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Review

Highlighting the Impact of Lactic-Acid-Bacteria-Derived Flavours or Aromas on Sensory Perception of African Fermented Cereals

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Abstract: Sensory characteristics and flavour profiles of lactic-acid-fermented foods are influenced by lactic acid bacteria (LAB) metabolic activities. The flavour compounds released/produced are directly linked to the sensory characteristics of fermented cereals. African fermented cereals constitute a staple, frequently consumed food group and provide high energy and essential nutrients to many communities on the continent. The flavour and aroma characteristics of fermented cereal products could be correlated with the metabolic pathways of fermenting microorganisms. This report looks at the comprehensive link between LAB-produced flavour metabolites and sensory attributes of African fermented cereals by reviewing previous studies. The evaluation of such data may point to future prospects in the application of flavour compounds derived from African fermented cereals in various food systems and contribute toward the improvement of flavour attributes in existing African fermented cereal products.

Keywords: African fermented cereals; lactic acid bacteria; sensory perception; flavour/aroma compounds

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1. Introduction

Superseding the significance of nutrition and health in influencing consumer food choice is the flavour and aroma attributes of food [1]. Flavour and aroma components in turn have an impact on the sensory perception of food [2]. Cereals such as sorghum, millets, rice, maize and wheat are the staple foods of a majority of the African population, with millets, sorghum and teff being recognised as indigenous crops [3,4]. The consumption of these cereals is widespread due to the fact they are affordable and easily available to both rural and urban communities. These cereals are also a major component of traditional weaning foods in Africa. The dietary significance of these cereals is their carbohydrate, vitamin, mineral, dietary fibre and bioactive phytochemical content [5]. However, the presence of anti-nutrients, low protein digestibility, low iron bioavailability and inadequate quantities of organoleptic-active compounds [5,6] necessitates processing techniques such as fermentation. With challenges relating to accessibility to sophisticated food processing and preservation technologies, fermentation remains a dominant food processing technique in the developing world, particularly in Africa. Fermentation is known to provide numerous benefits, including the enhancement of nutritional and sensory quality of food products, as well as increased shelf life and the production of bioactive compounds [7].

Cereal fermentations can be affected by a combination of bacteria and yeast metabolism [8]. Traditionally, the fermentation of cereals in Africa is spontaneous, activated by the presence of microorganisms in raw materials. Fermentation can be carried out in homes or on a micro industrial scale. Back-slopping, which introduces previously fermented material as an inoculum during fermentation, is a common technique [9]. However, controlled fermentation is gaining popularity due to the need to improve efficiency and ensure consistent product quality. During lactic acid bacteria (LAB)-based fermentations, catabolic and anabolic reactions take place to break down the substrate constituents and synthesise various compounds which influence the sensory qualities of cereals [5,10]. Different cereal substrates, fermentation conditions and the time and type of LAB strain/s used may lead to varying concentrations and types of flavour metabolites produced [5]. Flavour perception is influenced by taste (mainly non-volatile compounds), aroma (mainly volatile compounds), tactile and temperature factors [1,5,11]. In addition, non-volatile compounds may act as flavour precursors for the development of volatile flavour compounds [12].

Volatile flavour compounds are characterised by their vaporisation properties in the release from food and can be detected by the olfactory system during human consumption, which activates odour receptors [1,5]. They include compounds such as some carboxylic acids, ketones, esters, alcohols and aldehydes [13]. Non-volatile flavour compounds include salts, flavonoids, sugars, amino acids, peptides and some carboxylic acids, which interact with taste buds located in the tongue [14]. They are perceived during the gustation process by five taste attributes (sweet, sour, salty, umami and bitter) [14]. Cereal substrate constituents such as fatty acids, amino acids, carbohydrates, organic acids and other compounds released by LAB during fermentation are metabolised to various flavour compounds [5].

Several studies have investigated the sensory perception/consumer acceptability of African fermented cereals [15–20]; some have reported data on the volatile and non-volatile compounds produced as a result of LAB fermentation [21–26]. A few studies have identified aroma profiles and related odour descriptors [27–30]. Therefore, this review describes the LAB metabolic pathways that are responsible for the production of various flavour metabolites in non-alcoholic African fermented cereals and formulates a correlation between LAB-produced flavour metabolites and the sensory perception of the corresponding fermented cereals. The evaluation of such data will provide an understanding of the type of flavour compounds associated with the sensory perception of various African fermented cereals. These correlations could assist in the development of new products, the application of flavour-derived compounds from African fermented cereals in various food systems and the improvement of flavour attributes in existing African fermented cereal products.

2. An Overview of Significant African Fermented Cereal-Based Foods

Cereals are among the most popular fermentation substrates in Africa. Maize, millet, sorghum and, to a lesser extent, rice and wheat are fermented to produce a wide array of thin and thick porridges, beverages and bread with distinct sensory characteristics [31]. The products produced depend on the region and the most readily available cereal crops; products from different regions can also use similar substrates while differing in some areas of the production process, such as the temperature and duration of fermentation, and the use of additional processing steps such as malting. The cereals may be fermented individually, or they may be composited with other cereals [32,33], legumes or other food ingredients before or after fermentation. Traditionally, most cereal fermentation processes rely on uncontrolled fermentation techniques such as spontaneous fermentation and back-slopping. The microbial populations predominantly involved in the fermentation process are LAB and yeasts [34]. Commercially available starter cultures, which can be differentiated as single-strain (one strain of a species), multi-strain (more than one strain of a single species) or multi-strain mixed cultures (strains from different species), are mostly LAB-based strains [35]. LAB remain the most popular and frequently studied bacterial strains used in the fermentation of cereal-based foods [36]. While a pure *lactobacillus spp.* inoculum has been used in some studies, others have used mixed inocula which incorporate other organisms such as *Candida spp.*, *Saccharomyces cerevisiae*, *Streptococcus spp.* and *Acetobacter spp*. Lactic-acid-based fermentation is also gaining popularity due to an increased need for the production of probiotics with specific health and/or nutritional benefits [37,38], such as the increased production of folate in injera fermented with *L. plantarum* compared to spontaneously fermented injera [39].

