily adaptable at the industrial scales. For example, in the research by Elumalai et al. [14], it was observed that agricultural wastes can be used as the feedstock for protease production under submerged conditions at 40 °C and pH 8 [10]. In another submerged fermentation approach, *Rhodotorula mucilaginosa* CBMAI 1528 was used to produce protease by using glucose and casein peptone [11]. The temperature for the growth of this strain was only 20 °C. On the other hand, 60 to 65 °C was evaluated as the optimum temperature by Suleiman et al. showing a wide range of temperature for the production and action of this enzyme [12]. Many other examples of such studies are given in Table 1.

Lipases, on the other hand, are needed in many food industries mainly to enhance or modify the flavors [59]. Lipases help in the hydrolysis of ester linkages [60]. Lipases belong to the α/β hydrolase family with an active serine residue at the active site. Most of the microbial lipases are the esterases that are activated by binding to the lipid–water interface [61]. The cleaving of ester linkages is carried out through a variety of reactions such as esterification, acidolysis, alcoholysis, and hydrolysis [62]. Microbial lipases are prominent in biotechnology for their applications in the lipid–water interface [62]. Among various applications in the food industry, the prominent ones are the obtaining the desirable flavors and the production of modified acylglycerols with the help of interesterification processes carried out by lipases [62]. Lipases can be classified according to the specificity in the substrates and sources of the lipids. There are many different classification systems and microbial lipases are generally classified into fungal, yeast, and bacterial lipases.

The optimum production temperature for lipases is around 30 to 40 °C and the optimum pH can be from 5 to 7 (Table 1). Lipases are produced by many different types of microbial species, but most of the research focus is on fungal strains due to their potential for high enzyme productions (Table 1). While fungal strains are used in solid-state fermentation conditions because of their adaptability to low moisture environments, the submerged

fermentation techniques are being explored at accelerated rates due to their realization at large industrial scales [59]. *A. niger* and *P. fellutanum* are explored under submerged fermentation for lipase production with a temperature range from 30 to 35 °C and pH from 5 to 7 [15,16]. The novelty of such studies is their optimization approach through statistical designs such as response surface methodology. Through such optimization approaches not only optimum fermentation conditions but the optimum concentrations of media components are also determined hence giving an ideal fermentation mode for the specific product and microbial strain.

Many different types of carbohydrases are currently prevalent in the food industry. Carbohydrases are the enzymes that catalyze polysaccharides into oligo- and monosaccharides. Prominent examples include amylases, glucosidases, cellulases, and hemicellulases (Table 1). Among various applications of such enzymes in the food industry, the most prominent ones are the breakdown of starch by amylases and glucosides to produce simple sugars and clarification of juices by cellulases and hemicellulases (Table 3).

For cellulase and hemicellulase production, economical feedstocks, which are high in fiber, can be used. Economical feedstocks are agricultural wastes such as food waste or the byproducts of an industrial process. One example, in this regard, is the use of the byproduct of the corn ethanol industry, which is known as distillers dried grains with solubles or DDGS [19]. These inexpensive feedstocks can provide the essential carbon sources, while additional media elements such as nitrogen sources can further increase enzyme production. For most of these enzymes, *A. niger* strains are being employed and researched for high enzyme activities. Fungal strains especially *A. niger* and *Trichoderma reesei* can produce a wide array of such enzymes in a single fermentation batch [63,64]. This is the main reason that these two strains are researched more extensively for their optimum enzyme production conditions [63,64]. Overall, the production of enzymes through microbial fermentation has been adapted in various industries including the food industry for the last several decades. There are also recent advancements in the field of microbial enzyme productions, and it is important to mention that the market size of enzymes is increasing with every passing year.

Table 2. Some examples of inexpensive feedstocks with their pretreatment methods.

Inexpensive Feedstock	Products	Examples	Pretreatment Conditions	Refs.
Agricultural waste	Enzymes	Crop straw, Poplar wood, sawdust	Grinding	[65,66]
	Other value-added products	Cattle dung, rice straw, wheat straw	Hydrothermal treatment, Mild chemical treatment	[67,68]
Food waste	Enzymes	Banana skin, bagasse	Sulfuric acid hydrolysis	[65,69]
	Monosaccharides	Wheat bran, coffee waste	Mild chemical treatment, Hydrothermal treatment	[70]
	Other value-added products	Cucumber, tomato, lettuce, lemon peel	ultrasonic and ozone pretreatment	[71]
Oceanic seaweed	Lactic acid	Brown, red or green alga	Acid and/or enzymatic hydrolysis	[72]
	Other value-added products	Brown seaweed	Ethanol extraction	[73]

Table 3. Applications of value-added food ingredients from microbial fermentations.

