Current Research in Food Science 8 (2024) 100747

Contents lists available at ScienceDirect

Current Research in Food Science

journal homepage: www.sciencedirect.com/journal/current-research-in-food-science

Review Article

Flavor of extruded meat analogs: A review on composition, influencing factors, and analytical techniques

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ARTICLE INFO

Keywords:
High moisture extrudate
Meat analog
Flavor composition
Influencing factors
Analytical techniques

ABSTRACT

Meat analogs are anticipated to alleviate environmental and animal welfare concerns as the demand for meat rises. High moisture extrusion is commonly employed to produce meat analogs, and its flavor could influence consumers' choice. To improve the development and market demand of extruded meat analogs, flavor precursors and natural spices have been used in high moisture extrusion process to directly improve the flavor profile of extruded meat analogs. Although there have been many studies on the flavor of high moisture extruded meat analogs, flavor composition and influencing factors have not been summarized. Thus, this review systematically provides the main pleasant and unpleasant flavor-active substances with 79 compounds, as well as descriptive the influence of flavor-active compounds, chemical reactions (such as lipid oxidation and the Maillard reaction), and fiber structure formation (based on extrusion process, extrusion parameters, and raw materials) on flavor of extruded meat analogs. Flavor evaluation of extruded meat analogs will toward multiple assessment methods to fully and directly characterize the flavor of extruded meat analogs, especially machine learning techniques may help to predict and regulate the flavor characteristics of extruded meat analogs.

1. Introduction

Meat products are chosen by consumers for their rich nutritional content and unique taste. However, excessive consumption of meat can cause obesity, type II diabetes, heart disease and some cancers, which are harmful to health (López-Suárez, 2019). Moreover, the annual increase in meat consumption has led to challenges for livestock production in terms of animal welfare, zoonotic diseases, waste of soil and water resources and greenhouse gas emissions (Gonzalez et al., 2020). The development of meat analogs has been driven by increasing consumer demand for healthier diets and greater environmental protection. Currently, meat analogs have attained significant production levels and consistent sales in the market (Ishaq et al., 2022). These meat analogs are sourced from a variety of sources, including grains, seeds, legumes, as well as non-traditional substitutes like microbial proteins, edible mushrooms, and insect proteins (Grahl, et al., 2018; Zhang et al., 2022; Jiang et al., 2024).

Currently, meat analogs are produced through electrostatic spinning, extrusion technology, and 3D printing processes. These techniques aim to mimic the texture and mouthfeel of animal meat by inducing an anisotropic structure within the proteins. However, electrostatic spinning and 3D printing are yet to be integrated into continual industrial production due to technical challenges. Due to its high productivity, cost-efficiency, versatility and water conservation, the extrusion process is prevalently employed in the industrial production of meat analogs. The extrusion process has the potential to decrease anti-nutritional factors and elevate the general quality of the product (Nikmaram, et al., 2017; Usman et al., 2023). In recent years, high moisture (above 40%) extrusion has made meat analogs production easier and divided it into two categories. One type is the whole cut meat analogs, such as imitation chicken products (Wang et al., 2022). Another approach is to produce minced meat analogs by marinating or secondary processing of textured proteins, such as the development of various snacks and the preparation of vegetarian meatballs (Baune, et al., 2021).

With the increase in consumption and the improvement of dietary habits, consumers are not only concerned about the nutritional value of food but also about the sensory experience it provides. So, flavor profile of extruded meat analogs is crucial in boosting consumer acceptance and increasing market share (Starowicz et al., 2022). Several review articles have focused on summarizing the raw materials, operational

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https://doi.org/10.1016/j.crfs.2024.100747
Received 9 March 2024; Received in revised form 11 April 2024; Accepted 21 April 2024
Available online 22 April 2024

parameters, and mechanisms for forming fibrous structures in meat analogs though high moisture extrusion (Guyony et al., 2023; Zhang et al., 2022). However, the flavor composition of extruded meat analogs and the influence of extrusion process factors on flavor have not been comprehensively discussed and clarified.

The raw materials (such as soy protein) of high moisture extrusion naturally occur some unpleasant flavor-active compounds (such as hexanal) which restrict the consumer acceptance (Wang et al., 2021). On the other hand, the typical meat flavors such as monosodium glutamate, ribonucleotides and heterocyclic compounds containing sulfur, nitrogen and oxygen (thiophenes, furans, pyrazines, etc.), which is an important factor in consumer acceptability (Chen et al., 2022). The lack of typical meat flavors is also a challenge in meeting the flavor requirements of meat analogs. Therefore, flavor additives can used before or after extrusion to improve the flavor profiles of extruded meat analogs. Although extruded meat analogs marinated in flavor additives are more convenient, there is a high demand for flavor additives. Furthermore, the flavor additives become exposed on the surface of the extruded meat analogs during marination process, potentially resulting in uneven distribution and oxidation (Bhandari, D'Arcy and Young, 2001). The addition of flavor additives before the extrusion process results in their uniform distribution in extrudates. However, flavor components are lost with water vapor. In the current review, only the addition of flavor additives before extrusion and flavor retention in extrudates will be emphasized. The pleasant and unpleasant flavor-active compounds and their formation mechanism are reviewed. Additionally, the future research directions and challenges are also discussed. The objective of this research is to discuss the flavor composition, influencing factors, and analytical techniques of extruded meat analogs, providing a useful reference for investigating and improving flavor quality of these products.

2. Flavor compounds in extruded meat analogs

Protein, water, carbohydrates, lipids and some flavor enhancers are usually the raw materials in high moisture extruded meat analogs. As shown in Fig. 1, the flavor composition of extruded meat analogs includes flavor compounds present in the raw materials, such as hexanal, 2-pentylfuran, and saponins in legume proteins, as well as flavor substances formed through thermal reactions in the barrel. Certain flavor precursors from raw materials are broken down into flavor compounds due to the high temperatures in the environment of the barrel. For example, lipid, amino acids, and thiamin may occur lipid oxidation, Maillard reaction and thiamin degradation, which results in the production of volatile aromatic substances such as aldehydes, ketones, furans and sulphury compounds, which leads to changes in flavor substances and content during the extrusion process.

The flavor active components of the high moisture extruded meat analogs are shown in Table 1. Volatile flavor substances that have been detected in extruded meat analogs include aldehydes, alcohols, ketones, aromatic compounds, esters, alkenes, furans, pyrazines organic acids, nitro compounds, and terpene (Usman, et al., 2023; Yang et al., 2023). Hexanal, 2-pentylfuran, benzaldehyde, 1-octen-3-ol, 2-heptanone, 2-nonanone, and nonanal have most abundant in soybean-based extrudates (Yang et al., 2023). Flavor changes in faba beans and high moisture extruded faba bean meat analogs were investigated by Tuccillo et al. (2022). In addition to the volatile flavor components, non-volatile flavor-active compounds were also detected in the extrudate, such as palmitic acid, oleic acid, linoleic acid, α-linolenic acid, free fatty acids, free amino acids, and sucrose. Furthermore, some compounds with a

