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Review

Bio-Functional Prospects of *Moringa oleifera* Lam on Meat Quality-A Review

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Abstract: Research done by scholars on the utilization of the different parts of *Moringa oleifera* Lam. in improving livestock performance and boosting meat quality has increased over the years in many nations across the globe. *Moringa oleifera* has been identified as an essential bio-resourceful plant containing vital nutrients and bio-active compounds with proven functional properties, including antimicrobial and antioxidant activities. These properties are essential for promoting healthy and quality meat production. As a multi-purpose plant with well-established evidence of its beneficial attributes, such as its ability to withstand harsh environmental and weather conditions, rapid growth rate, resilience in drought conditions and high longevity, the use of *M. oleifera* to ameliorate emerging food challenges and food security could proof a worthwhile breakthrough in the meat industry. Moreover, its sustainable characteristics for mitigating climate change, make it an environmentally friendly option for meat production. Different plant parts of *Moringa oleifera* have been studied as additives, feed supplements and phytomedicine plants for different livestock, to improve their health, productivity and product quality (including meat, eggs and milk among others). In addition, the plant has been used to lessen microbial growth, lessen the process of oxidation and boost functional meat quality. However, its use in the meat sector is still limited. Conversely, the limited utilization might be due to paucity of information on the quantification of the exact amount of the varied segments of the *M. oleifera* (leaf, seed, root) required in meat, as well as the suitable form (extract, powder, or whole) of inclusion in meat. This information is crucial for the practical and effective application of *M. oleifera* to produce functional and healthy meat and its products. More studies are needed so as to broadly comprehend the beneficial prospects of the studied plant in improving the quality and consumer acceptability of meat fortification with the *M. oleifera* plant.

Keywords: *Moringa oleifera*, Functional Bio-Components, Meat, Food Security, Sustainability

Introduction

In November 2022, the United Nations (UN) proclaimed that the global number of humans had topped 8 (eight) billion. This marked a significant milestone in human history as the global population continues to surge at an unprecedented rate. This exponential growth, coupled with urbanization and an increase in the middle class, has significantly impacted dietary habits and preferences. In most developing countries, as more people move to the urban areas and experience an improved lifestyle, they tend to incline towards Westernized diets, which are mostly characterized by processed foods and meat (UN, 2022). Over the years, fresh and processed meat became a vital nutrient in human diets as sources of good quality protein and other important nutrients needed to maintain a balanced diet (De Smet and Vossen, 2016).

However, the nutritional richness of meat exposes it as a growth medium and spread of microorganisms, which predisposes it to deterioration as well as spoilage (Falowo *et al*., 2018). The growth of microorganisms and other chemical reactions in meat are the key contributing factors to deterioration and spoilage in meat (Luong *et al*., 2020). Furthermore, microbes cause putrefaction and detectable spoilage of meat quality (Falowo *et al*., 2014; 2018). Again, the acceptability of muscle food (meat) to consumers is mainly triggered by quality parameters such as taste, texture and flavor.

The most important precursors of flavor in cooked meat comprise fats and water-soluble compounds of low molecular weight (Resconi *et al*., 2013). Despite being beneficial in boosting meat flavor and texture (Lorenzo and Franco, 2012), the fat present in meat may reduce its dietary and sensory parameters as a result of high proneness to oxidative degradation (Qi *et al*., 2015; Pateiro *et al*., 2018). As a way of definition, fat oxidation is the primary non-microbial origin of putrefaction in muscle food (meat) quality (Contini *et al*., 2014). Microbial spoilage and lipid oxidation both result in poor shelf life, off-flavor, nutrient depletion and color deterioration in meat, potentially causing various kinds of food-borne illnesses in consumers (Luong *et al*., 2020).

For decades, natural and synthetic (man-made) antioxidants have been utilized to retard lipid (fat) oxidation in muscle foods (meat), howbeit, there has been a recent shift of interest to the use of natural antioxidants as a result of reported carcinogenic health hazards caused by synthetic (artificial) antioxidants (Kumar *et al*., 2015). For this reason, the potential of different natural plant resources as alternative antioxidants is being studied (Lorenzo *et al*., 2013). *M. oleifera* is a naturally available "super-plant" utilized as a rich avenue of bio-active compound as a result of its considerable inherent antioxidant, nutritional and phytochemical benefits when added to the human diet (Tshabalala *et al*., 2020). Conversely, its use in the meat industry is scanty. The limited use might be a result of a paucity of information on the exact amount of inclusion level of the plant in meat and its product (Falowo *et al*., 2014).