Category	Value-Added Ingredient	Application in Food Industry	Refs.
Enzymes	Protease	Coagulation of milk, Bread quality enhancement, Meat tenderization, Brewing	[74]
	Amylase	Baking, Brewing, Clarification of fruit juices	[74]
	Cellulase	Clarification of fruit juices, Animal feed	[74]
	Hemicellulase	Beer improvement	[75]
Antimicrobials	Nisin	Shelf-life extension	[76]
	Lysozyme	Decreasing the microbial population in food	[76]
	Natamycin	Inhibiting the growth of harmful mold	[77]
Vitamins	B2, B12, K	Improve food quality	[3]
Sweeteners	Sugar Alcohols	Improve the flavor, health concerns, diabetic food industry	[78]
Cultured meat	Non-animal-based meat	Vegetarian/vegan industry	[79]
Stabilizers	Xanthan gum	Shelf-life extension	[80]
	Gellan		[80]
	Curdlan		[80]

2.2. Antimicrobials

For decades, the food industry has been using chemical and physical methods for the preservation to inactive the harmful pathogenic and spoilage microorganisms, which have contributed to the loss of thousands of lives and billions of dollars [76]. On the other hand, some microorganisms and their natural metabolic products can prevent the growth of other microorganisms. There are many antimicrobial agents such as nisin, natamycin, and lysozymes that can be produced by the microbial fermentation process. Such antimicrobial agents have been approved by Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) for their safe use in the food preservation industry [76]. The improvement in the fermentation processes for the production of such antimicrobials is an ongoing research area as summarized on Table 1.

Among all of such antimicrobials, nisin is considered one of the most prominent antimicrobials in terms of its ability to improve food safety, quality, and increasing shelf-life [81]. Nisin is an antimicrobial peptide with bactericidal properties by binding to the bacterial cell wall through electrostatic interactions [82]. Then, nisin generates pores in the cell membrane and interrupts cell wall biosynthesis through specific lipid interactions [82].

This microbial peptide has been used in the food industry for many years as a natural and safe preservative. Nisin is effective against a wide array of Gram-positive bacteria and endospores. Therefore, it has been used in the dairy and canned food productions [81]. It is mainly produced by *Lactococcus lactis*, and there are many recent developments in the fermentation process to enhance nisin production (Table 1). One example is the development of biofilms reactors to immobilize *L. lactis* [20]. It has been demonstrated that high level of microbial cells bound to a solid matrix of porous material can result in higher nisin production as compared to the suspended cells reactors [20].

Among various other novel fermentation strategies to enhance the production of nisin, online recovery of nisin during fermentation, foam fractionation, addition of hemin to induce cell respiration, aeration with variable feeding rate, and co-culturing with other microorganisms are most prominent. Zheng et al. [83] reported the increase in the fermentation efficiency with the help of online recovery and foam fractionation. On the other hand, media optimization strategies such as the addition of hemin to stimulate the cell respiration have also been reported [84]. Culture condition optimization such as variable feeding and aeration rates has also proven to be effective in the increase of nisin production [85]. Microbial strains *Yarrowia lipolytica* ATCC18942 and *L. lactis* UTMC106 are co-cultured to enhance nisin production as well [86].

Natamycin is another antimicrobial peptide produced mainly by Actinomycetes including *Streptomyces chattanogenesis* and *Streptomyces natalensis* [77]. Natamycin acts by binding to ergosterol which is a primary sterol in fungal cell wall [87]. Among various food preservations applications, cheese is the most common [77]. Natamycin has low solubility, and therefore it is ideal to apply over the cheese surface. While simple sugars such as glucose can be used as the carbon source, natamycin can be produced at industrial scales by using molasses or soybean meal with the most commonly used microbial strains of *S. natalensis* or *Streptomyces gilvosporeus* [77]. The optimum temperature for this antibiotic production can be between 26 to 30 °C, and pH can be between 6 and 8. All such temperature and pH ranges are determined over the period of extensive research on the increase of this antibiotic production using novel fermentation strategies [77].

Lysozyme is found in many of the organisms in this world including humans. The enzyme acts as the protective mechanism in these organisms against Gram-positive bacteria by breaking the glycosidic bonds in the cell wall, which causes the cell lysis [88]. Lysozyme has been attributed to the extension of shelf life of meat products under refrigerated conditions [89]. Microbial lysozymes can be produced from different strains of *Pichia pastoris* (Table 1). Furthermore, the human lysozyme can be produced by genetically modified strain of *K. lactis* K7, and its production has been greatly enhanced by using biofilm reactors [21]. Strain selection and biofilm reactors are some of the fermentation strategies used recently to enhance lysozyme production. In conclusion, antimicrobial production through microbial fermentation is gaining interest at both research and industrial scales. The potential of using fermentation processes to produce antimicrobials has been explored extensively in recent years, as summarized on Table 1.