Examples of African fermented cereal food are presented in Table 1. Akamu/ogi is a porridge that can be consumed in a thin or thick constituency in Nigeria; it is commonly consumed as a weaning food [40]. Uji is a thin maize gruel popularly consumed in Kenya [32]. Ting is a fermented porridge made in Botswana, which may be consumed in a thin (motogo) or thick (bogobe) consistency [25]. Maheu/mageu is a non-alcoholic maize-based beverage that is popular in Southern Africa. Togwa is a beverage or gruel made in Tanzania from maize, millet, sorghum, cassava or their composites [41]. Kunun-zaki is a non-alcoholic beverage popularly consumed in Northern Nigeria made from millet or a combination of millet, rice and wheat [17].

Table 1. Selected African fermented cereals and the microorganisms used for fermentation.

Cereal	Product	Microorganisms	Reference
Maize	*Dogik (ogi)*	*L. pentosus and L. acidophilus*	[40]
	Akamu/ogi	*L. plantarum*	[31]
	Akamu/ogi	*L. plantarum/ L. cellobiosus*	[42]
Millet	*Kunun-zaki*	*L. plantarum/L. cellobiosus*	[17]
	Koko (ogi)	*Lb. fermentum KL4 and C. tropicalis MKY6*	[42]
	Kenkey		[43]
	Pito	*L. plantarum* (LpTx)	[44]
Sorghum	*Kisra*	*Lactobacillus fermentum, Lactobacillus amylovorus, Lactobacillus brevis and Saccharomyces cerevisiae*	[45]
	Ting	*L. reuteri FUA3168, L. harbinensis, L. fermentum FUA3165, L. coryniformis, L. casei FUA3166, L. plantarum FUA3171 and L. parabuchneri,*	[25]
Rice	*Idli*		[45]
	Dhokla		[25]
	Ice cream	*L. acidophilus LA-5 wer*	[39]
Maize/sorghum/millet/rice/ wheat/other materials	*Kunun-zaki*	*Lactobacillus plantarum, L. fermentum and Lactococcus lactis*	
	Maheu	*Lb. rhamnosus yoba*	[17]
	Togwa	*L. fermentum, L. brevis, L. plantarum, L. cellobiosus, and Pediococcus pentosaceus) and yeasts*	[46]
	Togwa	*Lactobacillus plantarum, Pediococcus pentosaceus, Lactobacillus casei and Lactobacillus fermentum*	[47]
	Uji	*Lactobacillus plantarum, L. brevis, L. buchneri, L. paracasei ssp. paracasei and Pediococcus pentosaceus.*	
	Sourdough	*Pedicoccus acidilactici O1A1, Pediococcus pentosaceus OA2, and Lactobacillus curvatus MA2*	[41]
	Breadfruit–corn	*S. thermophilus, L. bulgaricus and L. acidophilus*	

3. Lactic Acid Fermentation Pathways Involved in Flavour/Aroma Compound Production

Lactic acid bacteria belong to the Gram-positive, non-sporulating type of microorganisms in the phylum of Firmicutes and the order *Lactobacillales* [1,11]. The genera *Lactobacillus*, *Lactococcus*, *Leuconostoc* and *Pedicoccus* are mainly predominant in African fermented cereals [7]. The main metabolic pathways involved in flavour development during fermentation are carbohydrate metabolism, degradation proteins and fats [48]. However, the dominating pathway depends on the type of substrate. In the case of cereals, carbohydrate metabolism is dominant, while lipid hydrolysis is low [11].

3.1. Carbohydrate Metabolism during LAB Fermentation of Cereals and Its Link to Flavour and Aroma Compounds Production

As the main constituent of cereals, LAB use carbohydrates to generate ATP via fermentation, coupled to substrate-level phosphorylation [11]. Different LAB possess various abilities to utilise the type of carbohydrates present. Bacteria use the permease (PM) and phosphotransferase systems (PTS) to transport carbohydrates into the cell. The PTS ensures the conversion of glucose, sucrose, and so on into their corresponding phosphoesters during transport [49]. In cereal fermentations, homofermentative LAB can be found in association with heterofermentative LAB [36]. Homofermentative LAB produce lactic acid by metabolising hexoses via the Embden–Meyerhof pathway or pentoses via the pentose phosphate pathway to form lactate, while heterofermentative LAB metabolise hexoses and pentoses via the phosphoketolase pathway to form lactate, acetic acid, ethanol and carbon dioxide [11], as demonstrated in Figure 1. Homofermentative LAB prefer glucose as a substrate, while heterofermentative LAB prefer fructose, sucrose and maltose as their substrate, which speaks to their high levels in cereal porridges and sourdough, as these types of carbohydrates are available in abundance [36]. Cereals are a major source of complex carbohydrates such as starch, which may be hydrolysed during the initial stages of fermentation due to the presence of amylolytic LAB (*Lactobacillus fermentum*, *L. acidophilus*, *L. plantarum*, *L. pentosus*, *L. paracasei*, *P. acidilactici*, *Lc. lactis*, *Leuc. mesenteroides* and *W. confusa*) [24,50,51]. Amylolytic LAB can provide fermentable sugars to non-amylolytic LAB, depending on the catabolic repression characteristics of the bacteria in the presence of glucose [50,51]. Additionally, other enzymes such as sucrase, galactosidase, fructosidase and so on may be released to catalyse the respective substrates such as sucrose, raffinose and fructooligosaccharides [52,53].

