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Plant-Based proteins Industry in Sudan: Agricultural Potential, Processing Technologies, Consumer Acceptance, and Future Prospects – A Comprehensive Review

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Abstract*— Plant-based proteins materialize as one of the fastest-growing sectors of the global food industry, driven by increasing demand for sustainable, nutritious, and environmentally friendly protein sources. Despite its rapid international expansion, little attention has been given to the feasibility of developing this industry in Sudan. This review critically evaluates Sudan's potential to establish a competitive plant-based proteins industry by integrating evidence on agricultural resources, plant protein functionality, processing technologies, consumer acceptance, and industrial challenges. The review highlight that Sudan possesses substantial advantages, including abundant production of protein-rich legumes and oilseeds, extensive arable land, favorable agroecological conditions, and a long tradition of fermented plant-based foods such as Kawal, which may facilitate consumer acceptance of locally developed meat alternatives. Recent advances in high-moisture extrusion and related food engineering technologies have significantly improved the structural and sensory properties of plant-based meat products, creating new opportunities for industrial development. However, several constraints continue to limit commercialization, including inadequate food-processing infrastructure, limited technological capacity, insufficient regulatory frameworks, restricted industrial investment, and low consumer awareness. The analysis suggests that successful development of this sector will require coordinated efforts involving research institutions, government agencies, private investors, and the food industry to strengthen research and development, technology transfer, workforce capacity, and supportive policies. By strategically utilizing its agricultural resources and adopting modern food processing technologies, Sudan has the potential to develop a sustainable plant-based meat industry that enhances food security, promotes economic diversification, supports environmental sustainability, and strengthens regional competitiveness within the rapidly expanding alternative protein market.

Index Terms: Plant-based proteins, Sudan, Alternative proteins, Consumer acceptance, Plant proteins, High-moisture extrusion, Sustainability, Food security.

I. INTRODUCTION

The transition toward sustainable food systems has emerged as one of the most pressing global priorities in response to rapid population growth, climate change, environmental degradation, and the increasing demand for nutritious and sustainable protein sources (Godfray et al., 2018; FAO, 2024; Parodi et al., 2018). These interconnected challenges have intensified the search for alternative protein sources capable of enhancing food security while reducing the environmental footprint associated with conventional livestock production. Among the available alternatives, plant-based proteins have received considerable attention because of their environmental sustainability, nutritional value and compatibility with existing food production systems (Aiking, 2014; Wu et al., 2014; Loveday, 2020; Herreman et al., 2020). Consequently, alternative proteins are increasingly recognized by researchers, policymakers, and the food industry as important components of future sustainable food systems (McClements & Grossmann, 2021).

Alternative proteins encompass a wide range of sources, including plant proteins, cultured meat, edible insects, microbial proteins, algae, and precision fermentation-derived ingredients (Good Food Institute, 2024). Among these categories, plant-based proteins have emerged as the most technologically advanced and commercially successful segment because they are designed to mimic conventional meat while requiring fewer natural resources and generating substantially lower environmental impacts. Continuous growth in consumer demand, together with rapid technological innovation, has positioned plant-based proteins among the fastest-growing sectors of the global food industry (Good Food Institute, 2024; The Business Research Company, 2025).

Modern plant-based protein products are sophisticated food systems designed to replicate the appearance, texture, flavor, and nutritional characteristics of conventional meat through the strategic combination of plant-derived proteins, lipids, carbohydrates, natural colorants, flavoring compounds, and functional ingredients (Dekkers et al., 2018; Sha & Xiong, 2020). Significant advances in food engineering, particularly high-moisture extrusion technology, have substantially improved the development of fibrous structures, juiciness, and overall sensory quality, thereby enhanced consumer acceptance and accelerating market expansion (Dekkers et al., 2018; Chen et al., 2022).

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International Journal of Science, Engineering and Management (IJSEM)

Volume 13, Issue 08, August 2026

These technological advances have also contributed to the rapid expansion of the plant-based protein market (Good Food Institute, 2024; The Business Research Company, 2025). Emerging processing technologies—including shear-cell processing, precision fermentation, and three-dimensional (3D) food printing—are further expanding opportunities to improve product quality and diversify plant-based protein applications (Chen et al.,2022).

The functional properties of plant proteins are fundamental determinants of meat analogue quality and consumer acceptance (Loveday, 2020; McClements & Grossmann, 2021). Protein solubility, gelation, emulsification, foaming capacity, and water-holding ability directly influence the texture, structural integrity, stability, and sensory attributes of finished products **(Joshi and Kumar, 2015).**

Consequently, soybean and pea proteins have become the predominant commercial raw materials because of their favorable functional performance and well-established processing characteristics. Nevertheless, numerous underutilized legumes possess comparable technological potential and represent valuable alternative protein sources that warrant greater scientific investigation and industrial utilization (Loveday, 2020; Kyriakopoulou et al., 2021). From a nutritional perspective, appropriately formulated blends of complementary plant proteins can provide high-quality protein with balanced essential amino acid profiles) Loveday, 2020; Hertzler et al., 2020*)*. However, optimizing protein digestibility, bioavailability, and micronutrient composition remains an important research priority for the continued advancement of plant-based meat products (Hertzler et al., 2020).

Despite remarkable scientific and commercial progress, research on plant-based protein has concentrated predominantly on technological innovation, nutritional quality, and consumer behavior in high-income countries (Tso et al., 2023). Comparatively little attention has been devoted to evaluating the feasibility of developing plant-based protein industries in resource-rich developing countries, particularly those in Africa. Furthermore, relatively few studies have examined and explored how locally available agricultural resources, indigenous food knowledge, and existing agro-industrial capacity can be integrated to establish sustainable and economically competitive alternative protein industries in these regions (Godfray et al., 2018; Boland et al., 2013; Kyriakopoulou et al., 2021; Tso et al., 2023). Sudan represents a particularly compelling case for such an assessment.