2.3. Vitamins

Vitamins are the essential nutrient components that are required for the growth and health of humans. There are more than 30 vitamins, and at least 20 of them are essential for the metabolic functions [3]. Vitamins can either be produced from the chemical process, which can be energy-intensive and toxic for the environment. Microbial fermentation processes, on the other hand, have been recognized as the green "cell factories" for the low-cost production of vitamins [3]. In addition, microbial fermentations result in lesser intensive waste management strategies. Vitamins can be categorized into water-soluble or fat-soluble, and they each have a specific function in almost all the metabolic processes. Therefore, their deficiency can cause serious health problems in humans. Typically, different biotechnological techniques such as genetic engineering, metabolic engineering, media, and culture optimization with the development of special types of bioreactors have been developed and explored for the production of vitamins at industrial scales.

Production of most of the vitamins such as various types of Vitamin B and K takes place in submerged fermentation (Table 1). The majority of the carbon sources are simple sugars such as glucose or other monosaccharides with minerals and nitrogen sources, as mentioned in Table 1. Technical parameters such as optimized temperature, pH, and aeration rates are also mentioned in Table 1. As can be seen in the table, these fermentation parameters can have different ranges for different types of vitamins and microbial strains.

Therefore, it is crucial to know the optimized value according to every vitamin and other microbial products.

A recent trend that is gaining more interest due to the relative applications in scale-up is the development of biofilm reactors for vitamin production [25,26,90]. These biofilm reactors are equipped with plastic composite support (PCS) where the bacterial species can form biofilms and enhance the production of vitamins. In a recent study, Vitamin K was produced successfully under agitated conditions by using biofilm reactors, which will enable the fermentation scale-up easily for commercial production of Vitamin K as opposed to the currently used static fermentation [26]. The fed-batch bioreactors are another type of product enhancement strategy where the media is supplemented at regular intervals for the maximum production of the microbial product. Both of these strategies are being explored for vitamin production especially vitamin K [26].

2.4. Organic Acids

Organic acids are one of the most important platform chemicals that are needed for the production of several products in food and many other industries [91]. For example, lactic acid is used as an acidifier with antimicrobial agent in foods and in packing material. On the other hand, acetic acid is crucial in the production of vinegar, pickles, and some flavors. All such applications make organic acids important in the food industry. Citric acid is another important organic acid in the food industry. According to one estimate, organic acids had a market size of USD 6.94 billion in 2016 which is projected to increase to USD 12.54 billion by 2026 [91]. The overall impact of the increase in the demand for organic acids entails different research strategies to enhance the production through various improvement techniques in microbial fermentation (Table 1). The fermentation conditions are usually within the pH of 5 to 6 and temperature from 30 to 37 °C (Table 1). Among various microbial species, *Lactobacillus*, *Acetobacter*, *Gluconoacetobacter*, and *Gluconobacter* species are the most common for the production of organic acids. Most of these microbial species have been optimized for maximum production of organic acids under optimized culture parameters.

2.5. Sweeteners

Low calories alternatives of sugars in human diet become more attractive for food manufacturers and scientists, with the increasing of diseases and dependance on sugar consumption [78]. Polyols, such as sorbitol, mannitol, maltitol, lactitol, xylitol, and erythritol, are mostly used as a sweetener substitute of sugars, due to their low caloric, cariogenic properties with no effect on insulin resistance features. On the other hand, synthetic sweeteners (thaumatin and aspartame) are also widely used as a food ingredient in various industries [78,92]. Synthetic sweeteners are produced by chemical, enzymatic, and microbial techniques. There has been extensive research in the literature about enhancing the production of sweeteners, and most sweeteners, produced by fermentation, are notably erythritol [93,94]. Table 1, including recent research about fermentative production of sweeteners, shows that fungi, yeast, and bacteria are used for sweetener production. Considering producer microorganisms in Table 1, *Yarrowia lipolytica* and *Moniliella* ssp., *Rhodosporidium toruloides* and *Candida* ssp., and *Lactobacillus* ssp. are preferred for erythritol, arabitol, and mannitol production, respectively [36,95]. Moreover, genetically modified microorganisms are also used for boosting yield by researchers. On the other hand, evaluating different fermentation strategies (Batch, fed-batch, and solid-state fermentation) and the low-cost fermentation media ingredients (Crude glycerol, okara–buckwheat husk, waste oil, peanut press cake, sugarcane molasses, etc.) are also prominent strategies for increasing yield and reducing production costs as summarized in Tables 1 and 2.

2.6. Flavonoids

Flavonoids such as flavones, chalcones, flavanols, and isoflavones are bioactive compounds found in plants that play an active role in many health-promoting properties such as antitumor, antifungal, antiviral, and antibacterial attributes [96]. Therefore, research efforts have been promoted to develop different variations of such compounds. While the major source of such compounds is plants which possess the difficulty of large-scale culture, specific culture requirements, and low abundance of molecules of interest, the increasing demands for such chemical compounds are now met with the idea of producing such compounds in the microbial systems [96]. Various microorganisms have been genetically modified to produce flavonoids with the help of microbial fermentation. Traditional examples include *Escherichia coli* and *Yarrowia lipolytica* [96].