In African fermented cereals, homofermentative LAB such as *Pediococcus acidilactici*, *Lactococcus lactis*, *Enterococcus*, *Streptococcus*, *Lactobacillus casei*, *Lactobacillus acidophilus* and *Lactobacillus helveticus* have been isolated. Heterofermentative LAB such as *Lactpbacillus planturum*, *Lactobacillus brevis*, *Lactobacillus fermentum*, *Lactobacillus reuteri* and *Leuconostoc mesenteriodes* have also been noted (Tables 1 and 2). Lactate has been identified as the main non-volatile flavour compound in fermented cereals such as mawe or ogi (maize/corn), koko (millet) and mahewu (maize/corn), due the presence of mainly homolactic LAB. In products such as ting (sorghum) and bushera (sorghum), lactate and acetate have been identified due to the presence of heterofermentative LAB. Further, LAB such *L. paracasei* subsp. *paracasei* MINF98, *L. plantarum* MINF227 and *L. brevis* MINF226 have been associated with the production of acetylaldehyde, which is a volatile flavour compound produced via the heterofermentative pathway as an intermediate for ethanol synthesis [5,24]. Acetoin, butanediol and diacetyl, which contribute to the aroma of fermented cereals, are produced as a result of citrate metabolism via LAB such as *Leuconostoc mesenteriodes* and *Pediococcus acidilactici* [11,24]. During the spontaneous fermentation of the Ghanaian maize dough kenkey, the presence of diacetyl was related to the presence of LAB [28]. Citrate metabolism may be expressed by LAB during the late exponential growth phase, when acidic conditions persist due the presence of lactic acid [54]. A low-pH environment shifts the metabolism of carbohydrates to the utilisation of amino acids [36].

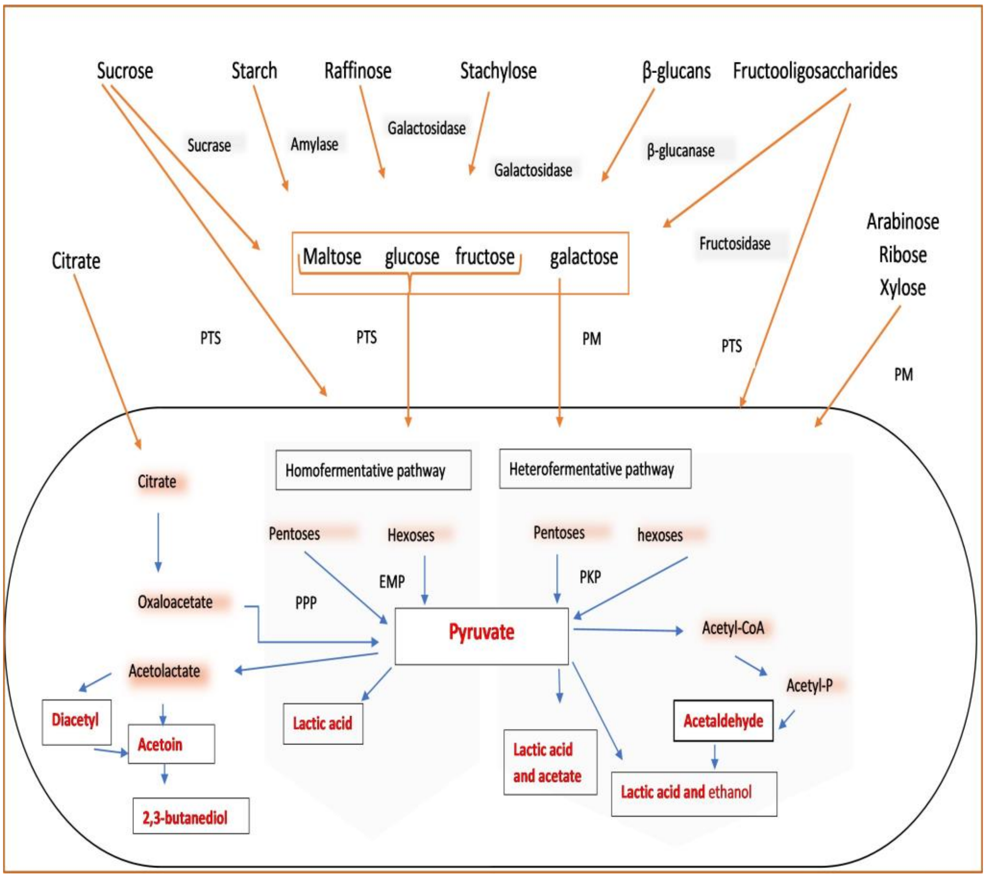

Figure 1. LAB carbohydrate and organic acid metabolism and flavour compounds produced. Phosphotransferase system (PTS), permease (PM), pentose phosphate pathway (PPP), Embden–Meyerhof pathway (EMP), phosphoketolase pathway (PKP). Flavour compounds labelled in red.

Table 2. Organoleptic properties of aroma and flavour metabolites identified in African fermented cereals.