With respect to the presence of tocopherols, carotenoids, polyphenols and antioxidant functions, *M. oleifera* extracts as well as leaves have been utilized to improve the quality of muscle foods (meat) as a natural antioxidant (Falowo *et al*., 2014). The quest for conventional replacements as compared to synthetic/ artificial antioxidants employed for improving meat in the muscle food sector has surged of late (Jayasena and Jo, 2013); as a result of its reactive functions to slow down lipid (fat) oxidation thus augmenting the quality of muscle food (meat) and shelf life. Again, the fact that *M. oleifera* plants (leaves, seeds, flowers) are seemly healthy when consumed by people and livestock, they are capable of being utilized to boost the quality of meat through fortification in animal feeds or by directly incorporating it into muscle foods (meat) and its derivatives (products). Generally, the animal diet has a functional effect on the chemical and nutritional constituents of muscle cells as well as on improving the quality of muscle foods (meat) including Water Holding Capacity (WHC), pH, tenderness, color, aroma and flavor. Several research works have evaluated the effects and significance of *Moringa oleifera* plant supplementation in the feed of different meat animals used for commercial or domestic purposes to improve the nutritive attributes of muscle foods (meat). However, limitations in some instances, on the presence of polyphenols that are available in orthodox antioxidants after they are consumed are found in the literature (Manach *et al*., 2004). Notwithstanding, research work has revealed that meat from livestock that were fed with *M. oleifera* feed possessed more antioxidant prospects (Qwele *et al*., 2013) and fat oxidative firmness (Nkukwana *et al*., 2014a). The reason for this is ascribed to the presence of a large amount of alpha-tocopherol in *M. oleifera* because dietary alpha-tocopherol can be added to the muscle tissue to enhance fat stability and the quality of muscle food (Falowo *et al*., 2014).

For this purpose, *Moringa oleifera* is of interest in this review. The current study, however, aims to explain the economic impact of fat oxidation as well as micro-organisms' activities on meat and the potential of *M. oleifera* Lam as an antioxidant and antimicrobial agent to improve meat quality for the purpose of consumers' nutritional benefits and health.

Lipid (Fat) Oxidation and Warmed-Over Flavour (WOF) Development in Muscle Foods (Meat)

Fat oxidation is a multifaceted procedure that entails chemical activities of Unsaturated Fatty Acids (UFA) with molecular oxygen by means of a free radical mechanism leading to fatty acyl hydroperoxides (Ayala *et al*., 2014). In cooked meats that are under refrigerated storage, oxidative degradation of meat lipids results in chemicals such as short-chain aldehydes or ketones (Falowo *et al*., 2014), that negatively affect the odor and palatability of meat. The unpleasant off-flavor and odor resulting from the oxidation of cooked meat is exclusively referred to as Warmed Over Flavour (WOF) (Lungu and Afolayan, 2022). Warmed Over Flavor (WOF) development is initiated by cooking or processing and continues even under refrigerated storage (Kim *et al*., 2016). It is usually noticeable upon warming the pre-cooked meats (Lungu and Afolayan, 2022). Membrane lipids including sphingolipids, glycolipids and highly unsaturated phospholipids are vital lipids causing WOF (Lungu and Afolayan, 2022).

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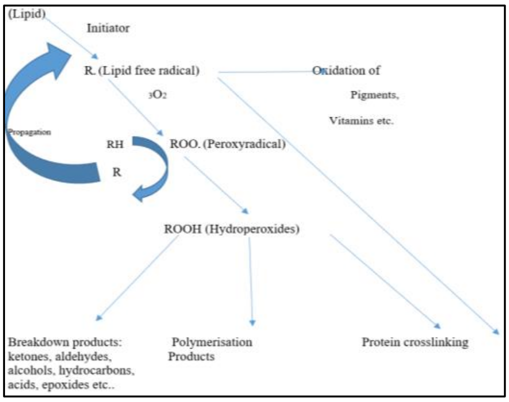

Fig. 1: Reactions involved in meat lipid oxidation source: Falowo *et al*. (2014)

The process of heating or mechanical grinding of meat disrupts muscle membrane systems and probes the discharge of Fe (iron) that naturally occurs in muscle foods (Kulkarni *et al*., 2011; Papuc *et al*., 2017). The iron then acts as a catalyst in oxidation reactions (Guyon *et al*., 2016) which breaks down meat lipids resulting in primary oxidation products. The principal end-products resulting from oxidation are then decomposed into lesser oxidation products including acids, pentanal, hexanal, ketones, lactones, 2,3-octanedione, alcohols and 2-pentyfuran which are responsible for WOF (Flores, 2018). Secondary oxidation products characteristically have a strong odor which can be detected even at low concentrations (Falowo *et al*., 2014). Hexanal, pentanal, 2,3-octanedione and 2-pentyl furan compounds are known to be highly associated with WOF development (Kim *et al*., 2016). A diagrammatic detail of the aforementioned oxidation reactions in cooked meats is shown in Fig 1. In brief, a hydrogen atom is detached from the fatty acid chain giving rise to an unrestricted (free) fat Radical ($R^{\bullet}$) that in turn combines with oxygen to produce a peroxy radical (ROO). The resultant ($ROO^{\bullet}$) extracts hydrogen from a different (RH) giving rise to hydroperoxide together with a new free radical that continues the chain reaction mechanism (Falowo *et al*., 2014). Hydroperoxides further decompose as mentioned earlier resulting in WOF compounds (Lungu and Afolayan, 2022).