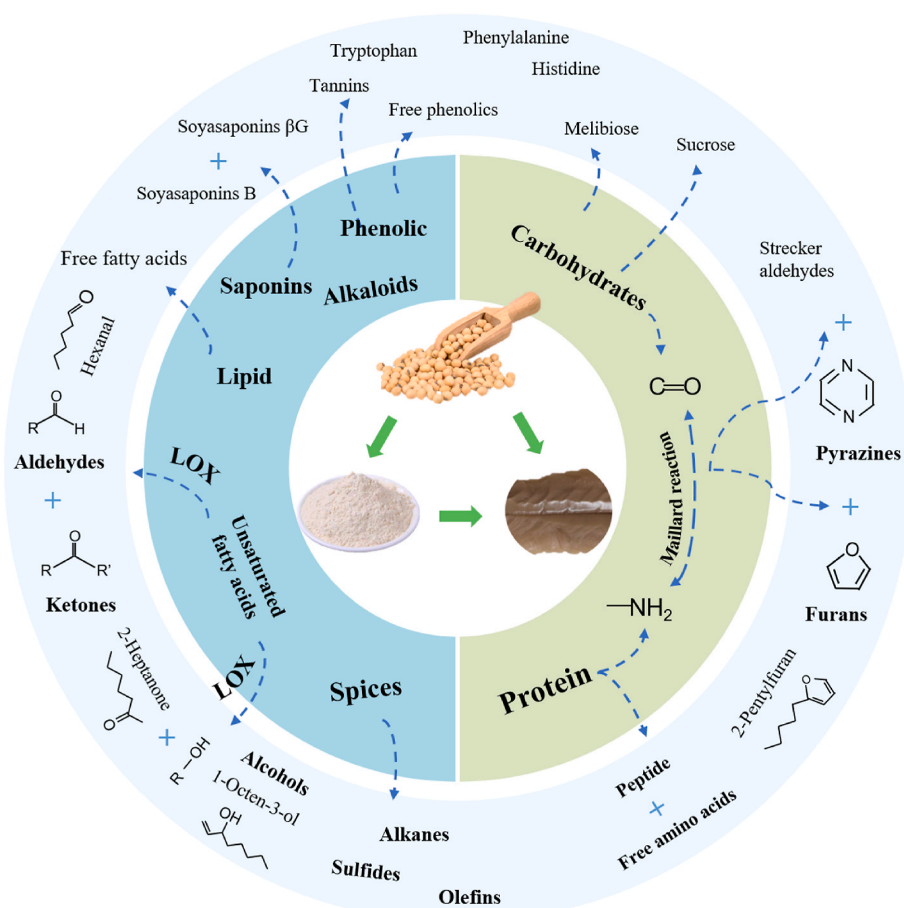

Fig. 1. The composition of flavor in high moisture extrudates.

Table 1
Flavor-active compounds from the high moisture extruded meat analogs.

Flavor-active compounds	CAS	Sensory attributes	References
Pleasant compounds			
Diallyl disulfide	2179-57-9	Meaty, Salty	Yuan, et al. (2023)
Terpineol	8000-41-7	Clove, Pine	Yuan, et al. (2023)
Linalool	78-70-6	Flowery, Waxy, Woody	(Yang et al., 2023; Yuan et al., 2023)
3-Carene	13466-78-9	Lemon, Resin	Yuan, et al. (2023)
α-Pinene	80-56-8	Pine, Turpentine	(Tuccillo, et al., 2022; Yuan et al., 2023)
2,4-Di-tert-butylphenol	96-76-4	–	Yuan, et al. (2023)
(E)-Oct-2-enal	2548-87-0	French fries	Usman, et al. (2023)
Diallyl sulfide	592-88-1	–	Yuan, et al. (2023)
Pentanal	110-62-3	Almond, Malt, Pungent	(Tuccillo, et al., 2022; Yuan et al., 2023)
1-Octanol	111-87-5	Waxy, Green, Mushroom	(Yang et al., 2023; Yuan et al., 2023)
3-methylbutanoic acid	503-74-2	Sweaty, Acid, Rancid	(Lan et al., 2020; Tuccillo et al., 2022)
2-methylbutanal	96-17-3	Malty	(Liu et al., 2023; Tuccillo et al., 2022)
3-methylbutanal	87994-87-4	Malty	(Liu et al., 2023; Tuccillo et al., 2022)
Unpleasant compounds			
Hexanal	66-25-1	Grassy, Green, Sweaty.	(Tuccillo, et al., 2022; Usman et al., 2023; Yang et al., 2023; Yuan et al., 2023)
Benzaldehyde	100-52-7	Bitter almond	(Tuccillo, et al., 2022; Usman et al., 2023; Yang et al., 2023; Yuan et al., 2023)
Heptanal	111-71-7	Fatty, Oily	(Tuccillo, et al., 2022; Usman et al., 2023; Yuan et al., 2023)
2-Pentylfuran	3777-69-3	Fragrant, Waxy, Eartly	(Tuccillo, et al., 2022; Usman et al., 2023; Yang et al., 2023; Yuan et al., 2023)
2-Nonanone	821-55-6	Fatty, Fresh	(Yang et al., 2023; Yuan et al., 2023)
Pentanoic acid	109-52-4	Stinky	Usman, et al. (2023)
Octanal	124-13-0	Fatty, Aldehydic, Waxy	(Usman, et al., 2023; Yang et al., 2023; Yuan et al., 2023)
2-Octanone	111-13-7	Soapy, Earthy, Herbal	(Yang et al., 2023; Yuan et al., 2023)
2-Heptenal	2463-63-0	Fatty	Usman, et al. (2023)
furfural	98-01-1	Sweet, Fragrant, Baked bread	(Yang et al., 2023)
1-Hexanol	111-27-3	Salty, Beany, Potato	(Tuccillo, et al., 2022; Yuan et al., 2023)
Nonanal	124-19-6	Orange-like, Grassy, Waxy	(Tuccillo, et al., 2022; Usman et al., 2023; L. Yang et al., 2023; Yuan et al., 2023)
3-Octen-2-one	1669-44-9	Earthy, Pungency	Yuan, et al. (2023)
2-Octenal	2363-89-5	Vegetable, Cucumber, Fatty	Yuan, et al. (2023)
(E)-2-octenal	2548-87-0	Fresh, Cucumber, Waxy	(Yang et al., 2023)
Decanal	112-31-2	Oily	(Yang et al., 2023; Yuan et al., 2023)
3,5-Octadien-2-one	30086-02-3	Grassy, Green	(Tuccillo, et al., 2022; Yuan et al., 2023)
1-Nonanol	143-08-8	Fatty, Citrus	Yuan, et al. (2023)
1-octen-3-ol	3391-86-4	Mushroom, Grassy	(Usman, et al., 2023; Yang et al., 2023; Yuan et al., 2023)
2-heptanone	110-43-0	Fragrance, Cheese, Green.	(Tuccillo, et al., 2022; Yang et al., 2023; Yuan et al., 2023)
2-decanone	693-54-9	Fermented, Cheesy.	(Yang et al., 2023; Yuan et al., 2023)
Indole	120-72-9	Mothball, Burnt	Yuan, et al. (2023)
2-Butylfuran	4466-24-4	Mild, Fruity, Wine	(Tuccillo, et al., 2022; Yang et al., 2023; Yuan et al., 2023)
2-Ethylfuran	3208-16-0	Earthy	(Tuccillo, et al., 2022; Yang et al., 2023; Yuan et al., 2023)
3-methyl-1-butanol	123-51-3	Balsamic	(Tuccillo, et al., 2022; Wang et al., 2021)
Free phenolics	–	Bitter, Astringency	(Karolkowski et al., 2023; Tuccillo et al., 2022)
Soyasaponins B	–	Bitter, Astringent	Tuccillo, et al. (2022)
Soyasaponins βG	–	Bitter, Astringent, Metallic	(Price et al., 1985; Karolkowski et al., 2023; Tuccillo et al., 2022)
Vicine	–	Bitter	Tuccillo, et al. (2022)
Convicine	–	Bitter	Tuccillo, et al. (2022)
Tannins	–	Bitter	Tuccillo, et al. (2022)
Phenylalanine	–	Bitter	Tuccillo, et al. (2022)
Tryptophan	–	Bitter	(Tuccillo, et al., 2022; Usman et al., 2023)
Arginine	–	Bitter	Usman, et al. (2023)
Histidine	–	Bitter	Tuccillo, et al. (2022)
Others			
2-Butyl-2-octenal	13019-16-4	Fatty, Cucumber	Usman, et al. (2023)
2-Nonenal	2463-53-8	Citrus peel-like	Usman, et al. (2023)
2-Heptenal, (E)-	18829-55-5	Pungent, Green, Fresh	(Yang et al., 2023)
(E, Z)-2,4-Decadienal	25152-83-4	Green, Grass	Usman, et al. (2023)
(E)-2-Octen-1-ol	18409-17-1	Cucumber, Grass, Green	(Usman, et al., 2023; Yang et al., 2023)
2-Nonen-1-ol, (Z)-	41453-56-9	Slightly waxy, Melon, Sweet.	(Yang et al., 2023)
2-Decen-1-ol, (E)-	18409-18-2	Waxy, Citrus	(Yang et al., 2023)
1-Hexanol, 2-ethyl-	104-76-7	Citrus, Fresh, Sweet.	(Yang et al., 2023)
2-Octen-1-ol, (E)-	18409-17-1	Fatty, Oily, Fruity.	(Yang et al., 2023)
Furfuryl alcohol	98-00-0	Alcoholic, Musty, Sweet	(Yang et al., 2023)
3-Nonen-2-one	14309-57-0	Oily, Blue cheese, Woody	(Yang et al., 2023)
Ethyl crotonate	623-70-1	Musty, Onion and garlic, Caramelly	(Yang et al., 2023)
Octanoic acid, ethyl ester	106-32-1	Sweet, Waxy, Fatty	(Yang et al., 2023)
Octane	111-65-9	Green, Fat, Citrus	Tuccillo, et al. (2022)
Furan, 2-ethyl-5-methyl-	1703-52-2	Fresh, gassy, and burnt.	(Yang et al., 2023)
2-n-Butyl furan	4466-24-4	Mild, Fruity, Wine	(Yang et al., 2023)
Pyrazine, methyl-	109-08-0	Nutty, Brown, Roasted	(Yang et al., 2023)
Pyrazine, 2,5-dimethyl-	123-32-0	Cocoa, Roasted nuts, Woody	(Yang et al., 2023)
Pyrazine, 2-Ethyl-6-methyl-	13925-03-6	Roasted potato	(Yang et al., 2023)