Metabolite	Lactic Acid Bacteria Identified	Fermented Cereal	Associated Sensory Characteristic	Reference
Acids				
Lactic Acid	*L. rhamnosus* GR-1 and *S. thermophilus*	Pearl millet	Unknown	[15]
Acetic acid	*L. fermentum* LB-11 * *L. pentosus strain CE56.28.1, CE56.19,* *L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial* *L. rhamnosus* GR-1 and *S. thermophilus*	Maize Pearl Millet	Sour odour, vinegar odour, pungent smell Unknown	[28] [29] [15]
Propionic acid	*L. fermentum* LB-11 * *L. pentosus strain CE56.28.1, CE56.19,* *L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Sharp, rancid odour	[28] [29]

Table 2. *Cont.*

Metabolite	Lactic Acid Bacteria Identified	Fermented Cereal	Associated Sensory Characteristic	Reference
Pentanoic acid	*L. fermentum* LB-11 *	Maize	Burnt rubber odour	[28]
Hexanoic acid	*L. fermentum* LB-11 *	Maize	Urine-like odour, hay odour	[28]
Heptanoic acid	*L. fermentum* LB-11 *	Maize	Rubber odour	[28]
Octanoic acid	*L. fermentum* LB-11 *	Maize	Urine-like odour	[28]
Nonanoic acid	*L. fermentum* LB-11 *	Maize	Roast nut odour, chemical odour	[28]
Hexadecanoic acid	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial* Not identified	Maize	Nearly odourless-Green/fatty/waxy flavour	[29,30]
tetradecanoic acid	Not identified	Maize	Green-fatty/waxy flavour	[30]
(E)-octadec-11-enoic acid	Not identified	Maize	Unknown	[30]
(E)-hex-2-enoic acid	Not identified	Maize	Animal	[30]
hexanoic acid	Not identified	Maize	Animal	[30]
Alcohols				
3H-pyrazol-3-one	*Leuconostoc mesenteroides* and *Pediococcus pentoseaceus*	Pearl millet	Unknown	[21]
3,4-furandiol, tetrahydro-,trans	*Leuconostoc mesenteroides* and *Pediococcus pentoseaceus*	Pearl millet	Unknown	[21]
Ethanol	*L. fermentum* LB-11 * *L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Alcohol, fruity (mild, ether)	[28,29]
Propanol	*L. fermentum* LB-11 * *L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12, *Weissella confusa partial*	Maize	Alcoholic, fruity, gum	[28,29]
2-Methyl-1-propanol	*L. fermentum* LB-11 *L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12, *Weissella confusa partial*	Maize	Sweet smell, fruity	[28,29]

Table 2. *Cont.*

Metabolite	Lactic Acid Bacteria Identified	Fermented Cereal	Associated Sensory Characteristic	Reference
2-Pentanol	*L. fermentum* LB-11 *	Maize	Gum, fruity	[28]
1-Butanol	*L. fermentum* LB-11 *	Maize	Pungent, rubber	[28]
1-Penten-3-ol	*L. fermentum* LB-11 *	Maize	Boiled potatoes	[28]
2-Methyl butanol	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12, *Weissella confusa partial*	Maize	Aroma of tuber	[29]
2-Methoxl phenol	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12, *Weissella confusa partial*	Maize	Sweet odour	[29]
2-Methyl propanol	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12, *Weissella confusa partial*	Maize	Buttery or creamy	[29]
3-Methyl-butanol	*L. fermentum* LB-11 * *L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12, *Weissella confusa partial*	Maize	Vegetables, green odour Choking alcohol odour	[28,29]
1-Pentanol	*L. fermentum* LB-11 *	Maize	Unknown	[28]
1-Hexanol	*L. fermentum* LB-11 *	Maize	Unknown	[28]
1-Octen-3-ol	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Heptanol	*L. fermentum* LB-11 **L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12, *Weissella confusa partial*	Maize	Alcohol	[28,29]
1-Octanol	*L. fermentum* LB-11 *	Maize	Orange, sweet, fruity aroma	[28]
2-Undecen-1-ol	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Nonanol	*L. fermentum* LB-11 *	Maize	Popcorn aroma, odour of vitamin pill	[28]
3-Nonenol	*L. fermentum* LB-11 *	Maize	Unknown	[28]
1,2-Butandiol	*L. rhamnosus* GR-1 and *S. thermophilus*	Pearl millet	Unknown	[15]

Table 2. *Cont.*

Metabolite	Lactic Acid Bacteria Identified	Fermented Cereal	Associated Sensory Characteristic	Reference
Amino acid				
Tyrosine	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Amide				
2-hydroxypropanamide	Not Identified	Maize	Unknown	[30]
Carbonyls (ketones and aldehydes)				
2,4-Dihydroxy-2,5-dimethyl-3(2H)-furanone	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Valerophenone	Spontaneous and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
3-Acetoxy-2-methyl-pyran-4-one	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
2′,6′-Dihydroxy-3′-methylacetophenone	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
2-Hydroxy-1-(10-pyrrolidiyl)-1-buten-3-one	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Benz[cd]indol-2(1H)-one	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
				[22]
Ethanone, 1-(3,4-dimethoxyphenyl)-	Spontaneous, *L. fermentum* FUA 3165	Sorghum	Unknown	[22]
4-Amino-7-diethylamino-chromen-2-one	Spontaneous, *L. fermentum* FUA 3165	Sorghum	Unknown	[22]
6-Ethyl-4,7-dimethyl-2,3-benzofurandione	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Diacetyl	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Pentanal	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Hexanal	*L. fermentum* LB-11 *	Maize	Green, grass, pine odour	[28]
2-Pentenal	*L. fermentum* LB-11 *	Maize	Unknown	[28]
2-Heptanone	*L. fermentum* LB-11 *	Maize	Bad, unpleasant odour	[28]
Heptanal	*L. fermentum* LB-11 *	Maize	Green, sour green	[28]
Furfural	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Nonanal	*L. fermentum* LB-11 *	Maize	Aquarium, green, fatty	[28]
2-Octenal	*L. fermentum* LB-11 *	Maize	Unknown	[28]
2,4-Heptadienal	*L. fermentum* LB-11 *	Maize	Hot, potato, silage	[28]
Benzaldehyde	*L. fermentum* LB-11 *	Maize	Hot, potato, silage	[28]
2-Nonenal	*L. fermentum* LB-11 *	Maize	Old, musty, onions	[28]
Benzeneacetaldehyde	*L. fermentum* LB-11 *	Maize	Unknown	[28]
2-Decenal	*L. fermentum* LB-11 *	Maize	Unknown	[28]
2,4-Nonadienal	*L. fermentum* LB-11 *	Maize	Fermented, deep frying	[28]