Controlling Oxidation and WOF Using Antioxidants

By definition, antioxidants are molecules that have stability such that it has the ability to release electrons to a free radical to defuse it, in this way plummeting potential mutilation (Lungu and Afolayan, 2022). Antioxidants possess the ability to preserve food by means of scavenging free radicals that initiate the oxidation process (Shahidi and Zhong, 2015). In the muscle food sector, antioxidants are substances utilized to inhibit oxidative degradation, discoloration and WOF in muscle foods (meat) and meat derivatives (Granato *et al*., 2018; Lorenzo *et al*., 2018; Fruet *et al*., 2019). They are also beneficial in maintaining the original and ideal sensory properties (Nkukwana *et al*., 2014a).

Antioxidants' mode of action includes mechanisms of freely releasing electrons to disrupt and end the oxidation cycle (at the transmission stage), retarding the formation of lipid radicals (Amaral *et al*., 2018), or elimination of ROS initiators so as to stop radicals (Falowo *et al*., 2014). The functional attributes of antioxidants are attributed to their chemical orientation and polarity, the former referring to characteristics such as the molecular weight and positioning of OH/OCH_3 radicals while the latter refers to the lipophilic or water-soluble compounds (Brewer, 2011; Santos-Sánchez *et al*., 2019). The mechanisms of action of antioxidants classify them into principal and trace compounds (Falowo *et al*., 2018). The two are distinct in that secondary (trace) compounds never translate free (lone) radicals into steady chalators like primary compounds, but they function as chelators of pro-oxidant in this way donating H + to primary antioxidants and act as oxygen scavengers (Hur *et al*., 2014; Lorenzo *et al*., 2018). In a nutshell, secondary antioxidants are accountable for enhancing the functions of antioxidant of primary antioxidants.

The stages of action of antioxidants are summarized in Table 1. The action of antioxidants in these levels can be described as preventive, scavengers and repair de novo (Falowo *et al*., 2014). Apart from being classified into primary and secondary compounds, antioxidants exist in two forms namely natural and synthetic antioxidants. Natural antioxidants largely constitute plant-based compounds while synthetic include compounds, such for example, Butylated Hydroxyanisole (BHA) and Butylated Hydroxyl Toluene (BHT) (Kumar *et al*., 2015; Waters *et al*., 2018). Synthetic or artificial antioxidants are revealed to have carcinogenic properties, hence, the recent interest in natural antioxidant research.

Antioxidants and Human Health

Oxygen, an element that is vital for life can under certain situations pose damaging effects on the human body (Nakane, 2020). Cells use oxygen to generate energy giving rise to free radicals formed during Adenosine Triphosphate (ATP) production in the mitochondria (Sen and Chakraborty, 2011). This cellular redox reaction yields ROS and Reactive Nitrogen Species (RNS) as end-yields. The uncontrolled formation of ROS from oxidation can result in substantial reversible or irreversible harm to numerous biological molecules (Falowo *et al*., 2014). Peroxynitrite radical, hypochlorite, hydroxyl radical, superoxide anion radical, nitric oxide radical and oxygen singlet are highly reactive species that can destroy biologically essential molecules including DNA, proteins, carbohydrates and lipid in the nucleus and cell membranes (Falowo *et al*., 2014). These reactive species have been identified as the most significant oxygen-possessing free radicals in several diseases.

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Table 1: Summary of the different levels of antioxidant action

Level of action	Category	Action
First line of defense	Preventive antioxidants	They suppress free radical formation. They break hydroperoxides and hydrogen peroxide to alcohols and water, respectively
Second line of defense	Scavengers	They scavenge active radicals to break chain propagation reactions They occur in hydrophilic and lipophilic forms e.g., albumin, bilirubin and uric acid hydrophilic while alpha-tocopherol and ubiquinol are lipophilic radical-scavenging antioxidants
Third-line defense	Repair and de novo antioxidants	They identify, degrade and get rid of oxidatively altered proteins and impede the buildup of oxidized proteins

Sources: (Lobo *et al*., 2010) (amended)

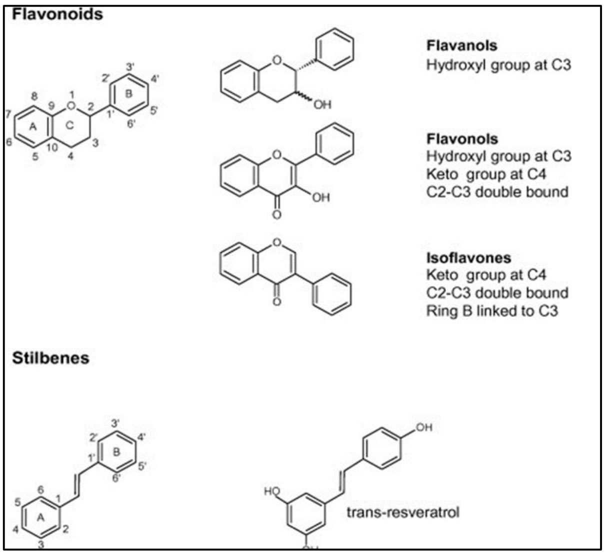

Fig. 2: Chemical structure of flavonoids source: (Fraga *et al*., 2010)