(continued on next page)

Table 1 (*continued*)

Flavor-active compounds	CAS	Sensory attributes	References
Pyrazine, trimethyl-	14667-55-1	Raw nut skin, Vegetable	(Yang et al., 2023)
Toluene	108-88-3	Sweet	(Yang et al., 2023)
Delta-3-carene	13466-78-9	Lemon, Resin	Tuccillo, et al. (2022)
(E)-2-Decenal	3913-81-3	–	Usman, et al. (2023)
Hexanoic acid	142-62-1	–	Usman, et al. (2023)
Nonanoic acid	112-05-0	–	Usman, et al. (2023)
3-Ethyl-benzaldehyde	34246-54-3	–	Usman, et al. (2023)
2-Hexenal, 2-ethyl-	645-62-5	–	(Yang et al., 2023)
2-octene	111-67-1	–	Tuccillo, et al. (2022)
Nitrohexane	25495-95-8	–	Tuccillo, et al. (2022)
Hexanoic acid, 2-phenyl-ethyl ester	6290-37-5	–	(Yang et al., 2023)

bitter taste were found in the extrudates, including free phenolics, soyasaponins B, soyasaponins βG, vicine, convicine and trace amounts of tannins.

As shown in Table 1, off-flavor compounds in extruded meat analogs are unpleasant flavor-active compounds formed by the material and extrusion process. They consist of volatile compounds such as aldehydes, ketones and alcohols, as well as non-volatile compounds such as bitter amino acids, free phenolics and convicine. Hexanal, hexanol, 1-octen-3-ol and 2-pentylfuran are considered to be important beany flavor compounds (Achouri et al., 2006), which have been identified in extruded meat analogs (Usman, et al., 2023). The faba bean protein extruded meat analogs (The total mass feed rate was 50 g/min, and the water content was 60%. The extruder barrel consisted of six temperature-controlled zones with the following temperature profile: 25, 40, 80, 100, 120, and 150 °C, respectively) was reported that its off-taste is strongly correlated to the presence of free phenols, vicine and convicine, which resulted in a distinct flavor profile of the extrudate characterized by both strong taste and aftertaste, bitterness, and a drying mouth sensation (Tuccillo, et al., 2022).

3. Flavor-related compounds

3.1. Flavor compounds in extruded materials

During extrusion, the material fed into the barrel undergoes high temperatures and pressures, which release small amounts of volatile flavors, and some of the flavor components carried by the raw material are retained in the meat analogs. Protein, as the main material for high moisture extrusion, has been detected for volatile flavor substances such as aldehydes, ketones, alcohols, pyrazines, furans and others. For pea protein, 25 volatile flavor substances have been identified, of which 2-methylbutanal, hexanal, geosmin, 2-hexanone, 1-octen-3-one, (E,E)-3,5-octadien-2-one, 1-nonen-3-one, 2-methylisoborneol, 1-pentanol, 2,3-diethyl-5-methylpyrazine, 2-sec-butyl-3-methoxypyrazine and 2-isopropyl-3-methoxypyrazine are the main aroma-active compounds (Liu et al., 2023). The presence of these compounds is probably related to the binding of proteins to lipid oxidation products during storage and processing into protein concentrates or isolates (Liu et al., 2023). And 69 aroma-active volatile compounds have been identified in algae, with alcohols, aldehydes, and ketones being the most prominent groups responsible for influencing the aroma of algae (Urlass, et al., 2023). Furthermore, non-volatile flavor components, such as fatty acids, organic acids, amino acids and other compounds, were also identified. Identified that the intensity of umami taste in pea protein isolate is mainly affected by a combination of three compounds, specifically 5′-adenylate (AMP), 5′-uridine monophosphate (UMP), and monosodium glutamate (MSG). Algae contain non-volatile substances with high sodium content that produce a savory flavor, as well as free fatty acids including α-linolenic, linoleic, tri-hydroxy and monohydroxy fatty acids, which produce a bitter flavor. Organic acids such as lactic, succinic and propionic acids are also present in algae, in addition to free amino acids that contribute to a fresh taste (Urlass, et al., 2023).

Natural spices, such as garlic, onion, and pepper, are natural plant ingredients. For their antioxidant and antimicrobial properties, natural spices have been used for clean labels. Natural spices are aromatic, pungent, bitter and sweet (Li and Li, 2020). Natural spices in powder or extract form are incorporated into protein raw materials to produce meat analogs by high moisture extrusion. The addition of natural spices results in the development of distinct flavor, while masking off-flavors, and contributing to the overall harmonization of extrusion flavor. The addition of natural spices to the high moisture extrusion process brings about aromatic constituents in the extrudate, including olefins, alkanes and sulfides (Guo et al., 2020). Of these, 3-carene, (+)-4-carene, d-limonene, caryophyllene and diallyl disulfide were identified in the extrudates, and their respective characteristics described as spicy, citrus, lemon, sweet and meaty or salty (Yuan, et al., 2023). This indicates that incorporating spices as ingredients in a high moisture extrusion process can effectively retain their flavor components and enhance the flavor profile of the extrudate.

3.2. Flavor precursors in extruded materials

Flavor precursors are substances that can react to form flavor compounds. As shown in Fig. 2, the flavor precursors of extruded meat analogs are proteins, lipids, carbohydrates, and flavor enhancers present in the raw materials. Reducing sugars, hydrolyzed proteins, yeast extract, amino acids and other Maillard precursors are often used for developing meat-like flavors to enhance umami flavor (Li and Li, 2020).

3.2.1. Protein

Protein, which provide macronutrient to meat analogs, serve as the main source materials in high moisture extrusion (van der Sman and van der Goot, 2023). Legume proteins are an excellent source of plant protein and are rich in nutrients (Zhang et al., 2022; Ke and Li, 2024; Wang et al., 2024). In addition to plant source proteins, algae proteins and yeast proteins have also been used (Grahl, et al., 2018; Xia et al., 2023). They are critical for the formation of anisotropic structures during high moisture extrusion, which are typically used in the form of protein concentrates or isolates (Beniwal et al., 2021). Proteins can provide flavor compounds for extruded meat analogs by binding to flavor compounds in the raw protein materials. In addition, it is worth noting that proteins may serve as flavor precursors, disintegrated into amino acids and peptides when exposed to high temperatures. These amino acids and peptides serve as precursors for certain volatile flavor compounds by offering amino groups for the Maillard reaction, resulting in elevated levels of volatiles (Riha, 1996). And these amino acids and peptides are important flavor components in meat analogs. Ho and Riha (2005) reported that the amino acid added produced volatiles substances content in the extrudates, and glutamine promoted higher levels of pyrazines, glutamic acid produced higher levels of furans. The type and quantity of free amino acids and peptides present contribute to the overall flavor properties. Umami amino acids such as glutamic and aspartic acid, as well as umami peptides, enhance the umami taste. Conversely, bitter amino acids such as isoleucine, tyrosine, tryptophan, and phenylalanine, as well as bitter peptides, provide an unpleasant taste in meat analogs.

