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PLANT-BASED MEAT ANALOG DIVERSIFICATION: POTENTIAL AND CHALLENGES OF FISHERY RESOURCES AS RAW MATERIAL ALTERNATIVE

Diversifikasi Daging Analog Berbasis Nabati: Potensi dan Tantangan Sumber Daya Perikanan Sebagai Bahan Baku Alternatif

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ABSTRACT

Growing public awareness of health, animal welfare, and environmental sustainability, lead to significant increase in demand for healthy and sustainable nutritious food segment. Plant-based meat analog (PBMA) has been development as alternative food ingredients that are in accordance with the current demands of the world community. However, currently raw materials of PBMA is still dominated from terrestrial plants which have limitations in terms of sustainability, land requirements, and specific nutritional profiles. These circumstances highlight the urgent need to diversify the raw material of PBMA and require further investigation. This paper focuses on potential and challenge of fishery resources as meat analog's raw material alternative. Fishery resources emerge as promising alternative source offering sustainability and high quality nutrient values. Microalgae are a promising source, rich in protein, essential fatty acids, providing vitamins, minerals, and offering various bioactive compounds with health benefits and potentially improve the quality of meat analog. Hydrocolloids derived from algae such as carrageenan and alginate act as thickening, gelling, and stabilizing agents which improve the overall structure and texture of PBMA. Amino acid and natural pigment in algae enhance sensory acceptance of PBMA by masking undesirable taste and mimicking meat like color. This review will be helpful in highlighting the potential fishery resources in attempt to diversify material sources for PBMA.

Keywords: Agriculture innovation; Beyond meat; Plant-based food; Protein source

ABSTRAK

Masyarakat saat ini semakin peduli terhadap kesehatan, kesejahteraan hewan, dan keberlanjutan lingkungan, sehingga menciptakan peningkatan permintaan akan segmen makanan bergizi yang sehat dan berkelanjutan. Daging analog berbasis nabati (PBMA) telah dikembangkan sebagai bahan makanan alternatif yang sesuai dengan tuntutan masyarakat dunia. Namun, saat ini bahan baku PBMA masih didominasi oleh hasil tanaman darat industri yang memiliki keterbatasan dalam hal keberlanjutan, kebutuhan lahan, dan profil nutrisi spesifik. Keadaan ini menyoroti kebutuhan mendesak untuk mendiversifikasi bahan baku PBMA dan memerlukan penelitian lebih lanjut. Tulisan ini berfokus pada potensi dan tantangan sumber daya perikanan sebagai alternatif bahan baku analog daging. Sumber daya perikanan muncul sebagai sumber alternatif yang menjanjikan, menawarkan keberlanjutan dan nilai gizi berkualitas tinggi. Mikroalga merupakan sumber yang menjanjikan, kaya akan protein, asam lemak esensial, menyediakan vitamin, mineral, dan menawarkan berbagai senyawa bioaktif dengan manfaat kesehatan dan berpotensi meningkatkan kualitas daging analog. Produk turunan alga seperti karagenan dan alginat bertindak sebagai agen pengental, pembentuk gel, dan penstabil yang meningkatkan struktur dan tekstur PBMA secara keseluruhan. Pigmen alami dalam alga meningkatkan penerimaan sensorik PBMA dan meniru warna seperti daging. Tinjauan ini akan bermanfaat dalam menyoroti potensi sumber daya perikanan dalam upaya diversifikasi bahan baku PBMA.

Kata Kunci: Inovasi agrikultur, Produk daging nabati, Makanan berbasis tumbuhan, Sumber Protein