Foods that contain antioxidants contribute to the physiological reactions in safeguarding living things from oxidative destruction (Falowo *et al*., 2014; Jiang and Xiong, 2016). Antioxidants can reduce oxidation via direct scavenging of the ROS. A good example of an antioxidant that is found in processed meats is alpha-tocopherol. They have been revealed to be of importance in immunocompetence due to their ability to boost humoral antibody protection, resist bacterial infections, repair DNA membranes, inhibit mutagen formation and hinder microcell line structure (Idamokoro *et al*., 2020).

Synthetic antioxidants including (BHT) and (BHA) have however, recently been reported to be a threat to human health (Kumar *et al*., 2015). This has been attributed to some of their physical properties including high volatility and instability at elevated temperature. These detrimental health claims against synthetic antioxidants have been followed by consumer demand for foods with natural antioxidants (Bolumar *et al*., 2016), a situation that has led to people sourcing other alternatives (harmless natural compounds) that possess some antioxidative activity.

Natural Antioxidants Characteristics

Plant-derived antioxidants have been recognized as naturally available compounds (Munekata *et al*., 2016; Falowo *et al*., 2017). Plant-derived antioxidants are incorporated in meats in powder forms or as water-soluble and water-insoluble extracts. The antioxidant activity of plants has been attributed to phenolic compounds found in them (Falowo *et al*., 2014; Roleira *et al*., 2015). These (phenolic compounds) are trace metabolites that comprise flavonoids, phenolic acids and flavonoid polymers (Fraga *et al*., 2010; Lungu and Afolayan, 2022). Polyphenols are produced from plants as trace metabolites which carry out varied processes, including pigmentation, growth, lignification and resistance against disease-causing organisms (Falowo *et al*., 2014). In their chemical structure, polyphenols possess one or several hydroxyl groups tied to a benzene ring. Over 8000 diverse polyphenols that are characterized as flavonoids and non-flavonoids can be obtained from edible plants. Flavonoids are assembled in a C6-C3-C6 form (Fig. 2), comprising two aromatic rings (A and B) connected by a three-carbon chain, normally arranged as an oxygenated heterocycle (ring C).

Phenolic compounds are known to inhibit the action of free radicals and chelating metal ions (Lorenzo *et al*., 2013). In addition to their antioxidant effects, phenols possess health benefits, (Fernandes *et al*., 2018; Lorenzo *et al*., 2018) and can be obtained at low costs which qualifies them to be potentially used in meat product formulations in order to meet consumer demands of a healthy product.

Table 2: Some of the natural sources used as antioxidants in meat and meat products

Source	Inclusion level	Meat type	Storage days	Storage temperature (°C)	Findings	Source
Pomergranate peel extract	0.5 and 1.0%	Beef meatballs	6 months	-18±1	DLO	Turgut *et al.* (2017)
Liophilised Rosemary Extract (LRE)	0.2%	Pork sausage	49	- 15	DLO	De Florio Almeida *et al.* (2017)
Rosemary extract	600 900 ppm 300 ppm 500, 1000 and 1500 ppm	Chicken nuggets Chicken sausage	9 months	-18	DLO	Liu *et al.* (2009)
Moringa leaf extract	0.25, 0.5, 0.75 and 1%	Chicken sausage	5	4	DLO	Jayawardana *et al.* (2015)
Ginger powder	1 and 2%	Pork burgers	7	4	DLO	Mancini *et al.* (2019)
	1 and 2%	Rabbit burgers	7	4	DLO	Maninci *et al.* (2017)
Thyme	0.5 and 1 g/kg	Ground	6	4±1	DLO	Zengin and Baysal (2015)
	0.125%	Chicken sausage	45	-18	DLO	Sharma *et al.* (2017)
Bidens Pilosa	0.5 and 1 g/kg	Ground beef	6	4	DLO	Falowo *et al.* (2017)
Clove	0.25%	Chicken sausage	45	-18	DLO	Sharma *et al.* (2017)
Plum blossom	0.1%	Chicken	3	4	DLO	Jo *et al.* (2006)

DLO = Decreased Lipid Oxidation

Plants contain compounds including dietary fibers, vital fatty acids, minerals, vitamins, oligosaccharides as well as antioxidants that make food functional (Lobo *et al.*, 2010). Antioxidant activity compounds derived from herbs and plants including oregano, garlic, ginger and rosemary have been studied in animal feed and meat product formulation. Moderate dosage levels are normally used when applying these antioxidants (Falowo *et al.*, 2014), because high levels may have adverse effects (Lungu and Afolayan, 2022). Generally, antioxidants should characteristically not have a negative effect on color, odor, or flavor; give better results at minimal concentration levels (0.001-0.01%); be well-matched with varieties of diets used; easy to incorporate and be able to maintain stability at processing and storage/preservation (Lorenzo *et al.*, 2018). Most importantly, they must be harmless. Some of the plants and herbs with derived natural antioxidants that have been experimented on in meat (muscle foods) as well as meat derivatives on their shelf-life are summarized in Table 2.