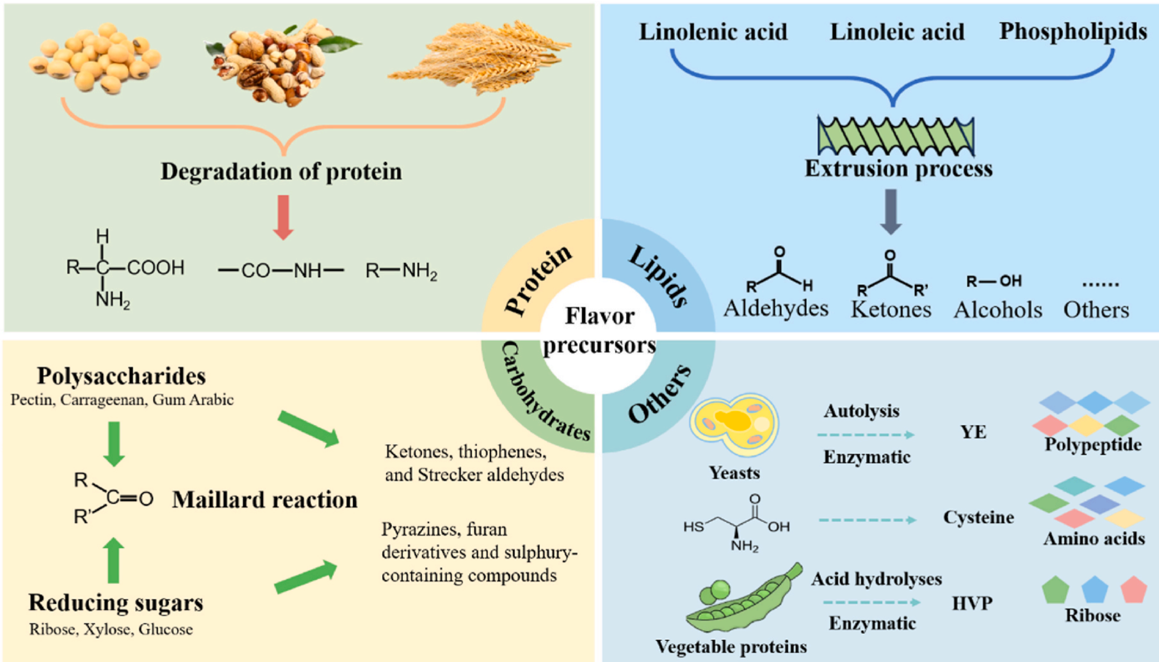

Fig. 2. Flavor-related compounds.

3.2.2. Lipids

Lipids are often used in the production of meat analogs to mimic the juiciness, tenderness and distinctive flavor of meat (Beniwal, et al., 2021). For high moisture extruded meat analogs, they are employed as extruded raw materials to participate in the extrusion procedure, whereby the involved lipids can be categorized as endogenous and exogenous lipids (Chen et al., 2023). Endogenous lipids are found in raw protein concentrates and isolates, like soy and algal proteins, that are lightly fractionated or not extensively refined. Exogenous lipids, such as peanut oil, linseed oil and medium-chain triglycerides oil, are added to the raw material to participate in the extrusion process. Exogenous lipids exert a more notable effect on the extrusion process. They are mixed with the raw material before being fed into the extruder, or added through an additional inlet in the extruder (Chen et al., 2021b; Zhang et al., 2022). Lipids serve as lubricants in the extrusion procedure, decreasing material temperature and torque whilst enhancing the stability of the extruder, and the addition of appropriate oil can effectively improve the springiness of the extrudate (Chen et al., 2021b; Kendler et al., 2021; Han et al., 2023).

Lipids are closely related to the flavor of meat analogs, acting as reservoirs or solvents for reactive lipophilic flavor compounds, playing a crucial role in the release of volatile flavors and influencing the flavor composition of meat analogs (Arancibia et al., 2011). Significantly, lipids additionally have a function in supplying flavor precursors throughout the extrusion procedure, culminating in generating distinct flavors and aromas. Lipids are degraded during heating to odor-active volatile compounds such as pyrazines, pyridines, furans, pyrans, aldehydes, alcohols and ketones (Liu et al., 2011).

3.2.3. Carbohydrates

Carbohydrates, contained in protein concentrates and isolates, which can interact with proteins during extrusion, affecting the rheological properties during extrusion processing and forming anisotropic structures. What's more, carbohydrates have frequently been employed in high moisture extrusion procedures, both simple carbohydrates and polysaccharides, to amplify the flavor, texture, and appearance of meat analogs.

Reducing sugars, main including ribose, xylose, and glucose, are considered to be important precursor substances for meat flavor. When added before extrusion, these sugars serve as prime commodities for the Maillard reaction and caramelization reaction, enhancing the taste and aroma of the final product (Brand et al., 2022; Li and Li, 2020). Farouk et al. (2000) found that addition of glucose and amino acids into the extrusion process increased the levels of pyrazine and furan derivatives, which ultimately improved the flavor profile of the extruded product. Xylose and glucose were used as raw materials in an extrusion process that successfully produced meaty flavorings (including produced pyrazines, furan derivatives and sulphury-containing compounds), that enhanced the intensity of the odor (Sasanam, et al., 2022). It is important to note that the caramelization reaction can only occur when the extrusion temperature is higher than the melting point of sugars (above 150 °C).

Natural polysaccharides, such as carrageenan, sodium alginate, pectin, and starch, have been extensively used in high moisture extrusion processes. They serve as macronutrients and aid in retaining water, improving the texture, and enhancing the fiber structure of meat analogs (van der Sman and van der Goot, 2023). In addition, polysaccharides can provide carbonyls for the Maillard reaction (Ke and Li, 2023; Li and Li, 2023b). Li and Li (2023a) reported the discovery of protein-polysaccharide Maillard conjugates from oat β-glucan and soybean isolate proteins through high moisture extrusion. The protein-polysaccharide Maillard conjugates contained some key flavor compounds of Maillard reaction, such as pyrazines, thiophenes, ketones, and Strecker aldehydes. Particularly, 3-ethyl-2,5-dimethyl-pyrazine, 2-ethyl-3,6-dimethyl-pyrazine, 2-ethyl-3,5-dimethyl-pyrazine, and 3,5-dimethyl-pyrazine contributed to the meat-like flavor of the extrudate (Zha et al., 2019).

3.2.4. Yeast extracts

Yeast extracts are the natural extract derived from edible yeast. It is frequently employed as the flavor enhancer due to their umami-enhancing effects in food processing. Yeast extracts play a significant role in the creation of meat flavors because the presence of flavor precursors and distinctive salty and meaty taste (Mahadevan and Farmer, 2006). Yeast extracts contain high concentrations of flavor precursors, reducing sugars, amino acids, nucleotides, peptides, lipids, thiamine and

5-ribonucleotides, particularly inosine 5-monophosphate and guanosine 5-monophosphate, which add umami and complexity to extruded meat analogs (Kerler et al., 2010). Yeast extracts can synthesize flavor substances through the formation pathways of meat flavor substances such as the Maillard reaction, lipid oxidation, and thiamine degradation, which produces a rich meat flavor and baking aroma and imparts a strong taste to extruded meat analogs (Lin, et al., 2014; Liu et al., 2015). Several crucial aroma-active compounds found in yeast extracts, which contribute to meaty flavors have been identified. Such compounds include 2-methyl-3-furanthiol, 2-methyl-3-methyldithiofuran, 2-methyl-3-methyl-thiofuran, dimethyl disulfide, 2-methyl-5-(methio)-furan, 2-furan methanethiol, 2-methyl-propanoic acid and 4-methyl-5-thiazole ethanol (Lin, et al., 2014; Mahadevan and Farmer, 2006). Additionally, high temperatures degraded peptides in yeast extracts to small molecular peptides, increased amino acid concentration, and raised taste substance content. However, yeast extracts may display unfavorable flavor profiles when exposed to excessively high temperatures. Alim et al. (2018) studied the effect of heat treatment on flavor active compounds in yeast extracts, and found that as temperature increases, there is a noticeable increase in the intensity of odors such as nutty and roast. At 140 °C, the prevailing odors shifted towards burnt, sour, and sulfur and became more intense than other odors.