Table 2. *Cont.*

Metabolite	Lactic Acid Bacteria Identified	Fermented Cereal	Associated Sensory Characteristic	Reference
2-Undecenal	*L. fermentum* LB-11 *	Maize	Fruity, cooked, rice	[28]
2,4-Decadienal	*L. fermentum* LB-11 *	Maize	Dough, fatty, soup	[28]
gamma.-nonalactone	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Vinylphenol	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Colour of grape wine	[29]
Ethyl caprylate	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Waxy odour	[29]
Ethyl caprate	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Waxy odour	[29]
2-methyl-naphthalene	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Unpleasant odour	[29]
1-methylnaphthalene	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Mothball smell	[29]
2-3-Butanediol	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Odourless	[29]
Ethyl isovalerate	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Strong odour	[29]

Table 2. *Cont.*

Metabolite	Lactic Acid Bacteria Identified	Fermented Cereal	Associated Sensory Characteristic	Reference
2-methoxy-4	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Pleasant, spicy odour	[29]
Ethyl dec-a-enoate	*L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial*	Maize	Odourless	[29]
Ester				
3-deoxy-d-mannoic lactone	*Leuconostoc mesenteroides* and *Pediococcus pentoseaceus*	Pearl Millet	Unknown	[21]
Pentyl acetate	Not identified	Maize	Fruity—tropical	[30]
Prop-2-enyl hexanoate	Not identified	Maize	Fruity—tropical	[30]
ethyl methyl carbonate	Not identified	Maize	Fruity—sweet	[30]
pentyl 2-methylpropanoate	Not identified	Maize	Fruity—sweet	[30]
pentyl butanoate	Not identified	Maize	Fruity—tropical	[30]
ethyl butanoate	Not identified	Maize	Fruity—tropical	[30]
ethyl nonanoate	Not identified	Maize	Fruity—tropical	[30]
pentyl 2-methylbutanoate	Not identified	Maize	Fruity—apple	[30]
1,2-Ethanediol, diacetate 1,2-Ethanediol,	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
l-Proline, N-methoxycarbonyl-, heptadecyl ester	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
4-Methoxyphenol, acetate Tetrahydropyran	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Salicylic acid, methyl ester Bromoacetic	*L. fermentum* FUA 3165	Sorghum	Unknown	[22]
Methyl 2-oxo-1-pyrrolidine acetate	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
1-Ethyl-2-pyrrolidinecarboxylic acid, methyl ester	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Proline, 1-acetyl-, methyl ester	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Phthalic acid, 4-chloro-3-methylphenyl ethyl ester	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Hydrocinnamic acid, 4-hydroxy-3-methoxy-, methyl ester	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]

Table 2. *Cont.*

Metabolite	Lactic Acid Bacteria Identified	Fermented Cereal	Associated Sensory Characteristic	Reference
3-Cyclopentylpropionic acid, 2-dimethylaminoethyl ester	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Phthalic acid, di(hept-2-yl) ester	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
Ethyl acetate	*L. fermentum* LB-11 *	Maize	Flowery, ester odour	[28]
Ethyl propionate	*L. fermentum* LB-11 *	Maize	Fruity, gum, sweet	[28]
Isoamyl acetate	*L. fermentum* LB-11 *	Maize	Fruity	[28]
Ethyl hexanoate	*L. fermentum* LB-11 *	Maize	Fruity, plant, pear	[28]
Hexyl acetate	*L. fermentum* LB-11 *	Maize	Green odour, onion aroma	[28]
Ethyl lactate	*L. fermentum* LB-11 *	Maize	Fruity	[28]
Ethyl heptanoate	*L. fermentum* LB-11 *	Maize	Flowery	[28]
Heptyl acetate	*L. fermentum* LB-11 *	Maize	Onion, green	[28]
Ethyl nonanoate	*L. fermentum* LB-11 *	Maize	Unknown Fruity—tropical	[28] [30]
Ethylphenyl acetate	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Ethyl dodecanoate	*L. fermentum* LB-11 *	Maize	Unknown	[28]
Myristic acid, methyl ester	*L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
9,12-Hexadecadienoic acid, methyl ester	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
cis-13-Octadecenoic acid, methyl ester	Spontaneous, *L. fermentum* FUA 3165 and *L. fermentum* FUA 3321	Sorghum	Unknown	[22]
n-Hexadecanoic acid		Pearl Millet	Unknown	[21]
trans-9-Octadecenoic acid, pentyl ester	*L. fermentum* FUA 3165	Sorghum	Unknown	[22]

* LAB identified during spontaneous fermentation.

3.2. Protein Metabolism during Lab Fermentation of Cereals and Its Association with Flavour and Aroma Compound Production

LAB require amino acids for nitrogen and carbon metabolism [55]. Some of the nitrogen sources are available as free amino acids in the substrate, while some have to be released from the parent polypeptide, which indicates the presence of a proteolytic system. The proteolytic mechanisms of LAB involve the degradation of proteins, various peptide transport systems, the degradation of peptides, and amino acid catabolism (Figure 2) [56]. LAB such as *Lb. plantarum*, *Lb. fermentum* and *L. deldrueckii* isolated from ting, bushera and maheu in studies have been reported to possess a proteolytic ability that enables them to hydrolyse proteins into peptides and amino acids [57]. This protein degradation may be initiated by cell envelope proteinases (CEPs) as well as substrate proteases activated by a low-pH environment [56,58,59]. The efficiency of the proteolytic system and pattern of protein hydrolysis may be affected by CEP differences (gene mutation or gene expression) and enzyme optimal conditions [59].