Natural Plant Sources in Preventing Microbial Spoilage in Meat

Meat is highly rich in nutrients which offers it a conducive environment for microbial growth (Bai *et al.*, 2015; Saucier, 2016). Processing techniques and storage further worsen its susceptibility to microbial spoilage. Microbial activity negatively affects the quality, safety, nutritive and organoleptic indexes of meat and meat derivatives (Jayawardana *et al.*, 2015; Hawashin *et al.*, 2016), resulting in food wastage and economic losses. It is well-accepted that microorganisms include *Brochothrix thermosphacta, Enterobacteriaceae, Leuconostoc* spp., *Camobacterium* spp. *and Pseudomonas* spp. Results in putrefaction of muscle foods persevered in the refrigerator (Jayasena and Jo, 2013). Apart from causing meat spoilage, microorganisms such as *Escherichia coli* 0157: H7, *Staphylococcus aureus*, *Listeria monocytogenes and Salmonella* spp., also cause food-related infections (Emrobowansan and Hosua, 2022). Given the predicted global population increase, the demand for animal protein will also increase. Therefore, to ensure food security, the wastage of meat through spoilage must be avoided. Of late, bioactive plants are now being explored as prospective natural antimicrobial sources that can improve meat shelf-life without negatively impacting human health (Das *et al.*, 2012; Elsser-Gravesen and Elsser-Gravesen, 2013; Irkin and Esmer, 2015).

Various plants, fruits, spices and herbs have demonstrated antimicrobial activities in muscle foods and meat derivatives. In a study that was conducted to explore the antibacterial conditions of various spices, Shan *et al.* (2007) reported that, out of the 46 extracts of spices that were studied, the majority of them displayed antibacterial properties against food-related micro-organisms and gram-positive bacteria remained largely the most responsive compared to the gram-negative bacteria. Other examples of studies where natural sources were used to inhibit microbial spoilage in meat are listed in Table 3. The antimicrobial actions of natural sources have been ascribed to the presence and quantities of phytochemical components including phenols, terpenes, alkaloids, tannins, flavonoids, carvacol and saponins (Sharma *et al*., 2017). Although the mechanisms by which polyphenols destroy or impede bacteria are unclear, their activity has been attributed to the reactions resulting from how they chelate iron which is believed to be paramount to most bacterial survival (Lopez *et al*., 2016). Also, polyphenols have been found to weaken bacterial cell integrity and prevent growth through the disruption of plasmic membrane and cell walls (Kumar and Pandey, 2013; Babuskin *et al*., 2014; Papuc *et al*., 2017). According to Aminzare *et al*. (2017), it was also reported that phenolic constituents modify the naturally known functions of cell walls including electron transmission, nutrient exchange, protein synthesis and enzymatic activity. Origins and distribution of *Moringa oleifera*

Moringa oleifera falls under the 13 species of *Moringa* plants that belong to the Moringacea family (Mbikay, 2012). It is also referred to as the horseradish (Sujatha and Patel, 2017). This plant originates from India and the Himalayan uphills (Makkar and Becker, 1997). However, it is presently being grown and has become naturalized in all tropical and sub-tropical areas globally (Mbikay, 2012). Likewise, a large production and commercialization of *M. oleifera* plant has gotten widespread popularity in many other nations such as Asia, Africa (including South Africa, Nigeria, Ghana, Niger, Benin) and South and Central America. Figure 3 gives a pictorial view of the geographical spread and distribution of *M. oleifera* species across the globe with *M. oleifera* Lam depicted in red.

Nutritional Components of M. oleifera Lam

M. oleifera is a unique tree that has recently been recognized for its usefulness for livestock purposes because of its well-known nutritional significance and minimal anti-nutritional factors. A report on the nutritional components of *M. oleifera* indicates that the plant is endowed with a sufficient and significant amount of nutritive attributes including minerals, protein, vitamins, vital amino acids, as well as other bio-functional components as elaborated in Table 4. However, it should be noted that variations sometimes occur in the nutritional component of *M. oleifera* ascribed to some factors including the stage of harvest, type of soil, location of growth, processing method, water and fertilizers and storage environments (Falowo *et al*., 2018; Sultana, 2020).

Another remarkable attribute of the plant as a suitable browse source for livestock improvement/meat quality over other plants is the fact that it possesses a relatively small quantity of anti-nutrients including phytates, tannins, saponins and oxalates (Shih *et al*., 2011). The inherent anti-nutrients in *M. oleifera* have been reported not to be necessarily harmful or deleterious, but they may however, impede to a small extent the rate of intestinal breakdown and absorption of some useful ingredients and nutrients in the plant when they are utilized by animals in large amount (Falowo *et al*., 2018). Stevens *et al*. (2015) revealed in their study that, the amount of saponin and phytate compounds in *M. oleifera* seed (2.23 %) and leaf (2.5%) was lower when compared to those reported for other vegetables.