3.2.5. Hydrolyzed proteins

Plant proteins, such as pea, soybean and wheat gluten protein, are hydrolyzed by acid and enzymatic hydrolyses to obtain hydrolyzed vegetable proteins, which are often used as the main raw material in the development of meat flavors. Hydrolyzed vegetable proteins are rich in a variety of amino acids and peptides, which can be used as a precursor substance for the Maillard reaction. Soy hydrolyzed proteins have been detected for volatile flavor substances and some of them were elevated after heat treatment, such as Strecker aldehydes, ketones, furans, furfurals, furanones and pyrazines was elevated after heat treatment (Aaslyng et al., 1999). Hydrolysis vegetable proteins subject to Maillard reaction produces furans and sulfur, which are vital meat-flavor compounds (Sun et al., 2023). However, the taste of the product may be adversely affected by the bitter peptides formed during hydrolysis. Animal protein hydrolysates have also been used as extruded meat analogs flavorings. Maillard-reacted beef bone hydrolysate was used in the extrusion process to produce meat analogs with meat flavor (Chiang et al., 2020).

3.2.6. Cysteine

Cysteine has been employed in high moisture extrusion processes for the production of meat analogs. During extrusion, cysteine promotes the exchange of disulfide bonds between SS and SH (van der Sman and van der Goot, 2023). The addition of an appropriate quantity of cysteine prior to extrusion improves the textural characteristics and fiber structure of the extrudate (Peng, et al., 2022). Cysteine is a precursor to the formation of meat flavor and is used to generate meat-like flavors through the Maillard reaction (Cao, et al., 2017). Cysteine is a compound that contains sulfur. When extruded under high temperatures, pressures and shear, cysteine promotes the formation of sulfur-containing compounds like sulfur-containing furans and thiophene compounds (Zhang et al., 2018). These compounds then oxidize and decompose, producing aldehydes, ammonia or hydrogen sulfide, which is critical for forming meat flavor. Dai and An (2022) incorporated low levels ($<$ 0.25%) of cysteine into a high moisture extrusion process to investigate the effect of cysteine levels on extruded meat substitutes. The E-nose results revealed that the addition of cysteine had a significant impact on the halides, hydrocarbons, sulfides, and amines in extruded meat analogs, effectively improved the odor characteristics of the extrudates.

4. Flavor compounds formation and changes during extrusion process

The flavor compounds of the premix are changed during extrusion (Fig. 3). During extrusion, some flavor substances are formed via the Maillard reaction and thermal degradation of flavor precursors, such as amino acids, lipids and carbohydrates. The flavor components carried by the raw materials and the newly formed flavor components interact with the proteins during the extrusion process, resulting in alterations to the flavors.

Some flavor precursors, such as proteins, lipids and thiamine, are degraded at high temperatures in the barrel (Fig. 3). During extrusion process, deamidation reactions occur as proteins, peptides, and amino acids release ammonia leading to the formation of volatile components such as alcohols, aldehydes, and sulfides (Riha, 1996). Lipids, unsaturated fatty acids (oleic and linoleic acids) present in the material experience oxidative degradation, leading to the production of aldehydes, ketones, and alcohols during the extrusion process (Yang et al., 2021; Yuan et al., 2023). Thiamine is degraded in a heated environment to form a number of flavor-active compounds and meat flavor precursors such as mercaptans, sulfides and disulfides (Li and Li, 2020).

The Maillard reaction, also known as non-enzymatic browning, is a complex reaction that occurs among carbohydrates with free aldehyde or ketone groups and amino compounds (amino acids and proteins). It consists of three stages, the first step is the condensation of amino groups and reducing sugars, followed by Strecker degradation to produce Strecker aldehydes, which are important for the flavor of meat analogs (Kathuria et al., 2023). In the final stage, aldol condensation leads to the formation of heterocyclic compounds, such as pyrazines, pyrroles, and furans (van Boekel, 2006; Wang et al., 2022; Zhu et al., 2023). The Maillard reaction provides a distinctive meaty and nutty aroma, have been identified as the most common volatile compounds in the Maillard reaction (Li and Li, 2020). This reaction commonly occurs between 121 °C and 177 °C during meat processing, which includes the temperature range of the melting zone in extrusion (Silva Barbosa Correia, et al., 2024). Thus, the extrusion process is an ideal environment for Maillard reaction. Yu et al. (2023) observed an increase in the degree of grafting between carboxymethylcellulose and protein during high moisture extrusion. They speculated that free amino groups were exposed from protein molecules under high temperature and shear force conditions, which then interacted with carboxymethylcellulose through the Maillard reaction. Several studies have demonstrated that extrusion leads to the formation of Maillard reaction compounds (MRC), which confirms that Maillard reactions occurs during extrusion (Li and Li, 2024). Mendowski et al. (2020) discovered that extrusion led to an increase in MRC content, especially when reducing sugars (Maillard reaction precursors) were added before the extrusion process. And Ames et al. (1998) reported that the extrudates prepared from starch, glucose and lysine produced non-volatile Maillard reaction products.

Additionally, for extruded meat analogs, protein is considered to be an important component contributing to flavor loss or release. Flavor and protein interactions have been extensively studied and are classified into covalent and non-covalent interactions, the latter consisting mainly of hydrophobic interactions, due to their reversibility, maintaining an equilibrium state between the bound and free flavor over a period of time (Kun, Wang, Susan, D., & Arntfield, 2016). Flavor compounds that interact non-covalently with protein play an important role in the flavor profile of extruded meat analogs. Such substances can be utilized to lower flavor loss and re-release flavors during consumption. Covalent interactions are irreversible and have significant impact on the release of flavor in extruded meat analogs, substantially contributing to the expulsion of flavors, and ultimately decreasing the flavor and shelf life of meat analogs. The conformation of the protein has a significant effect on the interaction with flavor compounds, as it provides chemical sites with which flavor compounds can interact. As shown in Fig. 3, the material was exposed to high temperatures and pressure during exrtusion,

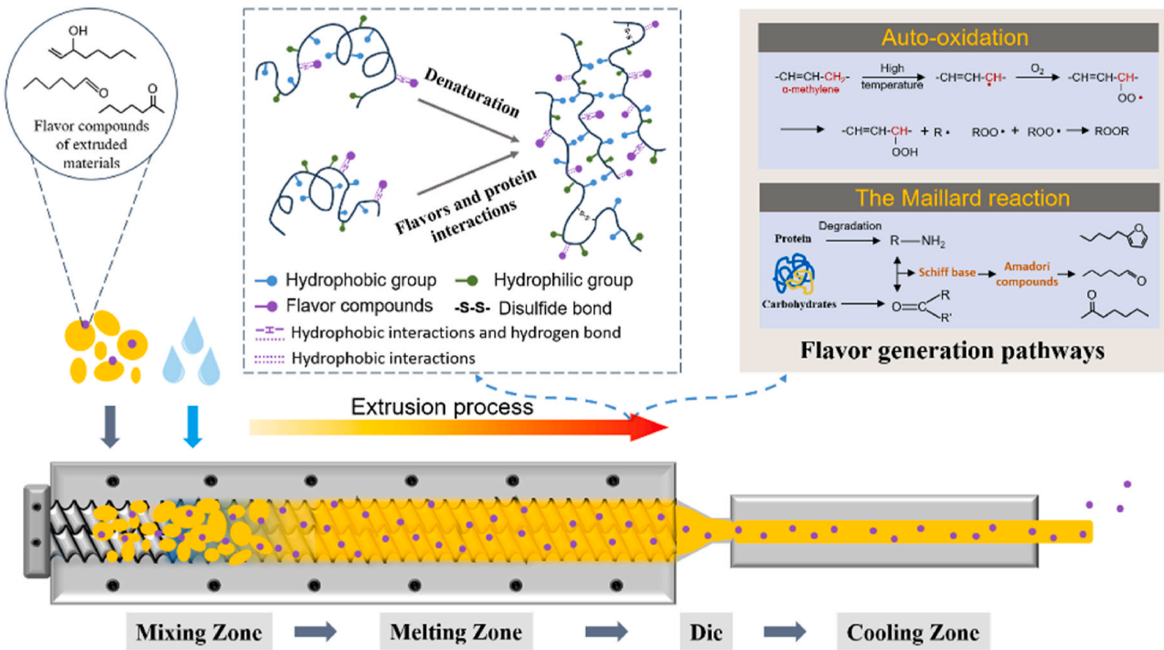

Fig. 3. Flavor change pathways during extrusion process.

leading to the denaturation of proteins and the exposure of internal hydrophobic sites (An et al., 2022). The protein conformational changes provide more binding sites to attract flavor ligands with active molecules, augmenting the interactions between the protein and flavor components (Zhang et al., 2021).