The country possesses extensive agricultural land, diverse agroecological zones, and abundant production of protein-rich legumes and oilseed crops—including groundnut, sesame, chickpea, faba bean, cowpea, and pigeon pea—that could serve as sustainable raw materials for plant-based meat production (FAO, 2024). In addition, Sudan has a long-standing tradition of producing fermented plant-based foods, particularly *Kawal*, which demonstrates indigenous expertise in plant protein utilization and may and may provide a favorable cultural basis for the acceptance of locally developed plant-based meat alternative (Dirar et al., 1985; Fangbo et al., 2024). Collectively, these agricultural resources, traditional food systems, and strategic geographic advantages distinguish Sudan as a promising candidate for developing a competitive plant-based meat industry.

Against this background, the present review critically evaluates Sudan's potential to establish a sustainable and competitive plant-based meat industry by synthesizing current scientific evidence on plant protein resources, functional properties, processing technologies, nutritional quality, consumer acceptance, and industrial development. Furthermore, the review identifies the principal technological, economic and socio-cultural barriers that may hinder commercialization and proposes strategic recommendations to support research, policy development, industrial investment, and sustainable value-chain expansion. By integrating global advances in plant-based proteins science with Sudan's unique agricultural resources and traditional food heritage, this review provides a comprehensive framework for future research, innovation, and industrial development aimed at strengthening national food security and enhancing Sudan's participation in the rapidly expanding global alternative protein sector.

II. LITERATURE REVIEW

A. Definition, Classification, and Raw Materials of Plant-Based Proteins

Plant-based proteins refer to food products formulated primarily from plant-derived ingredients and designed to reproduce the sensory characteristics, texture, appearance, and nutritional attributes of conventional meat products. These products are mainly produced from protein-rich plant materials, including legumes, cereals, oilseeds, algae, and fungal-derived ingredients, through advanced processing technologies that modify protein structure and functionality (Xiao et al., 2023).

The term *meat alternatives* represent a broader category that includes products developed to imitate different types of animal-derived foods. These products may resemble whole-muscle meat structures or processed meat products such as burgers, patties, sausages, and nuggets. Alternative proteins are generally classified into three major categories: plant-based alternatives produced from crops such as soy, pea, and other legumes; cell-based meat produced through animal cell cultivation; and fermentation-derived proteins such as mycoproteins produced by fungal fermentation (Sha & Xiong, 2020; Finnigan et al., 2019; Parodi et al. (2018); GFI, 2024).

Unlike traditional vegetarian products, modern plant-based meat analogues are engineered food systems designed to reproduce the complex characteristics of animal meat, including fibrous texture, juiciness, color, flavor

ISSN (Online) 2456 -1304
International Journal of Science, Engineering and Management (IJSEM)
Volume 13, Issue 08, August 2026

release, and cooking behavior. Achieving these attributes requires the selection of suitable protein sources combined with functional ingredients such as vegetable oils, hydrocolloids, natural binders, flavor compounds, and colorants (McClements & Grossmann, 2021).

Sudan possesses considerable agricultural potential that could support the development of a plant-based protein sector. The country has diverse agroecological zones and extensive agricultural resources (Table I) suitable for cultivating protein-rich legumes, cereals, and oilseed crops (FAO, 2024). Legumes such as faba bean, chickpea, lentil, cowpea, and pigeon pea represent promising sources of plant proteins, while sorghum, millet, maize, and rice can serve as complementary ingredients to improve nutritional quality and functional properties of meat analogues (Ali *et al*., 2025; Ibrahim *et al*., 2022; McClements & Grossmann, 2021).

In addition, Sudan is an important producer of oilseed crops particularly sesame and groundnut, which provide valuable vegetable oils and functional lipid components required for improving the texture, flavor, and juiciness of plant-based meat formulations. According to FAOSTAT agricultural production statistics, sorghum and sesame remain among Sudan's important strategic crops, highlighting their potential for future value-added food processing industries (FAO, 2025). The Food and Agriculture Organization has also emphasized the importance of strengthening agro-industrial processing of strategic crops in developing countries to improve food security and increase agricultural value addition (FAO, 2024).

To achieve desirable sensory characteristics, locally available plant materials can be combined with functional ingredients such as vegetable oils, hydrocolloids, natural binders, and flavoring systems. Advanced ingredients such as leghemoglobin may also enhance meat-like sensory properties in industrial formulations; however, their application remains dependent on technological availability and regulatory approval (Loveday, 2020; McClements & Grossmann, 2021).

Emerging alternative protein sources, including microalgae proteins and fungal-derived proteins, have received increasing research attention because of their nutritional potential and sustainability advantages (Zhang et al., 2024). However, their widespread commercial application remains limited due to challenges related to production cost, consumer acceptance, and processing requirements (Finnigan et al., 2019).

Table (I) reflect the major plant protein sources suitable for plant-based portions production, some of these resources are not cultivated in Sudan.

Table I: Major Plant Protein Sources Suitable for Plant-Based portions Production

Raw material	Protein (% dry basis)
Soybean	36–40
Lupin	35–40
Faba bean	26–31
Peanut	25–30
Lentil	24–26
Cowpea	23–25
Pea	22–25
Chickpea	20–23
Sesame seed	18–22
Oat	13–17
Sorghum	10–12
Maize	8–10
Rice	7–9

Note: protein content varies depending on cultivar, environmental conditions, agricultural practices, and analytical method.

Source: Sha and Xiong (2020), McClements and Grossmann (2021), and Singh et al. (2022).

B. Global Development of the Plant-Based Protein Industry

The global food system has undergone significant transformation during the last decade, with plant-based protein emerging as one of the most rapidly expanding sectors within the alternative protein industry. This growth has been driven by increasing concerns related to environmental sustainability, climate change, food security, public health, and animal welfare (Poore & Nemecek, 2018; Rout et al., 2024).