INTRODUCTION

Global demand for animal-based meat is increasing, lead to significant challenges for ensuring sustainable and sufficient food production (Zhong et al., 2021). However, traditional animal meat production has various negative impacts on the environment including land and water resources. In addition, The livestock industry is a significant contributor to global climate change, contributing between 12% and 18% of total greenhouse gas emissions (González et al., 2020). Plant-based meat analog (PBMA) has become popular meat alternative due to its lower environmental impact and health risks. PBMA is defined as a food product made from plant ingredients which is designed to mimic the appearance, texture, and taste of animal meat (Lee et al., 2024). The global market for meat analogs is estimated to reach approximately USD 21 billion in 2025, with expectations to grow to 230 billion USD by 2033 (Bohrer, 2019);(Wu et al., 2024). Compared to cell culture-based analog meat, PBMA get higher popularity because it is more acceptable in terms of ethics and religion, so that embrace a bigger consumer segment (Elhalis et al., 2023). PBMA contains lower total fat content, saturated fat, and cholesterol levels compared to animal meat products so that the risk of obesity and cardiovascular disease can be minimized (Ishaq et al., 2022).

Currently, PBMA is mostly produced from plant protein such as soybeans, wheat, peas However, this PBMA low of nutritional content compare with animal meat, such as vitamins B2, B12, iodine, zinc, calcium, potassium, selenium, and other nutrients (McClements & Grossmann, 2021). In addition, most of plant protein sources lack of amino acid, for instance wheat protein (low in lysine) and pea protein (low in methionine and cysteine) (X. Liu et al., 2023). Therefore, PBMA needs to be combined with other ingredients according to the nutritional deficiencies of plant raw materials. Plant proteins from nuts and wheat can be replaced or combined with other ingredients such as algae to balance nutrition of PBMA according to human nutritional needs (Espinosa-Ramírez et al., 2023). Moreover, PBMA faces critical challenges in creating a fibrous structure, succulent texture of animal meat, often resulting in weak, soft, or dry products. Key issues include limited protein texturization and poor water-binding capacity (Singh & Sit, 2022).

Fisheries is indeed a crucial source of food and nutrition for humans. Fisheries resouce is more sustainable food source with lower environmental impact compared to terrestrial food (Zhong et al., 2021). In recent years, microalgae have become an important crop for the global food industry. The reasons include the following : (1) high in protein, essential amino acids, and other healthy nutrients such as vitamins, antioxidants, omega-3 PUFA fatty acids, and minerals; (2) microalgae have the lowest carbon, water, and arable land footprint of all crops making them more sustainable; (3) their ability to remediate environmental pollution; (4) high productivity compared to terrestrial plants and animal (Y. Wang et al., 2021). Research conducted microalgae as materials for PBMA has been carried out, including the combination of *Auxenochlorella protothecoides* and soy protein (Caporgno et al., 2020a), the addition of *Haematococcus pluvialis* residues to increase the content of PBMA's fiber (Xia et al., 2022).

Various studies have been reported for beneficial roles of hydrocolloids in meat analog products. Hydrocolloids reported significantly affected textural properties by increasing the texture and the structure of meat analog (Rasul et al., 2024). The addition of hydrocolloids creates a fibrous structure, which is an important parameter for PBMA to resemble the texture of real meat (S. Liu et al., 2024). Hydrocolloids derived from algae such as carrageenan and alginate are widely used in the food industry as thickeners, gelling agents, and emulsifiers (Liao et al., 2021). Carrageenan can bind water in a 3-dimensional gel matrix, lead lower moisture loss during storage and cooking, resulting in juicier and more tender products (McClements & Grossmann, 2022). Alginate able form a network structure to trap water and protein, resulting in a denser texture (Wannasin et al., 2024). This review aims to provide insight about the potential fishery resources in attempt to diversify raw material of PBMA, aiming for nutritious and sustainable foods.

RESEARCH METHOD

This paper used Systematic Literature Review (SLR) method, aims to identify, examine, and interpret previous research. The references were collected from September to December 2025 from articles with keywords plant-based meat analog, meat analog, microalgae, carrageenan, and alginate. The datas are extracted and then analyzed further.

RESULT AND DISCUSSION

Potential of fishery resources in plant based meat analog formulation Protein Source

Texture is major parameter in the quality of PBMA. The quality and quantity of plant protein play an important role in providing texture of PBMA. The higher the protein content, the higher the binding and water holding capacity, resulting in a juicier texture. (Siddiqui, Khalifa, et al., 2024). The protein content in the raw material directly impacts the ability to achieve a fibrous texture in high-moisture meat analog (HMMA), with protein levels ranging from 50% (Ferawati et al., 2021). The combination of plant protein is studied to obtain PBMA with better texture (Chiang et al., 2019), inlucding, the proportion and type of plant protein to enhance texture of PBMA (Kyriakopoulou et al., 2021).