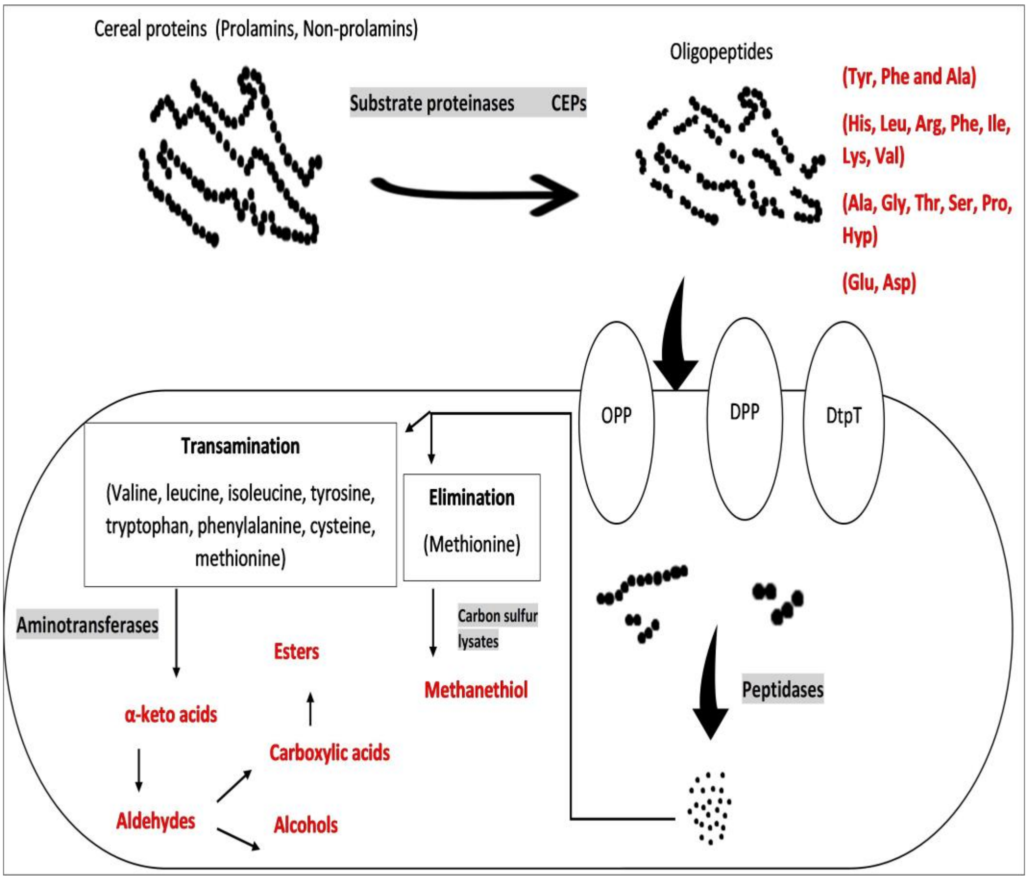

Figure 2. Protein metabolism via LAB in cereal substrates. Cell envelope proteinases (CEPs), oligopeptide permease (Opp), ion-linked transporter (DtpT), ABC transporter (Dpp). Flavour compounds labelled in red.

The presence of large hydrophobic peptides produced by the proteases is related to the bitter taste of fermented products. In fermented foods, the peptide His-Leu-Arg-Phe-Ile-Lys-Val has been associated with a bitter taste, while Tyr-Phe-Ala has been described as sour [11]. Ala-Gly-Thr-Ser-Pro-Hyp and Glu-Asp have been reported to have a sweet and umami/salty taste, respectively [11]. The produced peptides are internalised into the bacterial cell for further degradation into amino acids [58]. The utilisation of amino acids via LAB varies according to strains (genetic and adopted differences) as well as the availability of nutrients from the substrate [55]. The amino acids produced may be required for the survival of LAB in a hostile environment or for toxin synthesis [55].

The amino acids present in the bacterial cell can be further metabolised to produce important aroma compounds such as aldehydes, alcohols and esters via the transamination and elimination of amino acid catabolic pathways [11]. Branched-chain amino acids (isoleucine, leucine and valine), aromatic amino acids, (phenylalanine, tryptophan and tyrosine) and sulphur amino acids (methionine and cysteine) may be degraded via the transamination route, whereas methionine may be converted to methanethiol [60]. The transaminated amino acids are converted to α-keto acids, which can also be further metabolised to aldehydes. The aldehydes are metabolised to produce either alcohols, via alcohol dehydrogenase, or carboxylic acids. Esters are then synthesised from carboxylic acids via esterases [60]. Acetaldehyde, which has been detected in ogi (maize/corn), may also be produced via LAB from threonine catabolism [24,29]. Volatile compounds such as ethanol, propionic acid, 1-Propanol, acetic acid, 3-Methyl-1-butanol and hexanoic acid, all isolated from fermented maize products [28,29], may be metabolic products of Ala, Gly, Leu and Lys [61].