2.7. Cultured Meat Products

The current global population of 7.3 billion is expected to increase to 10 billion by 2050, which will result in the doubling of the demand for proteins which are currently met by an unsustainable meat industry [79]. While plant proteins are proposed as the alternative protein source, they also possess various issues including allergic reactions and low protein content. To solve such problems, a new technology employs cultured muscle cells as an alternative to real meat. This is a relatively a new technique, which is a type of in vitro cell culture technology where the skeletal muscle-derived cells are grown and used as meat for human consumption. The original source of the cells is from the slaughterhouse [79]. While it is still in its infancy stages, various bioreactor techniques can be used to enhance the production of cultured meat products with the help of various optimization strategies [79]. Products such as bio-artificial muscles (BAMs) can be produced using skeletal muscle resident stem cells or satellite cells, but much research is needed to develop technologies where such products can be used as the cultured meat products [97].

2.8. Oligosaccharides and Polysaccharides

Oligosaccharides are generally formed by 2–10 monosaccharides unit such as pentose and hexose and can be defined as an intermediate polymeric carbohydrate between monosaccharides and polysaccharides. They are naturally found in animals, microorganisms and plants [98]. These carbohydrates are commercially obtained from lignocellulosic biomass by physical, chemical, biological, or enzymatic pretreatment methods, and they supplement food products as a prebiotic due to their functional properties [98–100]. Biological pretreatment is known as the degradation of polysaccharides by microbial enzymes or using microorganisms directly (in situ) for producing oligosaccharides [101]. Because of requiring less energy, being eco-friendly, and being an efficient method, biological pretreatment is also used to produce well known oligosaccharides like fructooligosaccharides (FOSs), xylooligosaccharides (XOSs), and mannooligosaccharides (MOSs) [98]. In addition to these most used oligosaccharides, galactooligosaccharides (GOSs), pectic oligosaccharides, and human milk oligosaccharides (HMOs) are also produced by biological pretreatment [101,102]. FOSs are produced with sucrose bioconversion, which catalyzed by β-fructofuranosidase and fructosyltransferase enzymes, generally. This bioconversion process begins with enzyme production by fermentation and ending with enzymatic degradation [103]. In recent years, FOS production was carried out with different fermentation strategies such as submerged, solid-state, and co-cultured by using *Aspergillus* sp., *Lactobacillus* sp., *Bifidobacterium longum*, *Leuconostoc mesenteroides*, *Aureobasidium pullulans*, and a mutant strain of *Aspergillus oryzae* (Table 1). Moreover, cashew apple juice, aguamiel, sugarcane bagasse, coffee husk, pineapple peel, prickle pear peel, and banana peel waste were evaluated as alternative substrates (Table 1). XOSs, one of the other important attracted oligosaccharides, can be obtained from xylan and alternative substrates by using enzymes, which are produced by fermentation. Generally, microorganisms, able to produce endo-1,4-β-xylanase enzyme, such as *Aspergillus*, *Fusarium*, *Penicillium*, and *Trichoderma* are main XOS fermentation fungi [104]. Nevertheless, using recombinant enzymes, pro-

duced by *Bacillus subtilis*, and adding an alternative carbon source instead of xylan are promising alternatives (Table 1). MOSs are non-digestible and water-soluble dietary fiber and are used as a nutrient for human intestinal microflora in daily nutrition. MOSs can be produced by enzymatic hydrolysis of mannan and different plant sources. Production of these oligosaccharidesis is carried out by using of β-mannanase or directly cultivating the β-mannanase producer microorganism, which is *Aspergillus* sp. [5].