Microalgae, offer advantages over terrestrial plant proteins, mainly due to their high protein content (Li et al., 2024). Microalgae generally have high protein content-up to 70%, much higher than terrestrial plant protein sources (soybean: 35% and pea: 18%) and comparable to animal protein sources (turkey: 63% and beef: 50%) (Chen et al., 2022). Microalgae species have been studied for application in meat analogs, such as: *Nannochloropsis oceanica* (L. Zhao et al., 2024), *Spirulina* (Lopes et al., 2025); (Guo et al., 2024), *Auxenochlorella protothecoides* (Sägesser et al., 2024), *Chlorella* (Bakhsh et al., 2023), *Haematococcus pluvialis* (M. Liu et al., 2023). Microalgae production offer several benefit over land plant cultivation, primarily due to its rapid growth, efficient resource utilization, adaptability to diverse environments, and do not participate in the food crop versus energy crop conflict (Udayan et al., 2023). Microalgae can produce a higher biomass and protein yield per unit area than traditional crops, and they can be cultivated using wastewater and even saline waters (Abdur Razzak et al., 2024).

Binding agent

Binding agents have emerged as a necessary ingredient for producing a wide range of food products, including PBMA Binding agents are defined as a substance that helps hold together protein particles and other ingredients together, as well as to retain water and fat., mimicking the texture and structure of meat. Binders play a crucial role in mimicking meat's texture and properties by acting as stabilizers, gelling agents, thickeners, and emulsifiers (Herz et al., 2023). The incorporation of carrageenan and alginate as binding agents contributes to the formation of a fibrous structure, which is intended to increase the elasticity of PBMA (Dahal et al., 2025). Carrageenan is a high molecular weight polysaccharide composed of D-galactose residues linked in β-1,4 and α-1,3 galactose-galactose bond, extracted from red seaweeds such as *Kappaphycus* and *Eucheuma* species. Carrageenan widely used as a food additive in processed foods for its properties as a thickener, gelling agent, emulsifier, and stabilizer (Borsani et al., 2021). The addition of carrageenan will encourage the development of a more uniform and dense protein network structure and increase the water content of PBMA for the desired quality attribute. Carrageenan increase the viscosity of the liquid mixture by absorbing additional water. In addition to the biding function, carrageenan will leads to higher juiciness due to the intrinsic water holding function. (Su et al., 2024). Carrageenan showed better performance as binder than arabic gum, gellan gum, guar gum, and xanthan gum in enhancing texture and flavor parameter in pea protein, and konjac-glucomannan plant-based patties. Texture parameters exhibited high values by adding 2% carrageenan which was close to Beef Pattie. (Han et al., 2023). The incorporation of carrageenan and xanthan gum in mushroom-based sausage analogs enhance textural properties (purge loss and emulsion stability) compared to those produced with soy protein concentrate and casein (Arora et al., 2017).

Alginate is a polysaccharide derived from marine brown algae (*Phaeophyceae*) that is composed of 1,4-β-d-mannuronic (M) and α-l-guluronic (G) acids (Rashedy et al., 2021). Alginate used in enhancing quality attribues of PBMA (Zhang et al., 2020). The main mechanism action of alginate is resistance with heat. It helps to maintain meat anaolg shape and desired texture during cooking primarily because of the ionic cross-linking between alginate chains and divalent cations, example calcium. These cross-links create a stable, three-dimensional network that provides structure and resistance to heat, preventing the gel from collapsing or losing its form (Nath et al., 2022). The addition of alginate helps to minimize these obstacles and contributes to forming aligned fibers in the protein matrix through the elongation and orientation of the dispersed polysaccharide domains. Alginate offers unique advantages in certain aspects compare other binders. Alginate's gel formation with calcium can create a more firm and meat-like structure. Alginate had gelling mechanism which allowed it to create a network that entraped oil droplets within a water phase, functioning similarly to an emulsifier (Dahal et al., 2025).