3.3. Other Compounds which Can Contribute to the Flavour/Aroma of Fermented Cereals

Cereals generally have a low concentration of lipids. However, lipids can be hydrolysed by LAB, particularly the *Lactococcus* and *Lactobacillus* species, to release free fatty acids [11]. Free fatty acids such as butanoic acid, hexanoic acid and octanoic acid have been identified in fermented maize [28,30]. LAB can release esterases to produce ethyl butanoate and ethyl hexanoate from the esterification of ethanol with butyric and hexanoic acids, respectively. Free fatty acids can be oxidised to produce hydroperoxides and, subsequently, aldehydes. In addition, compounds such as alkanes, methyl ketones, esters, secondary alcohols and lactones can be formed as a result of free fatty acid oxidation [11]. Cereals are good sources of phenolic phytochemicals such as ferulic acid. Although these compounds are known to have some inhibitory activity against bacteria, some LAB (*Levilactobacillus brevis*, *Limosilactobacillus fermentum* and *Lactiplantibacillus plantarum*) have been found to have phytochemical degradation activities by decarboxylation and reduction reactions [56,62]. LAB may produce enzymes such as β-glucanase, which hydrolyses the β-glycosidic bond of conjugated phenolic compounds or ferulic acid esterase, to release a free form of ferulic acid [63]. Flavour compounds such as 4-vinyl phenol and 4-vinyl guaiacol may be produced via the decarboxylation of p-coumaric and ferulic acids [62]. Vinyl phenol has been detected after the spontaneous fermentation of maize, with LAB such as *L. pentosus strain CE56.28.1, CE56.19, L. plantarum strain* 28.19 E, NWAFU1572, *P. acidilactici strain* AA106, *P. pentosaceus strain* OO1, *L. fermentum strain* CAU:235, YLc37C, BB101, *Enterococcus faecium strain* AA109, *Weissella confusa* strain JBA12 and *Weissella confusa partial* being identified, among other microorganisms present in the substrate [29]. Guaiacol has been identified in sorghum fermented with *L. fermentum* FUA 3165 [64]. A reduction in vinyl phenols may lead to the production of flavour metabolites such as ethyl phenol and ethyl guaiacol [62].

4. Relationship between the Sensory Characteristics and Flavour/Aroma Compound of African Fermented Cereals

Fermentation results in biochemical changes in the substrate, which in turn determine the sensory characteristics of the fermented product, and thus influence the perception of consumers. The organoleptic properties of fermentation-derived metabolites have a significant impact on the appearance, aroma, texture and taste/flavour of the resultant products. The metabolites, and thus sensory perception produced, depend on the nature of the substrate, the inoculum used or lack thereof and other fermentation conditions such as duration and temperature [65]. Although the appearance and texture of fermented products are important, their aroma and flavour are more valuable studies, as these are distinguishing characteristics. To this end, several studies on African fermented cereals have attempted to determine the aroma and flavour metabolites produced by the fermentation of different cereals. This is essential to better understand how the fermentation process impacts the consumer acceptance of products. Table 2 depicts the flavour compounds identified in various African fermented cereals and their sensory descriptors. In general, LAB-fermented products are characterised by a sour/acidic flavour [66], which has been linked to the production of acetic acid from the breakdown of sugars [28,30,67]. The presence of alcohols in fermented maize has been associated with fruity (mild and ether), alcoholic, sweet-smelling, pungent, buttery or creamy scents, as well as the scent of rubber, boiled potatoes or a choking alcohol odour, as depicted in Table 2. The presence of alcohol is linked mainly to yeasts in spontaneously fermented cereals, while LAB contribute to a lesser extent [28]. Diacetyl, a carbonyl compound, has also been detected in fermented maize and is associated with a butter or butterscotch flavour.

Various types of esters have been identified in fermented maize, pearl millet and sorghum products [21,22,30]. Esters are usually associated with a fruity flavour [68] and can mask or reduce the flavour intensity of free-amino-acid-derived notes that are usually unpleasant [69]. The perception of a flavour compound may change with its increased concentration in a product [70]. Therefore, the overall sensory characteristics of African fermented cereals is ultimately determined by the interaction and balance between different flavour compounds. Fermentation, in conjunction with low pH, contributes to the sensory perception of the product. This is evidenced by the absence of desirable flavours associated with fermentation after the reduction in pH by the addition of lemon juice in non-fermented cereals [71]. Akamu (ogi) fermented with *L. plantarum* was better accepted compared to an unfermented, artificially acidified sample or unfermented, unacidified akamu [31]. *L. plantarum*-fermented akamu was characterised by flavour notes reminiscent of honey and apples [31].

Even though LAB are important players in spontaneous fermentation, the aroma profiles of products from controlled LAB fermentation differ from their spontaneous fermentation counterparts. For example, uji produced via LAB fermentation was dominated by acidic aromatic compounds, while the same spontaneously fermented product was dominated by aromatic esters [32]. The authors of this particular study suggested that the former was generally described as sour and unpleasant, and the latter was related to fruity aromas and was thus more likely to be accepted by consumers. Spontaneously fermented products sometimes develop off-flavours due to the presence and growth of undesirable microorganisms during the fermentation process [32]. Fermented products have also been negatively characterised as rancid or pungent by some consumers [30]. This is likely to have occurred due to the presence of butanoic acid, hexanoic acid and octanoic acids, which have been variously described to have rancid and cheesy aromas, a pungent aroma, and what has been pronounced to have a waxy, soapy, goaty, musty, rancid or fruity flavour, respectively. However, several factors may affect the odour and flavour profiles of fermented products.

5. Correlation between Sensory Characteristics and Consumer Preference of African Fermented Cereals

In general, African fermented foods provide a unique culinary experience which makes them sought after. Sensory perception plays a significant role in consumer acceptance. Therefore, it is important for studies on the fermentation of cereals to evaluate the sensory perception of products. Sensory evaluation entails the objective (examining the descriptive sensory analysis) and/or subjective assessment (such as hedonic studies) of the intensity and human preference towards the appearance, aroma, taste/flavour, texture and aftertaste of food products, following standard procedures that reduce bias and unwanted/erroneous variation [72].

Most studies reviewed for this work which have carried out sensory evaluations for controlled LAB-fermented products employed hedonic studies to determine the acceptability of the products by consumers [43]. These hedonic studies involved the use of a 'liking scale' of 7 to 11 points (pts), ranging from dislike extremely (lower end of the scale) to like extremely (upper end of the scale) [73]. Ideally, over 100 (minimum 50) consumers who regularly consume the same or similar products should be used for a study. Fermented products were generally liked, as indicated by a rating from 'like slightly' to 'like extremely' on a hedonic scale [17,33,74]. Many of the studies reviewed reported the use of marginal sensory methods; for example, most of the studies used less than 50 people and sometimes included staff and students who were working on the project, which may have led to the introduction of bias. For example, Banwo et al. [43], Obinna-Echem [31] and Tamene et al. [39] used 30 people, while Adesokan et al. [33] and Wakil and Kazeem [6] used as few as 10 people. The studies did not report whether or not these were regular consumers of the products.