Scientific evidence indicates that replacing a proportion of conventional meat consumption with plant-based alternatives may contribute to reducing greenhouse gas emissions, agricultural land requirements, water consumption, and biodiversity loss. Consequently, plant-based protein products have become an important component of strategies aimed at developing more sustainable food systems (Poore & Nemecek, 2018; McClements, 2024).

The commercial expansion of plant-based protein has stimulated substantial investment in food innovation, biotechnology, and processing technologies. The increasing number of companies involved in alternative protein development reflects growing consumer demand for products that more closely resemble conventional meat in appearance, texture, aroma, and taste (Good Food Institute, 2024; The Business Research Company, 2025).

Modern plant-based meat analogue production has therefore shifted from simple plant-based substitutes toward highly engineered food systems. Current research focuses on optimizing plant proteins, lipid systems, flavor compounds, colorants, and structural modification technologies to reproduce the complex organization of animal muscle tissues. Technologies such as high-moisture extrusion,

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Volume 13, Issue 08, August 2026

shear-cell processing, fermentation, and protein modification have become central tools in achieving improved sensory quality and consumer acceptance (Dekkers et al., 2018; Samard & Ryu, 2019).

Another important factor contributing to the rapid growth of the plant-based protein industry is the increasing prevalence of food allergies associated with certain animal-derived products. Plant-based meat alternatives provide a valuable option for consumers who must avoid specific meat products because of allergic reactions or dietary restrictions (Bakhsh et al., 2023). Consequently, the continued development of safe, nutritious, and high-quality plant-based meat products has the potential to improve dietary diversity while addressing the nutritional needs of this growing consumer group.

Despite rapid technological progress, challenges remain regarding sensory similarity, nutritional optimization, production cost, consumer perception, and regulatory frameworks. Addressing these challenges will be essential for the continued growth of the plant-based protein sector, particularly in emerging markets where local agricultural resources could provide alternative pathways for sustainable protein production.

C. Functional Properties of Plant Proteins in Meat Analogues

Plant proteins represent the structural foundation of plant-based protein products because their physicochemical and functional properties largely determine the quality attributes of the final product. Important functional characteristics include solubility, water-holding capacity, emulsification ability, gel formation, foaming properties, protein–protein interactions, and the ability to form organized structures during processing. These properties directly influence texture development, juiciness, cooking behavior, and sensory acceptance of meat analogues (Boye et al., 2010; Day, 2013; Lam et al., 2018; Samard & Ryu, 2019).

The functionality of plant proteins varies considerably according to botanical source, protein composition, extraction method, degree of purification, and processing conditions. Soy protein has traditionally been considered as one of the most widely used protein source for meat analogue production because of its excellent water-binding capacity, emulsification properties, and ability to form strong gel networks. These characteristics enable soy proteins to produce desirable fibrous textures during extrusion processing (Loveday, 2020; McClements & Grossmann, 2021).

Recently, alternative legume proteins such as pea, faba bean, chickpea, lentil, and cowpea have received increasing attention due to their nutritional value, availability, and potential to diversify plant-based protein ingredients (Kyriakopoulou et al., 2021; Xiao et al., 2023). Pea protein has gained substantial attention as an alternative to soy protein because of its favorable amino acid profile, functional properties, sustainability advantages, and suitability for consumers seeking soy-free products (Ćujić Nikolić et al., 2026).

From a Sudanese perspective, the functional properties of locally available legumes represent an important opportunity for developing indigenous plant-based ingredients (Table II). Crops such as faba bean, cowpea, chickpea, pigeon pea, groundnut, and sesame are already cultivated within the country and could provide locally sourced proteins and functional components. However, further research is required to characterize their extraction efficiency, protein functionality, digestibility, and performance under meat analogue processing conditions.

The development of Sudanese plant protein ingredients (Table I) could reduce dependence on imported protein isolates while increasing the value addition of agricultural crops. Combining different local protein sources may also provide complementary functional and nutritional advantages, allowing the formulation of products with improved texture, amino acid balance, and consumer acceptability.

Table II: Functional Characteristics and Potential Applications of Selected Plant Protein Sources Relevant to Meat Analogue Production

Protein source	Availability / agronomic relevance	Protein (%, dry basis)	Key functional properties	Potential applications
Soybean	Globally established commercial protein crop	36–40	Excellent gelation, emulsification, water-holding capacity, and fibrous texture formation	Extruded meat analogues, burgers, sausages
Pea	Widely cultivated; major emerging protein source	22–25	Good emulsifying capacity, mild flavour, and suitability for soy-free formulations	Burgers, nuggets, protein blends
Faba bean	Important legume crop in Sudan and many temperate regions	26–31	Good water-holding capacity, emulsifying properties, and relatively high protein content	Extruded meat analogues, protein concentrates
Cowpea	Drought-tolerant legume widely cultivated in Africa	23–25	Good water absorption, nutritional quality, and moderate emulsifying properties	Affordable meat analogues, composite formulations

ISSN (Online) 2456 -1304

International Journal of Science, Engineering and Management (IJSEM)

Volume 13, Issue 08, August 2026

Protein source	Availability / agronomic relevance	Protein (%, dry basis)	Key functional properties	Potential applications
Chickpea	Cultivated in Sudan and many semi-arid regions	20–23	Moderate emulsifying and water-binding properties with balanced nutritional quality	Protein blends, meat extenders
Peanut	Major oilseed crop in Sudan and other tropical regions	25–30	Good emulsifying properties and lipid functionality, contributing to improved mouthfeel	Hybrid protein–fat formulations
Sesame	Traditional oilseed crop in Sudan and the Middle East	18–22	Functional lipids, antioxidant compounds, and flavour enhancement	Protein–fat formulations and flavour enhancement
Lupin	High-protein alternative crop with increasing commercial interest	35–40	High protein concentration, excellent emulsification, and good gel-forming ability	High-protein meat analogues

Note: Protein contents are expressed on a dry weight basis. Functional properties and protein composition may vary depending on cultivar, environmental conditions, processing method, and protein extraction technique.