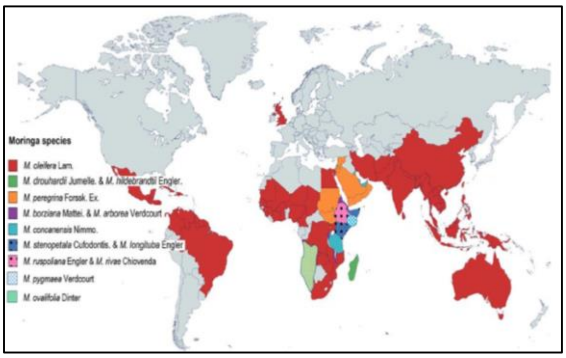

Fig. 3: Global map of *Moringa oleifera* plant species with *M. oleifera* Lam highlighted in red source: Tejas *et al*. (2012)

Table 3: Examples of natural antimicrobial sources and their actions

Natural source	Meat	Findings/conclusions	Source
Oregano	Chicken	Microbial load was reduced	Khaled *et al*. (2016)
	Ground beef	Inhibited *Listeria monocytogenes*	Apostolidis *et al*. (2008)
Rosemary	Chicken	Significantly decreased total viable counts	Zhang *et al*. (2016)
Rumex tingitanus	Minced beef	Inhibited the proliferation of *L. monocytogenes*	Mhalla *et al*. (2017)
Black pepper	Not specified	Possessed a good antibacterial activity against meat-borne *E. coli*	Zhang and Cao (2017)
Olive leaves	Ground beef patties	Reduced microbial load	Moawad *et al*. (2017)
Thyme	Chicken breast	Decreased the natural microflora present in the meat; total microbial content decreased down to 50%	Fratianni *et al*. (2010)
Clove	Minced meat (not specified)	Effective gram-negative strains tested (*Escherichia coli* and *Salmonella Enteritidis*)	Barbosa *et al*. (2009)
	Chicken	Decreased total viable counts	Zhang *et al*. (2016)

Table 4: Proximate assessment of *Moringa oleifera* plant (leaf and seed)

	Nutrient composition range (minimum-maximum)*	
Components	Leaf	Seed
Major nutrients		
Protein	10.74^{a}-30.29^{b}	9.98^{c}-51.080^{d}
Carbohydrate (g/100 gDM)	13.41^{a}-63.11^{b}	3.36^{c}-18.000^{d}
Fat (%)	6.50^{a}-20.00^{b}	38.67^{c}-43.060^{d}
Ash (%)	7.64^{a}-10.71^{b}	3.6^{c}-5.000^{d}
Crude fibre (%)	7.09^{a}-35.00^{b}	17.26^{c}-20.000^{d}
Macro-elements		
Ca (mg/100 g)	147.43^{a}-7230.00^{b}	1.55^{c}-751.007^{d}
K (mg/100 g)	120.96^{a}-1845.00^{b}	75.000^{c}
Mg (mg/100 g)	322.5^{a}-500.00^{b}	5.36^{c}-45.000^{d}
P (mg/100 g)	300.00^{a}	635.000^{b}
Micro-elements		
Mn (mg/100 g)	8.68^{a}	0.06^{a}-45.000^{b}
Fe (mg/100 g)	2.68^{a}-49.00^{b}	0.97^{c}-5.020^{d}
Zn (mg/100 g)	1.0^{a}-3.10^{b}	0.005^{c}
I (mg/100 g)	0.06	-
Vitamins and amino acids		
Vitamin A (beta-carotene) (mg/100 g)	13.48^{a}-18.50^{b}	-
Vitamin B_1	0.05^{a}	0.005^{b}
Vitamin B_2	0.80^{a}	0.006^{b}
Vitamin B_3	220.00^{a}	0.002^{b}
Vitamin C	245.13^{a}	4.050^{b}
Vitamin E	16.80^{a}-77.00^{b}	-
Total amino acid (g/100 g)	27.64^{a}-76.40^{b}	74.085^{c}
Total essential amino acid (g/100 g)	12.69^{a}-35.40^{b}	34.048^{c}
Total monounsaturated fatty acid (%)	4.48^{a}-4.61^{b}	-
Total polyunsaturated fatty acid (%)	37.4^{a}-52.21^{b}	-
Total saturated fatty acid (%)	43.31^{a}-58.00^{b}	-

Source: Adopted from Falowo *et al*. (2018) (*Least reported values-peak reported values). NB: 'A', 'b', ‘c’ or ‘d’ = Mean values within rows with different superscripts differ significantly between plant parts of *Moringa oleifera* (leaves and seeds) over the years from different studies