Texture properties of food products affect consumer perception, considerably. Accordingly, the production of quality foods in terms of visual and sensory perception is related with the controlling and characterization of rheological properties by some ingredients [105]. Quite a few polymers like exopolysaccharides are used as stabilizers, emulsifiers, and thickening agents in the food industry. This section focused on these polymers, which are produced by fermentation such as β-glucan, pullulan, xanthan gum, bacterial cellulose, gellan, dextran, and curdlan [80]. β-glucans, which are generally used as emulsifier and thickening agents, consist of D-glucose units linked by β-glycosidic linkages [40,106]. Despite bacteria, fungi, and yeast being able to produce β-glucans, fungi (*Aspergillus niger*, *Rhizopus oryzae*, and *Lasiodiplodia theobromae*) were mostly used in recent research (Table 1). The main substrate of β-glucan fermentation is glucose, but alternative substrates such as oat bran, sugarcane straw, soybean molasses, and potato juice were also evaluated (Table 1). Pullulan, produced by *Aureobasidium pullulans* substantially, is composed of repeated maltotriose units. Due to its characteristic properties, Pullulan is used in food products as an additive for stabilization and thickening. Carbon sources of pullulan fermentation include widely alternatives like glucose, fructose, sucrose, and some agro-wastes. Nevertheless, some studies, about the use of genetic modification techniques and/or low-cost medium component, appear in literature for lowering production cost of pullulan [101,107] (Table 1). Unlike β-glucans and pullulans, xanthan gum, consisting of D-glucose, D-mannose, D-glucuronic acid, and pyruvic acid, is a heteropolysaccharide. Xanthan gum is naturally produced by Gram-negative bacteria *Xanthomonas* sp. Through major properties of this polymer such as high viscosity, water solubility, and stability, market size reached about USD 23 million per year and was used for contributing to stabilization and thickening of food products. Using expensive substrates like glucose and sucrose is significantly responsible fir high production cost [108,109]. Some studies present strategies in Table 1 for avoiding of fermentation outgoings, which are regarding using alternative carbon sources, optimization of conditions, and using genetical tools.

2.9. Amino Acids

Since the production of monosodium glutamate, amino acids have been evaluated in the food industry as additives to be a flavorant [110]. The market size of amino acids reached nearly USD 25.6 billion, and amino acids, used for animal feed, are the largest part of demand at USD 10.4 billion [111]. This value-added compound can be produced by different methods such as extraction of proteins, chemical synthesis, enzymatic reactions, and fermentation. Fermentation processes can be used for amino acid production in two different ways: one, for production of enzymes to catalyze amino acid synthesis and second for direct amino acid production through fermentation using microorganisms. A great number of different amino acids can be produced by *Corynebacterium glutamicum*, *Brevibacterium* spp., and *Escherichia coli.* Moreover, the most commercially known amino acids, such as glutamic acid, methionine, tryptophan, lysine, tyrosine, phenylalanine, leucine, valine, arginine, histidine, and others, can be produced by these microorganisms (Table 1). Moreover, *C. glutamicum* and *E. coli* can utilize different type of carbon sources, and these bacteria are easily modified by metabolic engineering [112]. Due to those advantages of *C. glutamicum* and *E. coli*, several amino acid production studies were carried out in recent years (Table 1). On the other hand, agricultural biomass was used to boost the yield of amino acid production by genetically modified *C. glutamicum*. For instance, Han et al. extracted biotin from corn leaves to enrich the fermentation medium of glutamic acid. Glutamic acid fermentation was carried out in a bioreactor by using genetically engineered

C. glutamicum S9114, and they reported that glutamic acid can be efficiently produced by the addition of biotin extracted from corn leaves [113]. In another study, *C. glutamicum* with modified carbohydrate metabolism was used for L-lysine fed-batch fermentation in a medium containing beet molasses and corn step liquor. It was found that highly efficient production of L-lysine from mixed sugars could be achieved [54]. Except for these, some specific microorganisms could be used for amino acid production. For example, phenylpyruvic acid, which is a deaminated form of phenylalanine, can be produced by *Proteus vulgaris* in fed-batch or continuous fermentation [114].

2.10. Food Colorants

For many food preparations, food colorants are an integral part of the recipe and are added for the much-required aesthetic identity of the food products. Among various concerns regarding food colorants in terms of their safety, flavor, and nutritional profiles are the most important ones to consider. Currently, the food colorant market is USD 3.88 billion which is expected to increase to USD 5.12 billion by 2023 [115]. Mostly natural pigments that are being used as colorants are usually sources from plants, animals, or microorganisms, while synthetic pigments were also introduced in the food industry in the mid-nineteenth century. However, their safety is an issue still being debated among many nutritionists and medical researchers. Compared to the plant ones, on the other hand, microbial colorants are more stable, indifferent to seasonal variations, and cost-effective [115]. Therefore, many advances in the development of microbial fermentation for the production of colorants have been made in recent years. Some examples of microbial food-grade pigments are astaxanthin (*Xanthophyllomyces dendrorhous*), arpink red (*Penicillium oxalicum*), riboflavin (*Ashbya gossypii*), carotene (*Blakeslea trisporatrispora*), canthaxanthin (*Bradyrhizobium Spp.*), prodigiosin, *(Serratia marcescens*), phycocyanin (*Aphanizomenon flosaquae*), violacein (*Chromobacterium violaceum*), and lycopene (*Fusarium, Sporotrichioides* and *Blakeslea trispora*) [115,116].