Source: Compiled by the authors based on Sha and Xiong (2020), McClements and Grossmann (2021), Singh et al. (2022), and supporting literature on plant protein functionality and regional crop production.

D. Nutritional Quality of Plant Proteins in Meat Analogues

The nutritional quality of plant-based meat products is a major determinant of their potential contribution to sustainable food systems (Kyriakopoulou et al., 2021). Although animal proteins generally exhibit higher digestibility and a more balanced essential amino acid profile, properly formulated plant protein combinations can provide nutritionally adequate alternatives when appropriate processing and formulation strategies are applied (Sha & Xiong, 2020; Kyriakopoulou et al., 2021).

The nutritional performance of plant proteins depends not only on total protein concentration but also on amino acid composition, digestibility, bioavailability, and the presence of anti-nutritional factors. Evaluation methods such as the Protein Digestibility-Corrected Amino Acid Score (PDCAAS) and Digestible Indispensable Amino Acid Score (DIAAS) are widely used to assess dietary protein quality and nutritional adequacy (Hertzler et al., 2020). Legume proteins are particularly valuable for plant-based protein applications because of their relatively high protein content and potential for amino acid complementation when combined with other plant protein sources. However, many legumes are limited by lower levels of sulfur-containing amino acids, particularly methionine and cysteine. Combining different plant protein sources, such as legumes with cereals or oilseed proteins, can improve amino acid balance and enhance overall nutritional quality (Sharma et al., 2025). Processing techniques play an important role in improving the nutritional functionality of plant proteins. Traditional methods including soaking, germination, fermentation, and heat treatment can reduce anti-nutritional compounds such as phytates, tannins, and protease inhibitors, thereby improving protein digestibility and mineral bioavailability (Hertzler et al., 2020). These approaches are particularly relevant for Sudan, where traditional fermented plant-based foods demonstrate indigenous knowledge of biological processing methods that may provide a foundation for future applications in plant protein processing (Elskhalifa et al., 2007).

Integrating indigenous processing practices with modern food technologies could provide opportunities for developing nutritionally improved plant-based meat products using locally available crops.

E. Feed Conversion Efficiency and Resource Utilization

The efficiency of converting agricultural resources into edible protein has become an important indicator of sustainable food production. In conventional livestock systems, substantial quantities of feed crops are required to produce animal-derived foods because a considerable proportion of consumed nutrients is utilized for animal metabolism, maintenance, and physiological functions rather than direct edible protein production (Shepon et al., 2016).

Feed Conversion Ratio (FCR), defined as the amount of feed required to produce one unit of animal weight gain or define simply as the ratio of feed intake to body weight gain. FCR commonly used to evaluate livestock production efficiency (Table III). Among major livestock species, poultry and aquaculture generally exhibit lower FCR values compared with ruminants, whereas beef production typically requires substantially greater feed inputs due to slower growth rates and higher maintenance requirements (FAO, 2011; Mottet et al., 2017; Wilkinson, 2011).

However, plant-based meat production differs fundamentally from animal production because it avoids the additional biological conversion step required to transform plant-derived nutrients into animal biomass. Therefore, comparisons between livestock FCR and plant-based protein systems (Tble 4) should be interpreted as comparisons of resource utilization pathways rather than equivalent production ratios. Plant-based protein systems have the potential to improve protein-use efficiency by converting plant-derived resources more directly into human food while

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International Journal of Science, Engineering and Management (IJSEM)

Volume 13, Issue 08, August 2026

reducing resource losses associated with livestock production. This approach may contribute to lower land requirements, reduced water consumption, and decreased greenhouse gas emissions compared with conventional animal protein systems (Poore & Nemecek, 2018; Aiking, 2014; McClements & Grossmann, 2021).

For Sudan, this concept has relevance because large quantities of protein-rich crops such as faba bean, are already produced (Gasim et al., 2015; World Bank, 2020).

Utilizing these crops directly as ingredients for value-added food products rather than relying exclusively on livestock conversion pathways may enhance national protein availability, improve agricultural value chains, and support more resilient food systems.

Table III: Resource Conversion Efficiency of Major Protein Production Systems

Production system	Feed conversion characteristics (kg feed/kg live weight)	Resource efficiency
Beef cattle	6–10 or higher depending on production system	Lower efficiency due to high feed and land requirements
Sheep	4–6	Moderate efficiency
Pigs	3–4	Moderate efficiency
Broiler chickens	1.5–2.0	High efficiency among terrestrial livestock
Farmed fish	1.1–1.5	High efficiency
Plant-based meat	No livestock feed conversion stage	Direct conversion of plant proteins into human food

Note: Feed conversion ratio (FCR) is applicable only to animal production systems and represents kilograms of feed required to produce one kilogram of live animal weight. Plant-based meat products bypass the animal production stage; therefore, FCR is not directly applicable.

Source: Compiled by the authors based on FAO (2011), Wilkinson (2011), Mottet et al. (2017), Alexander et al. (2019), and Hull et al. (2021).

F. Sudan's Meat Industry Challenges and the Potential for Plant-Based Meat Development

Sudan possesses one of the largest livestock populations in Africa (**Alfadul, 2024; FAO, 2024)** and animal production remains an important component of the country's agricultural economy and food system. However, the development of a competitive meat-processing sector continues to face several structural and technological challenges, including high production costs, limited processing infrastructure, inadequate cold-chain systems, fluctuating livestock supply, and restricted adoption of advanced food-processing technologies.

The cost of conventional meat production is influenced by multiple factors, including animal procurement, feed availability, veterinary services, transportation, slaughtering operations, refrigeration, and quality-control requirements. These challenges can limit the capacity of domestic meat industries to achieve consistent value addition and compete effectively in regional and international markets (Mottet et al., 2017; Thornton, 2010)

In contrast, plant-based protein production provides an alternative pathway for utilizing Sudan's agricultural resources through the direct conversion of locally produced crops into value-added protein foods. Protein-rich crops including faba bean, cowpea, chickpea, pigeon pea, groundnut, and sesame represent promising raw materials for developing plant-based meat ingredients. These crops could support the production of protein concentrates, isolates, and textured plant proteins through modern processing technologies such as extrusion and fermentation **(**Samard & Ryu, 2019; Beniwal et al., 2021).