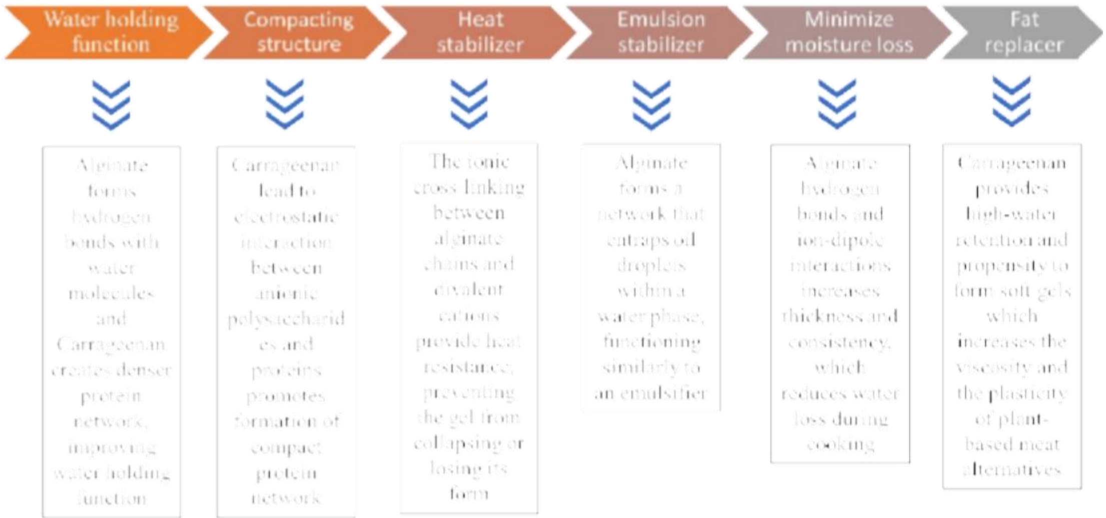

Figure 1. Mechanism of alginate and carrageenan in enhancing texture and structure of plant-based meat analog

Effects of fishery resources application in plant-based meat analogue properties

Physical properties

Quality attributes such as sensory acceptability, weight loss, and cooking yield can be determined or influenced by water holding capacity (Kothuri et al., 2025). Cooking yield refers to the weight of the product after cooking and represents the product's shrinkage during cooking (L. Huang et al., 2023). Water Holding Capacity (WHC) refers to the ability of a protein to hold water or the capacity per gram of protein to absorb water during the application of forces, pressing, centrifugation or heating (Moreira et al., 2023) Poor water holding capacity lead to fluid loss during transportation, storage, processing and cooking leading to changes in the texture of the final product (Shen et al., 2022); (Tarahi et al., 2024).

The addition of carrageenan showed significantly higher values of texture of pea protein, and methyleselluose vegan beef patties including hardness, cohesiveness, chewiness, and gumminess. Polysaccharides have the ability to prevent air release from the surface during the cooking process of vegan beef patties (Han et al., 2023). Soya-based meat analog with carrageenan addition showed better WHC capability as it had a more dense protein network which effectively traped water and resisted its release from the network after pressing lower compared to the control sample (Palanisamy et al., 2018). The addition if Iota carrageenan in pea – wheat glutten based meat analog promoted protein phase alignment and provided the opportunity to create the gluten network required for fibrous structure (Taghian Dinani et al., 2023). Alginates could firmly bind water through hydrogen bonds and ion-dipole interactions, increased product thickness and consistency, and reduce water loss during cooking (Chantanuson et al., 2022). Combination of potato protein and alginate produced a stronger composite gel, promoting the formation of a strong and flexible gel that can be advantageous in plant-based meat applications (Wannasin et al., 2024).