Some studies compared the impact of spontaneous versus controlled LAB fermentation on the acceptability of the products [31,39]. Other studies compared LAB-fermented products to their unfermented counterparts. The flavour of LAB-fermented akamu was moderately liked in a study by Obinna-Echem [31], with the controlled LAB-fermented akamu being preferred to the back-slopped fermented variant, while the unacidified, unfermented variant was neither liked nor disliked, and the artificially acidified variant was disliked [31]. Consumer preference for the controlled LAB-fermented akamu may have been due to its honey or fruity notes, which are a result of the production of alcohols and esters during the microbial fermentation of maize [28,30].

Sensory evaluation was used to compare different inocula. In a study, Maheu fermented via back-slopping from an original preparation of maheu inoculated with *L. rhamnosus* yoba was compared to a spontaneously fermented variant [38]. As expected, the authors reported a drop in the pH and an increase in the titratable acidity of both maheu slurries during fermentation. Although both maheu were generally liked, with scores above 5 on a 9 pt scale, the back-slopped maheu had significantly higher acceptability than the control in all the attributes measured at Day 0, with these being appearance, taste, colour, sourness and overall acceptability, but it only had higher acceptability for appearance, taste and colour by Day 20. The sourness and overall acceptability of both maheu preparations decreased between Day 0 and Day 20. This indicates that the overall acceptability of the maheu preparations decreased with increasing acidity. A similar study conducted by Mamhoud et al. [9] reported that the addition of spontaneously and control-fermented sourdough (wheat) significantly increased the intensity of the acidic flavour in the bread [9]. The bread made with the control-fermented sourdough was saltier and less sweet than that made from the spontaneously fermented sourdough. The authors linked these findings to the production of acids and saltiness due to the proteolysis of wheat proteins.

Only a few of the studies linked the consumer acceptability of products with their objective sensory perception, with one study only carrying out the latter [9,73]. Objective sensory evaluation entails the use of methods such as descriptive sensory evaluation, where a trained sensory panel generates sensory attributes (descriptors) and assesses the intensity of the sensory attributes in each product. In this study, Maheu/mageu was neither particularly liked nor disliked, as consumers rated it between 4.7 to 5.4 on a 9 pt scale [73]. A comparison with data from the trained sensory panel revealed that consumers in the study generally preferred a sweeter product, and the consumers recommended that the taste and flavour of the products should be improved. In another study, the sensory quality of bread made from wheat sourdough fermented via *Pedicoccus acidilactici* O1A1, *Pediococcus pentosaceus* OA2 and *L. curvatus* MA2 was assessed using 10 trained panellists [73]. The attributes assessed included the colour of crust and crumb, acid taste and flavour, sweetness, elasticity, and dryness. The fermented wheat sourdough breads were characterised by an acidic flavour and salty taste compared to the baker's yeast bread. The acidic flavour and salty taste were likely a result of the LAB carbohydrate and protein metabolic activities, as discussed in Section 3. Sensory evaluation was also carried out in some studies to determine the storage stability of fermented products [40].

6. Conclusions and Future Perspectives

Fermentation remains the dominant food processing technology in the developing world, and cereals are some of the most popular fermentation substrates in Africa. LAB and yeasts are the predominant microorganisms during spontaneous fermentation. However, LAB activities during cereal fermentations (spontaneous or controlled) contribute significantly to the production of flavour-active/aroma compounds and flavour precursors important to the sensory perception of fermented products. This review presented the biochemical pathways (carbohydrate, protein, lipid and polyphenol metabolism) related to the production of various flavour compounds found in African fermented cereals. Although it is recognised that lactic acid is dominant in homofermentative fermentations and acetic acid is dominant in heterofermentative fermentation, other fermentation metabolites produced also contribute to varied sensory perceptions of these African fermented cereal products. The flavour consortia of metabolites present in substrates (pearl millet, maize and sorghum) varies, suggesting that an elaborate flavour interdependency exists between the presence of LAB and substrate components. In order to understand the comprehensive flavour characteristics of African fermented cereals, sensory evaluation in conjunction with instrumental flavour/aroma analysis is required. As depicted in Table 2, more sensory lexicons should be developed to appropriately describe these fermented cereals and to identify compounds that influence consumers' preferences of these products. In the studies reviewed, the acceptability of products made from controlled LAB fermentation depended on the substrate or compositing of substrates, the inoculum used and the duration of fermentation.

In the future, African fermented cereal products should be designed to meet the changing consumer preferences. The product portfolio should be diversified to provide more flavour options to meet every consumer's preference. Microorganisms can be selected and used in controlled fermentation to impact the desired flavour in the products. For instance, some alcohols and esters produced via fermentation have a characteristic fruity flavour [28–30]; thus, microorganisms that produce such metabolites during the fermentation of cereals may be selected. Artificial flavourings and/or sweeteners may also be used. Furthermore, the fermentation time and temperature may be adjusted to obtain the desired flavour and aroma; for instance, the fermentation time may be adjusted to limit the production of acids and reduce the acidic flavour. Sensory evaluation techniques should also be applied to better improve the acceptance of these products. Future studies should endeavour to use many consumers (at least 100) who regularly eat the products studied to determine the sensory drivers of consumer preference. The objective characterisation of these products using a trained sensory panel and hedonic studies can be used to develop and tailor African fermented cereal products for non-African communities.

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