The development of a plant-based meat industry in Sudan should not be considered a replacement for the traditional livestock sector. Instead, it represents a complementary approach that can diversify national protein sources, improve agricultural value addition, reduce dependence on imported protein ingredients, and create new opportunities for food manufacturing and export-oriented products.

So, integrating locally available crops with modern food-engineering technologies may contribute to a more resilient food system by reducing vulnerability associated with climate variability, livestock diseases, and fluctuations in animal production. Such an approach aligns with global trends toward sustainable protein diversification and circular bioeconomy strategies (Godfray et al., 2018; FAO, 2024; McClements & Grossmann, 2021).

Primary materials, raw materials availability, processing and technological requirement for processing of conventional meat and plant-based meat production systems was concluded in in Table IV. the strength weakness point was highlighted in the comparison table in addition to supply chain challenges, environmental consideration up to food security contribution.

ISSN (Online) 2456 -1304

International Journal of Science, Engineering and Management (IJSEM)

Volume 13, Issue 08, August 2026

Table IV: Comparison Between Conventional Meat Processing and Plant-Based Meat Production Systems in Sudan

Comparison criterion	Conventional meat production	Plant-based meat production
Primary raw materials	Cattle, sheep, goats, and poultry	Legumes and oilseeds (e.g., faba bean, cowpea, chickpea, groundnut, and sesame)
Raw material availability	Influenced by livestock production cycles, feed availability, climate variability, and animal health	Dependent on seasonal crop production, storage infrastructure, and agricultural productivity
Processing requirements	Slaughtering, carcass handling, refrigeration, meat inspection, and cold-chain logistics	Protein extraction, ingredient formulation, extrusion/texturization, packaging, and quality control
Technological requirements	Slaughterhouse infrastructure, refrigeration, and meat-processing equipment	Protein extraction and food-processing technologies, particularly extrusion and texturization
Supply-chain challenges	Vulnerable to livestock diseases, transport costs, and feed shortages	Dependent on reliable crop production, storage, and food-processing infrastructure
Environmental considerations	Higher land, water, and greenhouse gas emission impacts	Generally associated with lower resource use and emissions, depending on ingredient sourcing and processing intensity
Value-addition opportunities	Meat processing and marketing of animal products	Development of functional foods, protein ingredients, and innovative meat analogue products
Contribution to food security	Provides high-quality animal protein but may be constrained by production costs and availability	Diversifies protein sources and promotes the use of locally available agricultural crops

Source: Compiled by the authors based on FAO (2024), McClements and Grossmann (2021), Chen et al. (2022), Poore and Nemecek (2018), and relevant literature on Sudanese agriculture.

G. Processing Technologies for Plant-Based Protein Production

Technological innovation represents the primary driver behind the development of modern plant-based meat products. Unlike traditional vegetarian foods, current meat analogues are highly engineered systems designed to reproduce the structural, mechanical, and sensory characteristics of animal-derived meat. Achieving meat-like properties requires controlled modification of plant proteins through thermal, mechanical, and biochemical processing approaches (McClements & Grossmann, 2021).

Among available technologies, high-moisture extrusion (HME) is currently considered the most established industrial approach for producing fibrous meat analogues. During extrusion processing, plant proteins are exposed to controlled combinations of temperature, moisture content, pressure, and shear forces. These conditions induce protein unfolding, alignment, aggregation, and formation of anisotropic structures that resemble the fibrous organization of muscle tissues (Dekkers et al., 2018; Samard & Ryu, 2019).

Low-moisture extrusion is another widely applied technology since early twenty century, particularly for producing texturized vegetable proteins (TVP). This process offers advantages including lower production cost, extended shelf stability, and suitability for dry protein ingredients; however, additional hydration and formulation steps are usually required before consumption (Lin et al., 2002).

Shear-cell technology represents an advanced structuring approach that uses controlled shear forces to align protein molecules into layered fibrous structures like whole-muscle meat. Although this technology can produce highly realistic textures, its application remains primarily at laboratory and pilot scales due to limitations in processing capacity and industrial scalability (Kyriakopoulou et al., 2021).

Fermentation-based approaches have also gained increasing attention because microbial fermentation can improve flavor development, digestibility, and functional properties of plant proteins (Özpınar et al., 2026). Similarly, protein fractionation and modification techniques can enhance solubility, emulsification, and gelation properties, allowing the development of improved protein ingredients for meat analogue formulations (McClements & Grossmann, 2021).

Emerging technologies, including three-dimensional (3D) food printing, provide new opportunities for designing complex food structures and personalized nutrition. However, their commercial application in plant-based meat production remains limited because of challenges related to production speed, ingredient compatibility, and large-scale manufacturing (Chen et al., 2022).

Despite significant progress, producing whole-muscle analogues that accurately reproduce the hierarchical organization of animal tissues remains technically challenging. Current commercial products therefore focus mainly on minced meat alternatives, burgers, sausages, and

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International Journal of Science, Engineering and Management (IJSEM)

Volume 13, Issue 08, August 2026

nuggets, while whole-cut products such as steaks continue to require further technological development (Zhang et al., 2024).

Agricultural Crops

(Soybean, Pea, Faba bean, Cowpea, Chickpea, Peanut, Sesame)

↓

Cleaning and Milling

↓

Protein Extraction and Fractionation

↓

Plant Protein Ingredients

(Concentrates /floure/ Isolates)

↓

Functional Modification

(Solubility, Gelation, Emulsification)

↓

Structuring Technologies

- High-moisture extrusion
- Shear-cell processing
- Fermentation
- Protein modification

↓

Meat Analogue Formation

↓

Sensory and Nutritional Optimization

↓

Plant-Based Meat Products

↓

Consumer Market

Source: Adapted from Dekkers et al. (2018), Samard and Ryu (2019), Kyriakopoulou et al. (2021), McClements and Grossmann (2021), and Özpınar et al. (2026).