2.11. Antioxidants

Antioxidants can defend biological molecules, which are important for human health, against oxidation. Thus, they contribute protection from diseases, caused by reactive oxygen. Some vitamins (ascorbic acid or vitamin E) and polyphenols such as phenolic acid, flavonoid, stilbenes, and carotenoids (lycopene and β-carotene) are commonly used compounds in food industry as antioxidant additives and supplements. These compounds are produced by extraction from plant source traditionally. However, microbial production of antioxidants becomes more favorable, due to typical advantages of biotechnological processes such as renewability, controlling of fermentation conditions, and manipulability of microorganisms. Antioxidants, involved in a wide range of biological molecules, are produced as directly or as secondary metabolites by Actinomycetes, bacteria, fungi, and engineered microorganisms [117,118]. Commercial production of lycopene and β-carotene was carried out by *Blakeslea Trispora* [119]. *Streptomyces* sp. can produce several antioxidants like terpenoids, gallocatechin gallate, isoflavonoids, etc. On the other hand, some phenolic compounds such as gallic acid and ferulic acid are produced by *Aspergillus oryzae*, *Mucor racemosus*, *Rhizopus oligosporrus*, and *Aspergillus niger*. In addition to that, phenolic content and antioxidant properties of some cereals can be improved by solid-state fermentation with these fungi [119,120].

2.12. Lipids and Fatty Acids

Microbial lipids, which are obtained from oleaginous microorganisms, are single cell oils, typically. Microbial lipids are produced by fungi such as *Mortierella* spp., *Mucor* spp., and *Cunninghamella* spp. as well as yeasts such as by *Rhodosporidium*, *Lipomyces*, *Yarrowia*, and *Cryptococcus* species. Although single cell oils have become more popular for obtaining biodiesel with increasing energy demand, they can be used as supplement or additive in foods because of contained essential or non-essential fatty acids [121,122]. There are

several studies in the literature on increasing the efficiency of microbial lipid production. Chen et al. studied the effect of methanol addition to the medium on lipid production. Crude glycerol was used as a carbon source in non-sterilized fed-batch fermentation. They showed that methanol could be used to control the growth of contaminants in non-sterilized fermentation while achieving 20.42 g/L of lipid production [123]. On the other hand, the effect of different dissolved oxygen concentrations on lipid production by *Trichosporon oleaginosus* was investigated in order to improve lipid production and reduce energy consumption. It was reported that energy consumption was reduced by 41%, and 11.77 g/L of lipids were produced [124]. Definition and usefulness of fatty acids vary according to length of hydrocarbon chain including double bonds and the location of those bonds. For example, polyunsaturated fatty acids like arachidonic acid, γ-linolenic acid, and eicosapentaenoic acid or lipids, involving these fatty acids, are commonly used in food industry to enrich of foods or to form stabile emulsions [125]. Microbial production of polyunsaturated fatty acids has been trending upward in the last decade in furtherance of meeting the demand and sustainable production. Consequently, there is a lot of research in the literature to improve production by different ways, such using alternative substrate [126,127], isolating new microorganisms [128,129], trying different fermentation techniques [130–132], and metabolic engineering [133–135].

2.13. Alcohols

Alcohols, which refer generally to ethyl alcohol or ethanol, are commonly used biotechnological products in the beverage industry and as bioethanol to reduce fossil fuel consumption. Global alcoholic beverages are beer, wine, and spirits, and especially beer and spirits are the most preferred drinks after water and tea. Ethanol is a product of alcoholic fermentation and can be mainly produced by yeasts [136,137]. Although *Saccharomyces cerevisiae* is the main producer of alcohol, other yeasts such as *Pichia*, *Torulaspora*, *Hanseniaspora*, *Candida*, *Metschnikowia*, *Lachancea*, *Schizosaccharomyces*, and *Brettanomyces* are used in brewing and winemaking fermentations. Mixed culture fermentation is another preferred application for alcoholic fermentation [138]. Moreover, while genetic engineering techniques and recombinant DNA technologies are proven methods for improving production yield, synthetic biology applications such as the *Yeast 2.0 Project* are also promising technologies. On the other hand, some bacteria such as *Zymomonas* spp. can produce ethanol with a different metabolic pathway (the Entner–Doudoroff pathway) [136]. Glycerol, a yeast metabolism byproduct, can be used as a food additive in the food industry. Although it is commonly produced by recovering from byproducts of fat and oil industries, many researchers have become interested in fermentation methods to produce glycerol. Apart from its use as a thickening agent, it is an important compound for the winemaking process. Glycerol may affect sensorial properties of red wine, which is produced by *Saccharomyces* and non-*Saccharomyces* yeast [139,140]. Glycerol can be produced by wide variety of microorganisms such as *Zygosaccharomyces*, *Candida*, and *Kluyveromyces* as yeast; *Rhizopus*, *Aspergillus*, and *Debaryomyces* as fungi; *Bacillus* spp., *Bacterium* spp., and *Lactobacillus* spp. as bacteria; and *Dunaliella* as algae [139].