5. Off-flavor formation mechanisms and elimination methods

5.1. Formation mechanisms of off-flavor

Plant proteins are main material for extruded meat analogs, especially legume proteins, which naturally occurring beany odor and bitter taste restricts sensory acceptability of meat analogs. The bitter taste components presented in the raw material and secondary lipid oxidation products (such as aldehydes, ketones and alcohols) are considered to be important causes of meat analogs off-flavors (Tuccillo, et al., 2022). Saponins and phenolic acids are found in plant seeds, and mostly retained in protein concentrates and isolated proteins (Damodaran and Arora, 2013). The materials experience higher shear rates during extrusion, which contribute to enzyme and lipid reactions, promoting lipid decomposition and the release of aliphatic aldehydes (Usman, et al., 2023). The unsaturated fatty acids, such as linoleic and linolenic acids undergo oxidation. Among these pathways, enzymatic oxidation is considered to be a major cause of off-flavors. Enzymatic oxidation refers to the degradation of polyunsaturated fatty acids through lipoxygenase, giving rise to volatile substances, including aldehydes, alcohols, and hexanal, which contribute to beany flavors. Furthermore, Off-flavors may result from the impact of heat on sugars and amino acids, such as through Maillard reactions, or from the thermal degradation of phenolic acids, carotenoids or thiamine (Roland et al., 2017). For instance, 2-Pentylfuran is identified as a distinct off-flavor compound in extruded meat analogs, which is attributed to the Maillard reaction of reducing sugars or the singlet oxygen oxidation of linoleic acid during extrusion process (Yang et al., 2023).

5.2. Eliminating methods of off-flavor

Currently, there are three main methods for eliminating off-flavor in high moisture extruded meat analogs: mask off-flavor, avoid off-flavor generation and remove off-flavor of materials, summarized in Fig. 4. Salt and spices can be used to marinate meat analogs as a flavor mask to hide odors. In addition, the addition of natural spices during high moisture extrusion is an efficient way to mask off-flavors of the extrudate. Yuan et al. (2023) found that the addition of spices decreased the levels of off-flavors in extrudates, such as nonanal, 2-pentofuran and 1-octen-3-ol. Polysaccharides can also be employed to avoid the release of unpleasant flavor components. Cyclodextrins are cyclic carbohydrate with truncated-cone conformation, which contribute to entrap various ligands into its internal hydrophobic cavity to form inclusion complexes, led to a significant reduction in the beany flavor (Cui et al., 2020). Polysaccharides could also interact with flavor compounds, leading to lower flavor release (Yven et al., 1998). However, further investigation is required to determine the impact of polysaccharides on the flavor of extruded meat analogs.

Off-flavor formation can be prevented through two methods, one is to remove off-flavor-causing precursors such as phospholipids and free fatty acids and the other is to reduce lipoxygenase activity. Cyclodextrins and phospholipase A_2 have been used to control or eliminate off-flavor development by removing phospholipids in soy protein isolates (Zhu and Damodaran, 2018). The heating of the extrusion keeps the lipoxygenase activity persisted at a low level (Yang et al., 2021). Pulsed electric fields (Chen et al., 2008) and gamma irradiation (Tewari et al., 2015) can effectively inactivate lipoxygenase activity to induce reduction in the off-flavor generation. Germination is a useful mean for decreasing lipoxygenase activity (Kumar et al., 2006). Usman et al. (2023) investigated the changes in beany flavor compound content of extrusion proteins after pulse and germination as well as found that pulse proteins treated by germination can effectively decrease the beany flavor.

Microwave-vacuum dehydration (VMD) and fermentation have been employed to remove off-flavor from legume proteins. VMD combines microwaves with vacuum conditions to remove volatile compounds at lower temperatures with a low thermal damage, which have proven useful in removing volatiles of pea protein isolates (Pratap-Singh et al., 2023). Fermentation is a common way to improve the flavor of bean-based products (Huo et al., 2023). Valtonen et al. (2023) compared the sensory properties of plant-based sausages, which prepared by combining the coarsely ground extrudates with fermented or native pea

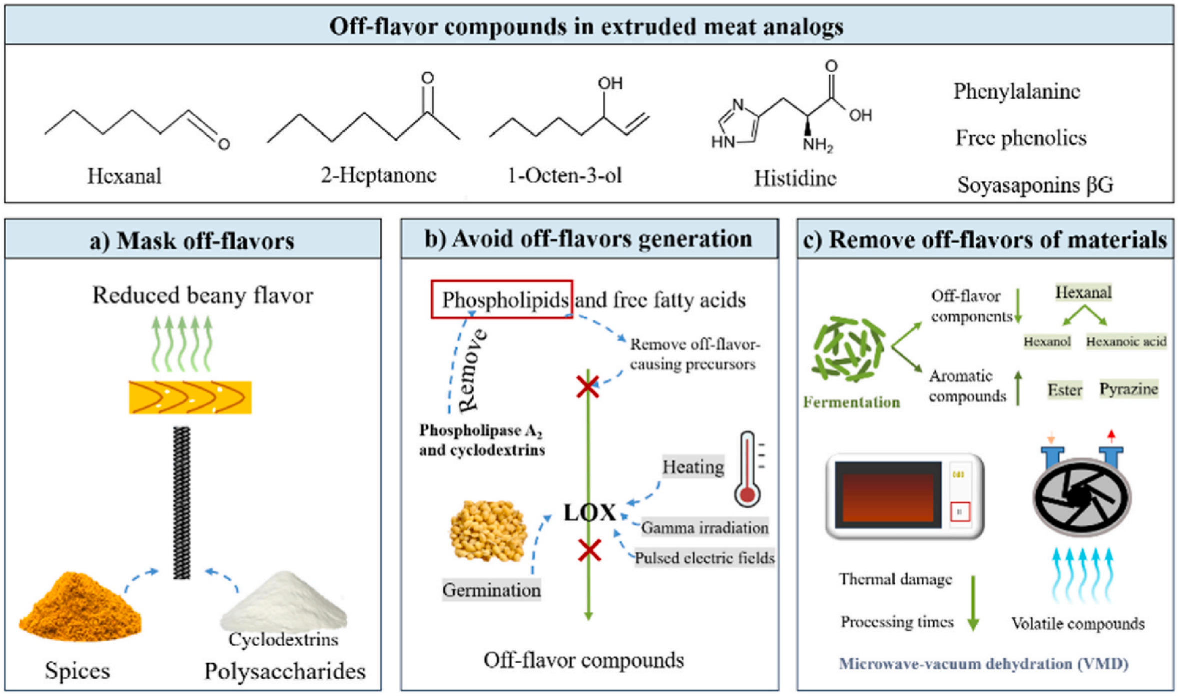

Fig. 4. The summary of methods used to eliminate off-flavor from extruded meat analogs.

protein isolate. The results showed that fermented pea protein contributed to decrease off-flavors, and it can serve as a viable raw material for meat analogs.

6. Relationship between fiber structure and flavor in extruded meat analogs

6.1. High moisture extrusion process

The fiber structure is a crucial characteristic for meat analogs. In the high moisture extrusion process, the materials were put into the feeder and conveyed to the mixing zone by the screws. After mix with water, the materials entered the melting zone, where the linear structure is formed by the unfolding of the globular structure along the flow direction, and the secondary structure of the protein is further transformed into the ordered state with the elevation of disulfide bonding content (Arora et al., 2020). The materials gelled in the melting zone and then passed though die into the cooling zone, where protein molecules underwent rearrangement and cross-linking (Chen et al., 2022). While in the cooling die, the materials were subjected to shear stresses perpendicular to the direction of extrusion inside, with the aqueous protein melt segregating into water-rich and protein-rich domains to the form the fibrous structures (Murillo et al., 2019).