Algae offer a promising, sustainable alternative protein source for human consumption and can help reduce the environmental impact of protein production, particularly in comparison to plant-based sources like soybeans (Taelman et al., 2015). Microalgae have been shown increasing the nutrient content but their excessive content can negatively affect the development of a strong fibrous structure of the extrudate.. The incorporation of *Auxenochlorella protothecoides* in up to 50% reduced texturing but increased tenderness in comparison to pure soy based extrudates (Caporgno et al., 2020b). The higher the concentration of *Spirulina* included in soy-based meat analogs, the lower the elasticity, fibrousness and firmness values (Grahl et al., 2018). Substitution of lupin protein and *Spirulina platensis* (30 and 50%) in meat analog showed decrease formation of fibrous structures, and led to lower cooking yield values (Palanisamy et al., 2019).

Table 1. The effects of various fisheries sources addition in plant-based meat analogue properties.

PBMA ingredients	**Parameters**	**Study findings**	**References**
Pea protein, Glukomanan konjak, Methylcellulose, κ-karagenan	WHC, Cooking yield, texture	The addition of carrageenan was not significantly effect on WHC. The addition of carrageenan showed significantly higher values of cooking yield, hardness, cohesiveness, chewiness, and gumminess.	(Han et al., 2023)
Soya protein concentrate, carrageenan	WHC and texture	Increased iota-carrageenan (ICGN) content lead to denser tissue, increased significantly elasticity ranged and WHC.	(Palanisamy et al., 2018)
Soybean flour, soya protein isolate, sodium alginate	WHC and microstruture	Sodium alginate reduced moisture loss during cooking, contributed to the smooth texture of some cooked meat alternative items.	(Chantanuson et al., 2022)
Potato protein, calcium alginate	Gel strength	Combination of potato protein and alginate increased the gel strength of potato protein, provides structural resistance to heat.	(Wannasin et al., 2024)
Soya protein concentrate, *A. protothecoides* powder	Texture	The incorporation of soy protein and microalgae reduced texturing but increased tenderness in comparison to pure soy based extrudates	(Caporgno et al., 2020b)
Soya protein concentrate, *S. platensis*	Texture and cooking yield	Spirullina decreased the elasticity, fibrousness and firmness values of extruded meat	(Grahl et al., 2018)
Lupin protein	Cooking yield	Incorporation of	(Palanisamy et al., 2019)

concentrate and isolate, *Spirulina*		Spirulina start from level 30% showed lower cooking yield than the control	
Soybean protein isolate, gluten, wheat starch, *H. Pluvialis*(HP)	Texture	The addition of HP start from 0,75% significantly increase hardness and chewiness	(Z. Huang et al., 2024).
Spirulina, duck Weed, and yellow Chlorella (YC)	Texture	The addition of 3% YC was optimum level to deliver vegan patty with the highest gumminess and chewiness	(Bakhsh et al., 2023)
Soy protein isolate, golden mutant *Auxenochlorella pyrenoidosa*	Texture and NMR water distribution	5% cell-disrupted biomass gave best results: optimal fibrous 3D structure; enhanced springiness, chewiness, and bound water	(B. Wang et al., 2025)

Sensory

Sensory evaluation is indeed a scientific method used to evoke, measure, analyze, and interpret such responses to products as perceived through the senses of sight, smell, touch, taste, and hearing. (Owusu-Apenten & Vieira, 2022). Sensory science and consumer plays a crucial role in the development and acceptance of meat analogs by helping to identify the sensory characteristics that drive consumer liking and pinpoint potential barriers to their acceptance (Giacalone et al., 2022). Consumer acceptance of PBMA is heavily influenced by these sensory attributes, and optimizing them is key to driving product success (He et al., 2020). Sensory assessing parameters of PBMA consist of odor, appearance, flavor, texture, mouthfeel and aftertaste, firmness, juiciness, elasticity, fibrousness, hardness, and chewiness (Dinali et al., 2024).