Figure 1. Processing Pathway to Produce Plant-base protein Products

Table V: Major processing technologies used in the manufacture of plant-based protein products

Technology	Principle	Advantages	Main limitations
High-moisture extrusion	Protein alignment under controlled heat, moisture, and shear	Produces fibrous meat-like texture; industrially established	Requires high capital investment
Low-moisture extrusion	Production of dry texturized vegetable proteins	Low cost; long shelf life	Requires rehydration before use
Shear-cell technology	Shear-induced protein structuring	Produces highly realistic fibrous structures	Mainly pilot-scale application
Fermentation	Microbial modification of proteins and flavor compounds	Improves flavor, digestibility, and functionality	Requires precise process control
Protein fractionation	Concentration and isolation of functional proteins	Improves protein quality and functionality	Additional processing cost
3D food printing	Layer-by-layer construction of food structures	Enables customized product design	Limited industrial scalability

Source: Compiled by the authors based on Dekkers et al. (2018), Samard and Ryu (2019), Kyriakopoulou et al. (2021), McClements and Grossmann (2021), Chen et al. (2022), and Özpınar et al. (2026).

a. Plant Based- Protein and oil Extraction Technological Process

As shown in **Figure 1** and data summarized in **Tables IV and V**, the production of plant-based protein ingredients involves several processing steps, including raw material preparation, protein extraction and fractionation, functional modification, and structuring using technologies such as extrusion and shear-cell processing. These processing steps are essential for producing plant-based meat products with desirable functional and sensory properties (McClements & Grossmann, 2021; Kyriakopoulou et al., 2021).

In Sudan, the vegetable oil industry is well established and mainly depends on locally produced oilseed crops such as groundnut and sesame. Many of the processing steps used in oil extraction, including cleaning, dehulling, milling, and oil extraction, are similar to those required for producing plant protein ingredients. In addition, the protein-rich by-products generated after oil extraction can be used as raw materials for protein extraction and further processing into value-added food ingredients (McClements & Grossmann, 2021; FAO, 2024).

Table VI compares the processing steps used in conventional oil extraction with those required for plant-based protein production. Although additional technologies, such as protein purification and texturization, are needed to produce meat analogues, the existing oil-processing industry provides a good foundation for developing a plant-based protein industry in Sudan. Utilizing oilseed by-products as a source of plant proteins could improve resource utilization, increase the value of local agricultural crops, and support the production of plant-based meat products using locally available raw materials (Poore & Nemecek, 2018; McClements & Grossmann, 2021).

ISSN (Online) 2456 -1304
International Journal of Science, Engineering and Management (IJSEM)
Volume 13, Issue 08, August 2026

H. Research Gap and Future Opportunities for Sudan

Although extensive research has investigated plant-based meat technologies, nutritional characteristics, consumer acceptance, and sustainability aspects, most published studies have focused on developed markets in North America, Europe, and Asia. Limited attention has been directed toward the application of alternative protein technologies in low- and middle-income countries, particularly within African agricultural contexts.

Despite possessing considerable agricultural resources, diverse protein-rich crops, and a long history of traditional plant-based fermented foods, Sudan has received limited scientific attention regarding its potential role in the emerging plant-based meat sector. Previous studies have primarily focused on crop production, livestock development, and food security challenges, while the integration of agricultural resources with modern alternative protein technologies remains largely unexplored.

A major research gap exists in evaluating the suitability of Sudanese plant protein sources for meat analogue production, including their functional properties, extraction efficiency, nutritional quality, processing behavior, and consumer acceptance. Locally available legumes such as faba bean, cowpea, chickpea, and pigeon pea require further investigation as potential ingredients for developing indigenous plant-based protein products.

Future research should therefore focus on a multidisciplinary approach combining food science, agricultural biotechnology, processing engineering, nutrition, and consumer studies. Initial investigations should characterize the functional and nutritional properties of Sudanese plant proteins, followed by pilot-scale processing studies using technologies such as extrusion, fermentation, and protein modification.

The establishment of a plant-based meat sector in Sudan could provide opportunities for agricultural value addition, diversification of protein sources, improvement of food security, and development of innovative food industries. However, successful commercialization will require investment in research infrastructure, processing capacity, regulatory frameworks, and consumer awareness programs.

Although plant-based meat has been widely studied in terms of processing technologies, nutritional quality, sustainability, and consumer acceptance, most research has focused on North America, Europe, and parts of Asia. In contrast, limited studies have examined the potential of plant-based meat production in African countries, including Sudan.

Sudan has abundant agricultural resources and produces several protein-rich crops, such as faba bean, cowpea, chickpea, groundnut, and sesame. However, these crops have mainly been studied for conventional food and oil production, while their potential for manufacturing plant-based meat products has received little attention. Information on their functional properties, protein extraction, processing performance, and suitability for meat analogue production is still limited.

Future research should focus on evaluating the functional and nutritional characteristics of locally available plant proteins and their performance in meat analogue formulations. Studies on protein extraction, extrusion, fermentation, and consumer acceptance are also needed to support the development of locally adapted products.

Developing a plant-based protein industry in Sudan could increase the value of local crops, diversify protein sources, strengthen food security, and create new opportunities for the food processing sector. Achieving these goals will require continued research, investment in processing technologies, and collaboration between researchers, industry, and policymakers.

III. SUDAN'S AGRICULTURAL POTENTIAL, CHALLENGES, AND FUTURE PROSPECTS FOR PLANT-BASED MEAT DEVELOPMENT

A. Sudan's Agricultural Potential for Plant-Based Meat Production

Sudan possesses considerable agricultural potential that could support the development of a plant-based meat industry based on locally available protein resources. The country is characterized by extensive agricultural land, diverse agroecological conditions, and the capacity to cultivate a wide range of legumes, cereals, and oilseed crops suitable for food processing applications. These resources provide an opportunity to shift from the export of agricultural commodities toward the production of higher-value protein-based foods.