As extrusion progresses, degradation and Maillard reactions take place in flavor precursors, resulting in the production of volatile flavor substances. The protein denaturation and the hydrophobic groups were exposed, providing more binding sites to bind with the flavor components. Thus, the flavor substances bind tightly to the protein and are retained (Zhu et al., 2023). Flavor in extruded meat analogs is affected by not only the composition of protein but also its structure. With the aggregation of macromolecules and the formation of structure, flavor substances are obstructed and encapsulated, thus increasing the retention of flavor substances in the extrudates (Zhang et al., 2021). After the materials flowing out of the cooling die, the extrudates form dense structure with characteristic shapes. The dense structure of the extrudates act as the spatial barrier to retain flavor substances in the high moisture extruded meat analogs matrix (Sun et al., 2023).

6.2. Extrusion parameters

Moisture content, temperature, feed rate and screw speed affect protein denaturation and degradation, which change the fiber structure, further impact flavor in extrudates. The moisture content is a crucial extrusion process variable that significantly impacts extrudate performance, and is used to categorize high moisture and low moisture extrudates. During the extrusion process, moisture serves a variety of purposes, such as lubrication, thermal conductivity, aiding molding, and acting as a reaction solvent. Compared with low moisture extrusion, the cooling zone of high moisture extrusion can reduce the evaporation of volatile flavor components at high temperatures, and the more compact structure leads to enhanced flavor retention. In high moisture extrusion processes, an increase in moisture content contributes to protein denaturation, conversely, a decrease moisture levels facilitate flavor retention (Hossain Brishti, et al., 2021; Saldanha do Carmo et al., 2021). The high moisture extrusion process reduces the moisture content, increases the viscosity of the material in the extruder, extends the residence time, and significantly improves the hardness, chewiness, and aggregation of the extrudates, creating a favorable environment for the flavor retention of extruded meat analogs (Chen et al., 2010). Guo et al. (2020) introduced natural flavor powder into the high moisture extrusion. The results showed that the microstructure of the meat analogs was denser as the moisture content increased from 50% to 80%, while the retention of volatile flavors had a significant reduction. This phenomenon could potentially be attributed to elevated levels of moisture, heightened water evaporation, and a greater loss of volatile compounds.

The high moisture extrusion temperature includes the temperature of each section within the barrel and the cooling zone. The temperature of the barrel regulates the point at which the material becomes molten, ensuring its thorough melting. The extent of protein denaturation, raw material degradation and Maillard reactions, as well as lipoxygenase activity, are all influenced by this. As the temperature increases, the level of disulfide bondse content increases, leads to a compact structure and improvement flavor retention of the extrudates (Chen et al., 2021a; Wang et al., 2022; Yuliani, Torley, D'Arcy, Nicholson and Bhandari, 2006). However, too high temperature causes the extrudate to have a smooth and non-porous on the transection surface, which is not conducive to the creation of a fiber structure. And overheating resulted in greater outflow of flavors, while higher temperatures cause more water evaporation from meat analogs, releasing more volatile flavors and resulting in lower flavor retention. Further, higher temperatures led to increased sensory intensity of spoilage odor in meat analogs (Hao, et al., 2023).

During the extrusion process, the feed rate and screw speed affect the length of the residence time of the material in the barrel. At relatively high screw speeds, meat analogs can be extruded with a uniform structure, smooth surfaces and textures (Sun, et al., 2022). And the higher the screw speed can cause the higher pressure and fluid temperature in the barrel, and promote the formation of fluid plug flow, resulting in a denser the product structure to affect total volatile flavor intensity of high moisture extruded meat analogs (Pietsch et al., 2019; Usman et al., 2023). The effect of screw speed on flavor retention in high moisture extruded meat analogs has recently been investigated by Xun et al. (2019). The results showed that a moderate rise in screw speed led to a denser microstructure of the extrudate, which positively impacts flavor retention. Additionally, increasing the screw speed can expose partial hydrophobic groups during extrusion, leading to enhanced adsorption of volatile flavor substances by proteins and ultimately culminating in greater flavor retention. However, the constant increase in screw speed decreased the residence time of the material in the barrel, reducing the adsorption time of flavor substances and proteins. Moreover, the increased shear rate may enhance the shearing action on the material, resulting in the release of volatiles that were physically trapped by the protein and polysaccharides, creating an unfavorable environment for adsorption of flavor substances within the barrel, leading to reduced flavor retention (Usman, et al., 2023).

6.3. Raw materials

As the protein sources of extruded meat analogs are diverse, the structures of protein types have differences, leading to different binding capacity with flavor components. Furthermore, due to differences in the physicochemical properties of protein, the type of protein affects the texture and fiber structure of the extrudates, which further affects the flavor of the extrudates. For example, some studies found that increasing wheat gluten content in the extrusion process promoted a greater degree of aggregation formation, leading to a softer and more elastic extrudate, in contrast, the soy protein isolate played a crucial role in determining the hardness and tensile strength of the extrudates, resulting in a denser and more polished structure (Zhang et al., 2018). Guo et al. (2020) found that the addition of wheat gluten enhanced the viscosity of the substance within the barrel, improving protein adsorption onto volatile flavor substances, thereby increasing the retention of flavor. With an increase in wheat gluten content, the microstructure of extrudate had a denser layered structure and free from fractures, ultimately leading to the retention of a greater amount of flavor substances. However, an excess amount of gluten led to slight expansion and lowered the hardness of the extruded meat analogs, resulting in less retention of flavor.

7. Flavor evaluation of extruded meat analogs

7.1. Sensory evaluation

Sensory evaluation plays a crucial role in determining the flavor properties of meat analogs. Quantitative descriptive analysis and consumer tests have been employed to evaluate flavor properties of meat analogs (Grahl, et al., 2018). Experts trained in the field evaluate meat analogs by means of observation, taste and smell to determine their characteristics and quality. Pori et al. (2023) used generic descriptive analysis to study the flavor properties of extrudates. The resulting flavor profile had five attributes, including pea odor, meat stock odor, meat's frying fat odor, umami and pea flavor. Tuccillo et al. (2022) conducted sensory profiling of meat analogs and focused on odor, taste, and mouthfeel. Currently, fuzzy logic model is widely used as a statistical model for sensory evaluation of food products, where all samples are ranked according to specific sensory attributes to clarify the acceptability and sensory attributes of the product (Kumar et al., 2021). The fuzzy mathematical evaluation method can be used as an evaluation index to supply an evaluation method, which helps to establish a sensory evaluation system for extruded meat analogs. Sensory evaluation can rapidly and directly ascertain the flavor quality of food and it also account for differences that cannot be detected by instruments. As sensory experiments are often subjective and not easily quantifiable, sensory evaluation is commonly combined with instrumental measurements when assessing the flavor properties of meat analogs.

7.2. Instrumental characterization

The flavor of meat analogs includes odor and taste, which is associated with its volatile odor compounds and non-volatile taste compounds. The instrumental analysis typically employed to assess flavor in food products can also be applied to evaluate the flavor properties of meat analogs.

7.2.1. Volatile compounds

Supercritical fluid extraction, solid-phase microextraction, vacuum distillation and solvent assisted flavor evaporation are used to isolate volatile compounds. Solid-phase microextraction is commonly employed to extract volatile compounds, including those present in meat analogs. Gas chromatography-mass spectrometry (GC-MS), gas chromatography-ion mobility spectrometry (GC-IMS) and gas chromatography-olfactometry-mass spectrometry (GC-O-MS) are widely used for identifying volatile substances in food items. To determine the impact of a volatile flavor compound on the overall taste of a food, ascertain the concentration of each volatile substance and its odor activity value (OAV), which the concentration of a flavor substance to its sensory threshold.

GC-MS was used to detect the volatile components of faba bean meat analogs by Tuccillo et al. (2022). Gas chromatography is used to separate complex constituents. Mass spectrometry characterizes and quantifies volatile components. GC-IMS is used for identifying volatile compounds by measuring differing ion mobilities in the gas phase. GC-IMS has been applied to identify flavor profiles of plant-based foods (Yang et al., 2021). GC-O-MS, which combines human sense of smell with mass spectrometry to analyze and identify flavor characteristics of food products. It can be used to analyze the primary volatile compounds of meat analogs. Yang et al. (2023) employed GC-O-MS to identify the volatiles of textured soybean protein. They combined this with the odor activity value (OAV) to determine key flavor actives (OAV >1). Furthermore, key volatile aromas of the extruded meat analogs can also be further identified through sensory-directed aroma recombination and deletion experiments. Additionally, electronic noses are frequently used as a supplementary technique to evaluate and recognize the flavor features of food items through mimicking the human olfactory perception. It has been employed to quickly analyze the odor profile of extruded meat analogs (Dai and An, 2022).