3. Inexpensive Substrates for Such Fermentations

Only the nutritional need of humans is not sufficient as it is estimated that four billion tons of agricultural and food processing waste will be generated by 2050 [141]. For example, 88 million tons of food waste are generated in only Europe according to the European Commission [142]. Moreover, agricultural and food wastes cause many environmental problems and greenhouse gas emissions. Due to these reasons, management of agricultural and food wastes and evaluation of the production of value-added products are important in terms of a sustainable economy and prevention of environmental pollution. In this section, some agricultural and food wastes, which are used as carbon or nitrogen sources for food ingredient fermentation, are summarized.

3.1. Agricultural Wastes

Agricultural wastes can be categorized as crop residues, livestock wastes, poultry wastes, agro-industrial wastes, pulps, and oil-seed cakes, in general. Some of these materials could be mentioned as leaves, corn stover, rice, wheat, oat, and barley straws (crop residues); eggshells and farm animal skins (poultry wastes); wastewaters of farms (livestock wastes); molasses, sugarcane bagasse rice husk, vegetables, and pomaces (agro-industrial wastes); and cotton, safflower, sesame, palm kernel, and soybean (oil-seed cakes) (Figure 1). Agricultural wastes require physical, chemical, or biological pretreatment, generally [143]. Much of the research present in the literature is about value-added food ingredient fermentation by using agricultural wastes, which include lignocellulosic structure. Some of these ingredients are erythritol (sugarcane and beet molasses) [33], FOSs (cashews and apple juice) [144], MOSs (wheat bran, rye bran, oat husk, and barley husk) [5], inulinase (sugar beet molasses) [145], β-mannanase (carob pods) [4], Pullulan (corn bran) [46], and microbial lipids (wastepaper enzymatic hydrolysates) [146].

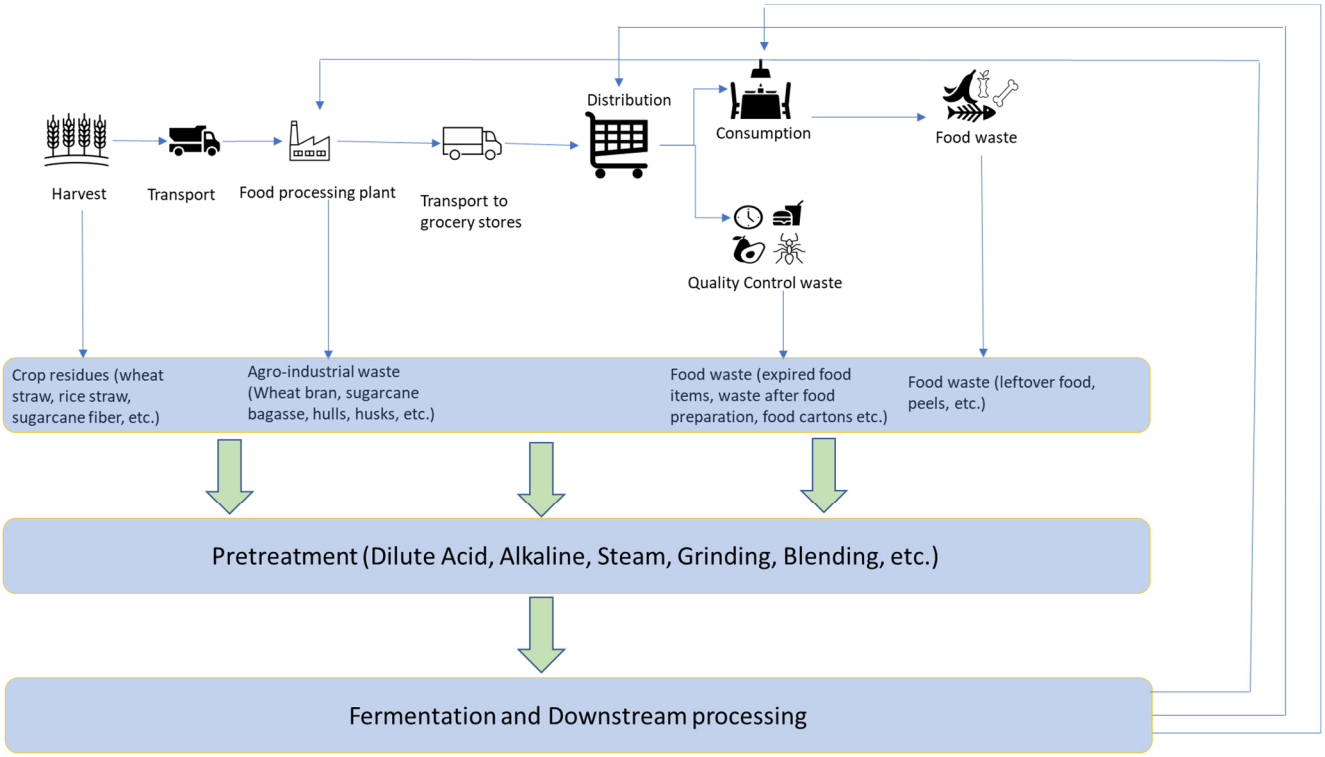

Figure 1. Supply chain of inexpensive feedstock for microbial fermentations.