Several crops cultivated in Sudan have significant potential as raw materials for plant-based meat production. Legumes including faba bean (*Vicia faba*), chickpea (*Cicer arietinum*), cowpea (*Vigna unguiculata*), pigeon pea (*Cajanus cajan*), and soybean (*Glycine max*) contain substantial protein levels and may be processed into protein concentrates, isolates, and textured plant proteins. In addition, oilseed crops such as groundnut (*Arachis hypogaea*) and sesame (*Sesamum indicum*) provide valuable protein fractions and functional lipids that can contribute to improving the texture, flavor, and nutritional quality of meat analogue formulations.

The utilization of these locally available crops for plant-based meat production could enhance agricultural value addition by creating new markets for farmers, reducing dependence on imported protein ingredients, and supporting the development of innovative food industries. However, further research is required to evaluate the extraction efficiency, functional properties, nutritional quality, and processing performance of Sudanese plant protein sources under meat analogue production conditions.

Beyond agricultural resources, Sudan possesses a cultural advantage through traditional fermented plant-based foods.

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International Journal of Science, Engineering and Management (IJSEM)
Volume 13, Issue 08, August 2026

Kawal, a fermented product traditionally produced from *Cassia obtusifolia* leaves, represents an example of indigenous knowledge associated with plant protein utilization and fermentation practices. Although Kawal differs from modern plant-based meat products in composition and processing technology, its historical consumption demonstrates familiarity with fermented plant-derived foods and may provide a cultural foundation for introducing innovative plant-based protein products (Canoy et al., 2024).

B. Consumer Acceptance and Market Considerations in Sudan

Consumer acceptance represents one of the most important factors determining the successful commercialization of plant-based meat products. International research indicates that sensory characteristics, particularly taste, texture, aroma, and appearance, remain the primary determinants influencing consumer willingness to purchase meat alternatives. Additional factors, including price, nutritional value, perceived health benefits, cultural familiarity, environmental concerns, and trust in food technologies, also influence consumer attitudes toward these products (Hoek et al., 2011; Siegrist & Hartmann, 2020; Michel et al., 2021).

Although direct studies evaluating Sudanese consumer acceptance of plant-based meat products are currently limited, evidence from international markets suggests that affordability, sensory quality, and compatibility with traditional dietary practices are likely to be major determinants of acceptance. In Sudan, where food affordability and nutritional security represent important considerations, successful products may require emphasis on accessibility, local ingredients, and acceptable sensory characteristics rather than relying solely on environmental or ethical motivations.

The cultural presence of traditional fermented plant-based foods such as Kawal may provide an initial familiarity with plant-derived protein products. Therefore, developing plant-based meat products based on indigenous crops and adapting formulations to local preferences could improve consumer acceptance and facilitate market introduction.

Future consumer research in Sudan should focus on sensory evaluation, willingness-to-purchase studies, price perception, nutritional awareness, and the role of cultural factors in shaping acceptance of alternative protein products.

C. Major Challenges Facing Plant-Based Protein Development in Sudan

Despite its agricultural potential, Sudan faces several technological, economic, regulatory, and social challenges that may limit the establishment of a competitive plant-based protein industry. regarding technological and industrial challenges, this remain limited within Sudan food processing sector since modern factories requires advanced technologies, including protein extraction, fractionation, high-moisture extrusion, texturization, sensory optimization, and quality-control systems.

Limited access to industrial financing and economic instability may restrict private-sector participation and slow technological development.so as plant-based protein industry requires investment in processing equipment, pilot facilities, analytical laboratories and skilled human resources.

Reliable supplies of standardized raw materials are necessary for consistent industrial production of plant-based proteins in Sudan although of production of several protein-rich crops. Seasonal production patterns, post-harvest losses, inadequate storage facilities, and transportation limitations may affect the availability and quality of plant protein ingredients. In addition to the above challenge production of plant based protein requires clear regulatory frameworks covering product definitions, labeling, nutritional claims, safety standards, and quality specifications, which is quality assurance barrier so create national guidelines for international practices will be essential to ensure consumer confidence and facilitate future market expansion.

Finally, there is human Capacity and Research Challenges, this type requires expertise in food science, protein chemistry, food engineering, nutrition, sensory evaluation, and industrial management. Universities should collaborate with academic institutions and industry for building the required technical capacity.

IV. SWOT ANALYSIS FOR PLANT-BASED MEAT INDUSTRY DEVELOPMENT IN SUDAN

A strategic assessment of Sudan's potential for developing a plant-based meat industry reveals a combination of significant strengths and opportunities, together with technological, economic, and institutional challenges that must be addressed. The SWOT framework summarizes the internal and external factors influencing the feasibility of establishing a sustainable alternative protein sector in Sudan.

Table VI: SWOT Analysis of Plant-Based Meat Industry Development in Sudan

Strengths	Weaknesses
Abundant agricultural resources and availability of diverse protein-rich crops, including legumes and oilseeds.	Limited industrial infrastructure for protein extraction, isolation, and texturization technologies.
Existing production of faba bean, cowpea, chickpea, groundnut, sesame, and other potential protein sources.	Insufficient research capacity and limited specialized facilities for alternative protein development.
Traditional knowledge of fermented plant-based foods such as Kawal, indicating	Limited consumer awareness and lack of familiarity with modern

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Volume 13, Issue 08, August 2026

Strengths	Weaknesses
cultural familiarity with plant-derived foods.	plant-based meat products.
Large agricultural workforce and potential for value-added food processing.	Limited investment capacity and restricted access to advanced food-processing equipment.
Opportunities	**Threats**
Rapid global expansion of the alternative protein market and increasing demand for sustainable food products.	Economic instability and fluctuations affecting industrial investment and food-sector development.
Potential to convert agricultural commodities into high-value protein products rather than exporting raw materials.	Climate variability and environmental stresses affecting crop production.
Opportunities for regional export markets in Africa and the Middle East.	Competition from imported processed food products and established international brands.
Contribution to food security through diversification of protein sources.	Limited regulatory frameworks and uncertainty regarding emerging food categories.