Table 5: Some selected bio-functional compositions in the M. oleifera plant responsible for improving meat quality and their mechanisms

S/N	IUPC/Molecular formula	Part of *M. oleifera* plant	Mechanism of bio-functions	Reference
1	1,2-Benzenedicarboxylic acid, diethyl ester/$C_{12}H_{14}O_4$	Leaf extract	Antimicrobial action	Karthika and Mariajancyrani (2011)
2	1,2-Benzenedicarboxylic acid, bis-2-ethylhexyl ester/ $C_{24}H_{38}O_4$	Leaf extract	Antimicrobial action	Karthika and Mariajancyrani (2011)
3	Octadecanoic acid/$C_{18}H_{36}O_2$	Leaf extract	Antibacterial action	Ayon Bhattacharya *et al*., (2014)
4	Oleic acid/$C_{15}H_{28}O_2$	Leaf extract	Antibacterial action	Muthukumar *et al*. (2014)
5	Palmitic acid/ $C_{16}H_{32}O_2$	Leaf extract	Antioxidant action	Karthika and Mariajancyrani (2011)
6	Tetradecanoic acid/$C_{14}H_{28}O_2$	Leaf extract	Antioxidant action	Ayon Bhattacharya *et al*. (2014)
7	γ-Tocopherol/$C_{28}H_{48}O_2$	Essential oil from leaf	Antioxidant action	Zhao and Zhang (2011)
8	Ethyl alcohol/C_2H_6O	Leaf extract	Antibacterial action	Karthika and Mariajancyrani (2011)
9	Linalool oxide (2)/$C_{10}H_{18}O_2$	Leaf extract	Antioxidant and antimicrobial	Karthika and Mariajancyrani (2011)
10	Phytol/$C_{20}H_{40}O$	Leaf extract	Antioxidant action	Falowo *et al*. (2017)
11	Phenethyl alcohol/$C_8H_{10}O$	Leaf extract	Antimicrobial action	Karthika and Mariajancyrani (2011)
12	Trans-Linaloloxide/$C_{10}H_{18}O_2$	Leaf extract	Antioxidant and antimicrobial	Karthika and Mariajancyrani (2011)
13	Benzyl isothiocyanate/C_8H_7NS	Root extract	Antimicrobial action	Ayon Bhattacharya *et al*. (2014)
14	gamma.-Sitosterol/$C_{29}H_{50}O$	Leaf extract	Antioxidant action	Ayon Bhattacharya *et al*. (2014)
15	L-Galactose, 6-deoxy-/$C_6H_{12}O_5$	Leaf extract	Antioxidant action	Ayon Bhattacharya *et al*. (2014)
16	L-(+)-Ascorbic acid 2,6- dihexadecanoate/ $C_{38}H_{68}O_8$	Leaf and seed extract	Antioxidant action	Muthukumar *et al*. (2014)
17	Lactic acid / $C_3H_6O_3$	Leaf extract	Antibacterial action	Karthika and Mariajancyrani (2011)

Moringa oleifera Phytochemistry

Numerous biologically active compounds found in plants are called phytochemicals and these usually impact their flavor, odor (smell), texture and appearance (Lungu and Afolayan, 2022). Extensive research that has been done on most plants has shown that their phytochemicals are possible natural antioxidants. Active substances in plants are habitually influenced by intrinsic dynamics such as harvest season, plant parts used, geographical area and some extrinsic conditions including additive production methods (Subha Ganguly, 2013).

The *M. oleifera* plant constitutes compounds containing the common sugar rhamnose and a unique group of chemical substrates called glucosinates and isothiocyanates (Falowo *et al*., 2018). Different segments of *M. oleifera* contain phenolic acids (Coppin *et al*., 2013), tocopherols, carotenoids and polyunsaturated fatty acids (Saini *et al*., 2014). Among the

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glucosinolates, 4-(α-L-rhamnopyranosyloxy)-benzyl glucosinolate (glucomoringing) is found in significant concentrations in the leaves, stem, seeds and flower pods (Amaglo *et al.* 2010). Among flavonoids, flavonol glycosides of quercetin > kaempferol > isorhamnetin are mostly seen in numerous segments of the tree, excluding seeds and root region (Saini *et al*., 2016). The leaves contain an estimated amount of kaempferol and quercetin in the region of 0.07-1.26 and 0.05-0.67%, respectively (Coppin *et al*., 2013). A summary of the bio-functionals present in *M. oleifera*, their mechanism of action and how they contribute to improving meat quality is presented in Table 5. The potential role of *M. oleifera* towards nutrition and health.