7.2.2. Non-volatile compounds

The electronic tongue can be used to analyze and identify the taste characteristics of meat analogs by simulating the human sense of taste. Non-volatile taste-active compounds, such as 5′-nucleotides, soluble sugars, small peptides, free amino acids (FAAs), organic acids, trimethylamine oxide (TMAO) and betaine, are essential for forming distinct taste attributes (Wang et al., 2023; Xin et al., 2023). High-performance liquid chromatography (HPLC) and nuclear magnetic resonance (NMR) can be utilized for the quantitative characterization of non-volatile flavor compounds (Jin, et al., 2023; Winstel et al., 2021). Metabolomics technology allows for the comprehensive detection of a wide range of small molecule compounds present in foods. Numerous studies have applied this technique to examine the composition of taste-active compounds (Guo et al., 2023). The combination of smart analytical devices, such as electronic nose and electronic tongue, with gas and liquid chromatography techniques offers a multidimensional characterization of the flavor profile, which contribute to the complementary evaluation of flavor of meat analogs.

7.3. Chemometric analysis

The methods used to detect and analyze the flavor characteristics of the extruded meat analogs are shown in Table 2. The analysis of variance (ANOVA) and Duncan's test are statistical tools used to compare the flavor substance content between treatments and determine statistical significance. Clustering heatmap, principal component analysis (PCA), and partial least squares regression (PLS) has been employed to analyze the flavor of extruded meat analogs.

Principal component analysis (PCA) is a well-established multivariate statistical approach that employs eigenvector analysis. Yuan et al. (2023) conducted PCA to investigate the divergence in flavor characteristics of extruded meat analogs, flavored using different spices. There were clear separation tendencies among the extrudates treated with different spices. The cluster heatmap is a combination of the heatmap and hierarchical clustering analysis. It visually displays changes and differences in samples in a progressive and intuitive manner through color changes, as well as showing the degree of similarity. Usman et al. (2023) applied the cluster heatmap and PCA to explore flavor differences between germinated and ungerminated pulse proteins and their extrudates. From observation, volatile and odor profile of different ingredients and extruded meat analogs have good clustering. (Usman, et al., 2023). PLS can be employed to predict a set of variables, known as responses, using another set of variables, known as predictors. And PLS enables the elucidation of interdependencies between two sets of multiple related variables. Tuccillo et al. (2022) successfully established a relationship between flavor-related compounds and sensory attributes of extruded meat analogs using PLS analysis. The results clearly showed the correlation in terms of flavor-related chemical components, appearance, flavor attributes, odor attributes, and texture.

In recent years, the regulation and prediction of food flavors have been effectively aided by machine learning techniques (Ji, et al., 2023). Flavor evaluation of extruded meat analogs is presently focused on the detection of flavor-related compounds. Thus far, there have been no studies employing machine learning techniques to predict and regulate the flavor characteristics of extruded meat analogs. Future studies on the flavor of extruded meat analogs could be based on machine learning methods to improve the comprehension of the relationship between meat analog structure and flavor, as well as to predict changes in flavor under varying conditions.

8. Conclusion and future perspectives

The flavor of extruded meat analogs is determined by the flavor compounds present in the raw materials, alongside the flavor precursors (proteins, lipids and carbohydrates) which undergo degradation and Maillard reaction during the high moisture extrusion process. To enhance the odor and taste of extrudates directly, natural spices, hydrolyzed proteins, cysteine, and yeast extracts can be intruded to the high moisture extrusion process. Masking or avoiding the liberation of off-flavor, preventing the generation of off-flavor, and removing off-flavor from materials can effectively eliminate off-flavor in extruded meat analogs. During extrusion, flavor of meat analogs is influenced by their matrix and protein interactions. Moreover, extrusion parameters (moisture, temperature, screw speed) and material types alter material flow characteristics in the barrel, as well as the fiber structure of the extrudates, all of these aspects ultimately affect the flavor of extruded meat analogs. Modulating the flavor properties of extruded meat analogs presents challenges. Furthermore, the selection principle of flavor additives and optimal conditions for flavor retention in extruded meat analogs remains insufficiently clear and experience dependent. There are no effective methods for regulating and predicting the flavor properties of extruded meat analogs.

The difficulty in flavor modulation of extruded meat analogs lies in the following five areas. Firstly, influenced by the bean flavors carried by plant proteins and the undesirable flavors generated by the reaction at high temperatures, it can create an unpleasant sensory experience for the extrudate. Secondly, since meat flavor is related to a variety of complex reactions, the extrusion process is still in the "black box" stage, so it is hardly possible to predict the flavor of extrudates by adding flavor precursors. The meat-specific muscle fibers are different from the fiber structure obtained by protein denaturation and molding in the extrusion process, resulting in the extruded meat analogs still having a certain gap

Table 2
Summary of the application of flavor measurement techniques to extruded meat analogs.

Detection Methods	Analytical methods	Aim	Findings	References
Sensory evaluation	ANOVA, PCA	Exploring flavor differences between 3 main sample groups.	The extrudate, containing beef and textured pea protein, possessed a more intense meat stock odor and umami taste. Fatty acid showed a positive correlation with meat-like odor properties.	Pori, et al. (2023)
Sensory evaluation, GC-O-MS, HPLC	ANOVA, PCA, HPC	Exploring flavor differences between germinated and ungerminated pulse proteins and their extrudates.	Both germination and extrusion have affected the odor profile of extruded meat analogs.	Usman, et al. (2023)
Sensory evaluation, GC-MS	ANOVA, PCA	Exploring flavor distinctions among extrudates seasoned with diverse spices.	The addition of various spices had a significant impact on both the quantity and composition of volatile compounds in extrudates.	Yuan, et al. (2023)
Sensory evaluation, GC-MS, UPLC, HPLC	ANOVA, PLS	Exploring changes in flavor components.	Bitterness seemed to be related to the existence of free phenolics, vicine, convicine, phenylalanine, tryptophan and histidine.	Tuccillo, et al. (2022)
		Analysis of the effect of flavor actives on the flavor properties of extruded meat analogs.	3-methyl butanoic acid, alpha-pinene, nonanal, and D-limonene have been found to be correlated with the flavor and aroma of cooked peas. The presence of 2- and 3-methylbutanal was found to be related to the attributes of odor and taste intensity.	
GC-O-MS	ANOVA	Exploring changes in the concentrations of the main volatile beany flavor compounds in the textured soybean proteins under various energy inputs.	The concentrations of flavor compounds decreased initially and then decreased at higher SME and temperatures.	(Yang et al., 2023)
Electronic nose	ANOVA, DFA	Exploring the effect of odor on extrudates with different cysteine additions.	The addition of cysteine contributed to enhance the halide, hydrocarbon, sulfide and amine content of the extrudate.	Dai and An (2022)

in the flavor retention compared to the meat, and the ability of secondary processing needs to be improved, such as cooking and marinating. Fourthly, the effect of the addition of flavoring and coloring on the structure of the extrudate is uncertain, while controlling the structure and flavor of the extrudate is a major challenge. Last but not least, considering that the structural toughness of meat analogs is not as good as that of meat, the water-holding property, flavor stability, and structural stability of extrudates after freezing and thawing during storage still need to be studied. For the purpose of substituting meat products, changes in the quality characteristics of extruded meat analogs during storage are equally important. The study of shelf-life flavor stability of extruded meat analogs is necessary.

Funding

This study was grateful for the financial support provided by Heilongjiang Province "Tens of Millions" Project Science and Technology Major Special Projects (No. 2021ZX12B04-03) and Natural Science Foundation of Heilongjiang Province (LH2020C030).

CRediT authorship contribution statement

Wanrong Jiang: Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Xiaoyu Yang:** Conceptualization, Writing – original draft, Writing – review & editing. **Liang Li:** Conceptualization, Writing – original draft, Writing – review & editing, Resources, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this article.

Data availability

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

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