Vegan beef paties based carrageenan 2% and bit has dark brown color that gives a meaty appearance, resulting in higher appearance scores from the panelists. The application of 2% carrageenan showed a high firmness intensity score from the panelists ($p < 0.05$), indicating that the firmness intensity level satisfied the panelists (Han et al., 2023)Sensory evaluation showed that encapsulation of flavoring agents in calcium alginate gel successfully mimics the flavor release profile of real meat during cooking, offering an authentic sensory experience similar to conventional meat. Flavored calcium alginate gel consistently enhanced flavor release in PBMA during cooking, without negatively affecting appearance or flavor stability, maintaining flavor retention at 4 °C for 10 days (Kang et al., 2024). In order to mimic the color real meat, mostly red or yellow algae are used because chlorophylls resulting the wrong color profiles. Several researchs about the using of microlage in PBMA, for instance red microalgae *Haematococcus pulvialis* in pea protein-based meat (Xia et al., 2022). Incorporated of *A. Protothecoides* enhanced consumer acceptance of HMMA by imroving appearance and giving chicken-like tenderness (Caporgno et al., 2020a). Red phycoerythrin also potential used in PBMA by its ability to support color changes as heat-labile red coloring agents. The addition of red phycoerythrin in PBMA giving consumers the same cooking experience as animal-derived meat products by deliver PBMA color changing after the cooking process (Wu et al., 2024).

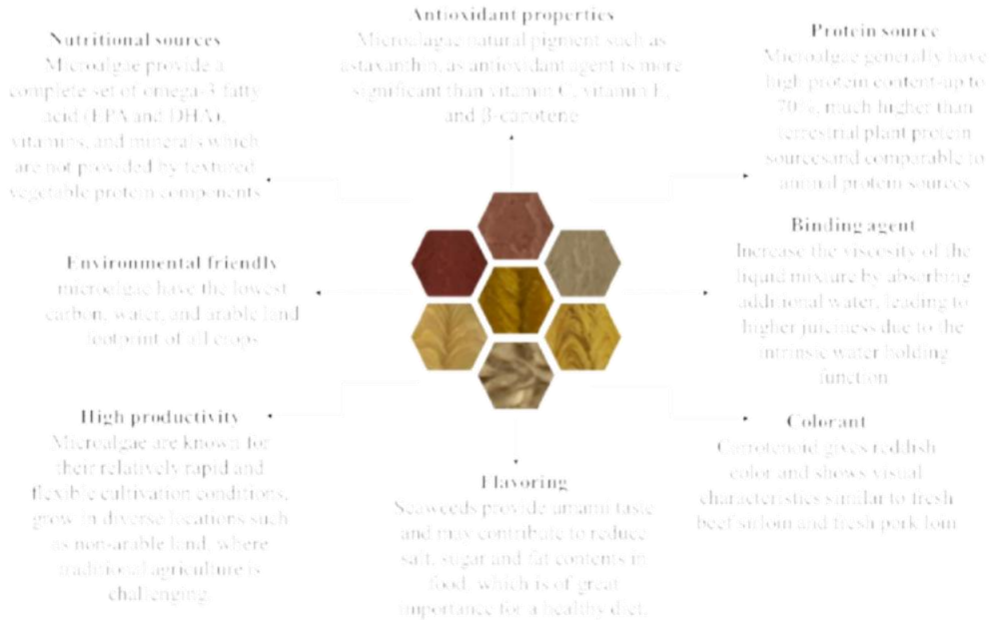

Figure 2. Key features of potential marine resources in plant-based meat analogues production

Nutritional Contribution of fishery resources in plant-based meat analog

While many consumers consider meat substitutes to be healthier than meat products, most of PBMA products currently on the market are not nutritionally equivalent alternatives to conventional meat products. The differences in terms of energy and nutrient conten that PBMA and animal meat can not be considered equivalent alternatives. The textured vegetable protein components (soybean, pea, and wheat), major constituents of PBMA do not provide nutrients as complete as animal meat (Cooper et al., 2025). In general, the comparison of the content, nutrients in PBMA products and animal meat can be explained as follows: 1) lower protein and cholesterol content; 2) higher carbohydrate, dietary fiber, and sodium content; 3) greater variation in fat content; 4) lower micronutrient content such as Vitamin B12, zinc, etc (Ketelings et al., 2023). Algae have emerged as a promising alternative to PBMA. Their protein content and other beneficial nutrients, makes it a valuable addition to meat substitutes (Fu et al., 2021). Incropration of *Ulva lactuca* powder in vegan patty contributed in improvement of protein and mineral (Harsha Mohan et al., 2024).