For instance, by-products of sugar factories and wineries were evaluated in erythritol production by Valsero et al. [33]. Sugar cane molasses, beet molasses, and grape musts were added to the fermentation medium as carbon sources, and 106 g/L of erythritol was produced by shake-flask fermentation with sugar cane molasses medium. Dried and milled agro-industrial wastes, such as sugarcane bagasse, coffee husk, pineapple peel, prickle pear peel, and banana peel waste, were used as substrate for FOS production by solid-state fermentation. It was found that sugar cane bagasse was the most promising substrate [103]. In another study, MOSs were produced by solid-state fermentation from dried and chopped wheat bran, rye bran, oat husk, barley husk, and spent coffee grounds. According to this, the highest MOS production was achieved in the fermentation of spent coffee grounds [5]. Gürler et al. studied the large-scale production of β-mannanase from carob extract. Broken and seedless carob pots were used in fed-batch fermentation after pre-treatment with water extraction. They reported that microparticle-added carob extract is a promising carbon source to produce β-mannanase [4]. Corn bran, an agricultural by-product, was enzymatically pretreated to produce pullulan by shake-flask fermentation. It was found

that more than 19 g/L of pullulan can be produced from hydrolyzed corn bran [46]. Apart from these, fermentation strategies, pretreatment conditions, and productivity of some ingredients produced from wastes are shown in Table 1.

3.2. Food Wastes

Food wastes consist of food processing wastes and kitchen wastes (Figure 1). While processing wastes are generated from the dairy industry, meat processing, vegetable and oil processing, and cereal processing, kitchen wastes are generated from dairies, meats, cereals, fruits, and vegetables at homes, restaurants, and cafeterias [146,147]. Food wastes are mostly rich content sources owing to their inclusion of carbohydrates, proteins, fats, lipids, and inorganic components. Thus, they could be evaluated for bioconversion to energy and production of value-added products by fermentation. Many of food ingredient could be produced by different fermentation strategies with or without using pretreatment [146,148]. Table 2 includes some of these studies about enzymes, monosaccharides, and other value-added products produced by using various food wastes such as cucumber, tomato, lettuce, and lemon peel. Food processing and kitchen wastes can be utilized for food ingredient production as carbon sources. However, more research is needed to find economically feasible and productive methods of this promising bioconversion process [146].

4. Conclusions and Future Perspective

Current advancements in the field of microbial fermentation to produce value-added food ingredients have been discussed with the help of specific examples of enzymes (proteases in cheese making industry, lipases in flavor modification and carbohydrases in juice and baking industries, etc.), antimicrobial agents (nisin, natamycin, lysozyme, etc.), vitamins (Vitamin B, K, etc.), organic acids (citric acid, acetic acid, etc.), sweeteners, flavonoids (flavones, chalcones, flavonols, and isoflavones), cultured meat products (BAMs), stabilizers, emulsifiers, oligosaccharides, amino acids, food colorants (Astaxanthin, carotene, Canthaxanthin, Lycopene, etc.), antioxidants, lipids, fatty acids, thickening agents, and alcohols. While microorganisms can produce many of such food ingredients efficiently and abundantly, the improvement in the basic fermentation processes with the help of genetic engineering, metabolic editing, and optimization is still an ongoing research topic. The future holds many possibilities to produce microbial products as food ingredients which will be safe, natural, and environmentally friendly. More studies should be performed to optimize the microbial production process parameters such as temperature, pH, and aeration at larger scales. The design of new bioreactor techniques such as biofilm reactors should also be a focus to cause the adaptation of microbial production at larger scales. In addition, the design of new bioreactors for innovative research products such as cultured meats should be researched. The fermentation sector also promises to utilize organic waste of food industries thus recycling most of the resources back into value-added products.

Author Contributions: Conceptualization, A.D. and I.T.; validation, A.I., A.O., A.D., and I.T.; formal analysis, A.D. and I.T.; investigation, A.I. and A.O.; resources, A.D.; writing—original draft preparation, A.I. and A.O.; writing—review and editing, A.D. and I.T.; supervision, A.D. and I.T.; project administration, A.D.; funding acquisition, A.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by USDA National Institute of Food and Agriculture Federal Appropriations under Project PEN04671 and Accession number 1017582.

Data Availability Statement: Data can be provided as needed.

Acknowledgments: This work was supported in part by FULBRIGHT Student Program by providing scholarship to Attia Iram.

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

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