Source: Developed based on the current review findings and supported by FAO (2024), McClements and Grossmann (2021), and Poore and Nemecek (2018).

V. FUTURE ROADMAP AND RESEARCH PRIORITIES

Building a viable plant-based protein sector in Sudan will not happen through a single intervention but rather through a gradual, coordinated effort that brings together researchers, policymakers, and private investors around a shared long-term vision. This process can reasonably be imagined as unfolding across four interconnected stages. The starting point lies in the laboratory, where indigenous plant protein sources native to Sudan need to be systematically identified and characterized—examining their amino acid profiles, testing functional behaviors such as solubility, gelation, emulsification, and water retention, screening for anti-nutritional compounds that might limit digestibility, and refining extraction techniques suited to these local materials. Once this foundational knowledge is in place, attention would naturally shift toward translating such findings into tangible food products: piloting techniques like high-moisture extrusion and fermentation, fine-tuning texture and flavor to match consumer expectations, running sensory panels with Sudanese tasters, and confirming that these prototypes remain safe and stable over time. With workable products in hand, the emphasis then moves to building the industrial and institutional scaffolding needed for market entry—commercial-scale facilities, national quality standards, regulatory guidelines specific to plant-based meat, a trained workforce of food scientists and technicians, and partnerships that bridge public institutions with private enterprise. Finally, as the domestic industry matures, the goal broadens toward regional and international competitiveness, with products that draw on Sudan's own agricultural heritage, sustained innovation fed by ongoing research-industry collaboration, and an ambition to establish Sudan as a genuine contender among Africa's sustainable protein producers

A. Study Constrains

This review provides a comprehensive assessment of Sudan’s potential for developing a plant-based meat industry; however, several limitations should be acknowledged.

First, the analysis was primarily based on published scientific literature, international reports, and available secondary data, while recent national statistics and industrial information related specifically to Sudan’s food-processing sector remain limited.

Second, although Sudan possesses several promising protein-rich crops, this review does not include experimental validation of their functional properties, processing performance, or suitability for producing meat analogue products.

Third, consumer acceptance, economic feasibility, and market potential were evaluated mainly through evidence from international studies due to the limited availability of Sudan-specific consumer research.

Future studies should therefore prioritize experimental product development, techno-economic assessment, life-cycle analysis, sensory evaluation, and consumer behavior studies under Sudanese conditions to validate the commercial feasibility of locally developed plant-based meat products.

VI. CONCLUSION

This review highlights the considerable potential of Sudan to participate in the emerging global plant-based protein sector through the utilization of its abundant agricultural resources, diverse protein-rich crops, and traditional knowledge of plant-based food processing. Legumes such as faba bean, cowpea, chickpea, and pigeon pea, together with oilseed crops including groundnut and sesame, represent valuable raw materials for developing locally produced plant-based meat ingredients and value-added protein foods.

Despite these advantages, the transition from agricultural production to a competitive plant-based protein industry requires overcoming several technological, economic, and institutional barriers. Limited processing infrastructure, inadequate access to advanced protein technologies, insufficient research capacity, absence of comprehensive regulatory frameworks, and limited consumer studies currently represent major constraints.

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Volume 13, Issue 08, August 2026

The integration of Sudanese agricultural resources with modern food-engineering approaches, particularly protein extraction, high-moisture extrusion, fermentation, and product optimization, provides a promising pathway toward sustainable food innovation. Such development should be considered complementary to the existing livestock sector rather than a replacement, offering opportunities to diversify protein sources, improve agricultural value addition, strengthen food security, and create new industrial opportunities.

Future progress will depend on coordinated efforts among universities, research institutions, government agencies, and private-sector stakeholders. Investment in research, technology transfer, regulatory development, workforce training, and consumer education will be essential to transform Sudan's agricultural potential into a sustainable plant-based protein industry capable of serving domestic needs and contributing to regional markets.

VII. RECOMMENDATIONS

Based on the findings of this review, the following strategic recommendations are proposed:

1. Establish Research Programs on Sudanese Plant Proteins

Develop multidisciplinary research initiatives to evaluate the nutritional composition, functional properties, processing behavior, and technological suitability of indigenous protein crops for meat analogue production.

2. Develop Pilot-Scale Processing Capacity

Invest in research and pilot facilities equipped with relevant technologies, including protein extraction, high-moisture extrusion, fermentation, and texturization systems.

3. Strengthen University–Industry Collaboration

Promote partnerships between academic institutions, food industries, agricultural organizations, and international alternative protein research centers to facilitate knowledge transfer and innovation.

4. Develop Regulatory and Quality Standards

Establish national guidelines for plant-based meat products covering definitions, labeling, nutritional claims, safety requirements, and quality control procedures.

5. Improve Human Capacity and Technical Training

Integrate alternative protein science, food engineering, sensory evaluation, and sustainable food technologies into university curricula and professional training programs.

6. Conduct Consumer and Market Research

Implement Sudan-specific studies investigating consumer preferences, sensory acceptance, price sensitivity, and cultural factors influencing adoption of plant-based meat products.

7. Promote Value Addition and Sustainable Food Industries

Encourage the transformation of locally produced legumes and oilseeds into high-value protein products to support farmers, enhance food security, reduce dependence on imported ingredients, and improve economic diversification.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT (OpenAI) to assist with language editing, improving clarity, organization of the manuscript, and stylistic refinement. All scientific content, interpretation, critical evaluation, and final decisions were reviewed and verified by the authors, who take full responsibility for the content of the published work.

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