Microalgae offer an excellent and sustainable source for vegetarians and vegans to obtain the omega-3 fatty acid, as they are primary producers of EPA and DHA. Microalgae are indeed the primary source of DHA (docosahexaenoic acid) in the marine food chain, and they are used to produce algal oil supplements for human consumption (Venkatesh & Muthu, 2025). Microalgae are excellent source of micronutrient including vitamins such as vitamins A, B1, B2, B6, B12, C and E as well as minerals such as potassium, iron, magnesium, calcium and iodine (Koyande et al., 2019).The United States Food and Drug Administration (FDA) has approved several microalgae species that are "Generally Recognized as Safe" for human consumption, including *Arthrospira maxima, Arthrospira platensis, reinhardtii, Chlorella protothecoides, Dunaliella bardawil, Haematococcus pluvialis, Prototheca moriformis, Schizochytrium* sp., and *Ulkenia* sp. (Siddiqui, Ucak, et al., 2024). Regulation (EU) No. 2015/2283, the European Union, through EFSA mentioned, the new EU food list are *Haematococcus pluvialis, Odontella aurita, Schizochytrium* sp., *Tetraselmis chui, Ulkenia* sp. (de Oliveira & Bragotto, 2022).

Challenge of fishery resources application in plant based meat analog

The content of pigments in microalgae should be considered alongside nutritional content in PBMA formulation. For instance, chlorophyll, a green pigment, can significantly alter the color of PBMA, potentially creating a visually undesirable green hue, especially when trying to mimic the natural appearance of meat. Research conducts the addition of microalgae to food can result in a green color and a bitter taste, which may negatively impact consumer acceptance (Parniakov et al., 2018). High level of spirulina affects the color of PBMA becoming black and the appearance of an earthy taste and slightly musty odor (Grahl et al., 2018). Substitution of lupin protein with *Spirulina platensis* (30 and 50%) in HME meat analog, changes the color from yellow to dark green (Palanisamy et al., 2019).

Microalagae may have a strong unpleasant taste and odor that many consumers could hardly tolerate, especially its application in food products. The unpleasant aroma of microalgae do not stem from a single compound, but rather from a complex mixture of various volatile organic compounds. Depending on their molecular weight and degree of saturation, they can be associated with unpleasant odors such as grassy aroma (Nunes et al., 2023). *Spirullina platensis* exhibits a distinctive salty and umami taste arising from inorganic ions and 5'-nucleotides, as well as a "muddy" odor attribute mainly associated with sulfur compounds. *Chlorella proteinosa* and *Chlamydomonas reinhardtii* display sweet and bitter taste attributes mainly contributed by free amino acids, as well as "seaweed" and "mushroom" odor attributes associated with aldehydes and alcohols (Y. Zhao et al., 2024).

CONCLUSION

Fishery resources are considered as important food resource for humans due to their nutritional content, high production potential, sustainability, and lower environmental impact compared to terrestrial plants. Fishery resources such as microalgae generally contain higher protein content than terrestrial plant sources and are comparable to animal protein. In addition, microalgae provide a complete set of essential amino acids, vitamins, and minerals which are not provided by textured vegetable protein components such as soybean, pea, and wheat. This may help change consumers perceptions of PBMA, which are considered not nutritionally equivalent alternatives to conventional meat products. Algae and microalgae contain natural pigment, potentially contribute mimicking meat like color and antioxidant properties. The addition of algae-derived such as carrageenan and alginate may improve the quality attributes of PBMA. However, the utilization of fishery resources face challenges in the form of undesirable sensory and a reduction in the physical characteristics of PBMA. In conclusion, the incorporation of fishery ingredients into PBMA has great potential, but further research is needed to significantly reduce the potential negative impacts.

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