The "miracle tree", "god's gift to man", "tree of life" and "vitamin tree" are among the various names by which the *M. oleifera* tree has been referred because of its multipurpose contribution to human nutrition and health. It is well-accepted that almost all parts (leaves, flowers, seeds, roots, pods) of the *M. oleifera plant* can be consumed (Kumar *et al*., 2017). In India, the Philippines and tropical Africa, the leaves, flowers, roots, edible fruits and seed oil of *M. oleifera* have formed part of the diet as a vegetable (Anwar and Bhanger, 2003). Evidence from scientific research has shown that *M. oleifera* is enriched in essential ingredients such as vitamins, iron, amino acids and potassium (James and Zikankuba, 2017). Other scholars state that *M. oleifera* provides 15 times more potassium, 7 times vitamin C, 10 times vitamin A, 17 times Ca (calcium) and 25 times Fe (iron) compared to bananas, oranges, carrots, milk and spinach (Gopalakrishnan *et al*., 2016). The leaves of *M. oleifera* contain an estimated 20-30% protein on a dry matter basis (Agbogidi and Ilondu, 2012) as well as omega-3 and omega-6 Polyunsaturated Fatty Acids (PUFAs), in the form of α-linolenic acid and linoleic acid respectively (Saini *et al*., 2016).

Moringa oleifera is further reported to contain numerous medicinal properties (Ashfaq *et al*., 2012; Cuellar-Nuñez *et al*., 2018). The flowers, roots, leaves, stems and seeds are extensively utilized in treating Human Immunodeficiency Virus (HIV), bacterial and fungal contagions as well as gastrointestinal and hematological maladies (Kasolo *et al*., 2010). Animals are no exception to the nutritive as well as the health potentials of this "Miracle tree". Research has shown that the *M. oleifera* plant can be incorporated into animal feed to improve growth rates, gastrointestinal health and meat quality (Mukumbo *et al*., 2014; Nkukwana *et al*., 2014b; Qwele *et al*., 2013; Abd El-Hack *et al*., 2018). All these above-mentioned nutritional and medicinal properties of *M. oleifera* make it a vital resource in improving both animal and human health and nutrition in this way ensuring food security. Moreover, the plant is a rapidly emergent and drought-tolerant tree (Daba, 2016) which means it is a sustainable resource.

Prospects of Moringa oleifera Lam as Antimicrobial Agents of Meat Quality

Meat is generally prone to attract microorganisms due to its rich nutrient content which exposes it to rapid deterioration and spoilage (Falowo *et al*., 2014). *Moringa oleifera* lam is also utilized as an antimicrobial ingredient to lessen the growth and spread of microbes in nutrient media (Segwatibe *et al*., 2023). Research interest has lately turned its attention towards studies involved in the direct incorporation/fortification of *M. oleifera* into muscle foods and meat derivatives to boost its physical and chemical attributes and nutritive quality. The antimicrobial activity of *M. oleifera* leaves was revealed to enhance the preservative time-length of chicken sausages refrigerated for 5 weeks when it was fortified with the plant (Jayawardana *et al*., 2015). The sausages which were fortified with 1 %, 0.75 and 0.50 % of the leaf powder of *M. oleifera*, respectively had low TBARS, low acid-base ratio level (pH) and low microbial Total Plate Counts (TPC) in comparison to the control group of sausages treated with Butylated Hydroxytoluene (BHT) which is an artificial (synthetic) antioxidant (Jayawardana *et al*., 2015). Low microbial Total Plate Counts (TPC) of a food substance is a sign of reduced microbial activities on the food which in turn improves their shelf life. There is also a link between the pH and microbial plate count of food material. Low pH levels of a food product often inhibit the spread of microbes and invariably increase their preservative length-time. *M. oleifera* leaves possess low-weight proteins and peptides with antimicrobial potentials (including antifungal and antibacterial activity) (Falowo *et al*., 2014). Furthermore, the leaves of *Moringa oleifera* are revealed to possess pterygospermin, a complex substance capable of dissociating itself into two benzyl isothiocyanate molecules; which possesses antimicrobial effects when applied to a substance or material (Falowo *et al*., 2014). Research works abound on the use of *M. oleifera* leaf extract in inhibiting microbial activities in meat (El Abed *et al*., 2014; Hazra *et al*., 2012), other reports have also shown no significant improvement in the pH and microbial counts in meat (Falowo *et al*., 2018). These contradictory reports may be a result of the binding effects of antimicrobial reactive elements on food substrates. According to El Abed *et al*. (2014), the protein and lipid presence in food is capable of binding to phenolic compounds which lessens the effectiveness of antimicrobial reactions. There seems to be limited work on the utilization of the *Moringa* plant as an antimicrobial reagent, hence, there is a necessity for further research to explore the scientific impact of antimicrobial activities of *M. oleifera* plant parts (leaf, seed, stems, flowers) in meat. The amount of

Moringa oleifera fortification in meat may be another factor for poor reports of its antimicrobial effect in meat. According to Muthukumar *et al*. (2014), a low amount of *Moringa oleifera* plant (leaf, seed, stem) inclusion lowered the antimicrobial action of the plant. However, a higher amount of plant inclusion may negatively affect consumers' acceptability of pork meat (Lungu and Afolayan, 2022). The study by Jayawardana *et al*. (2015) reported that the fortification of meat with 0.5 g/100 g *M. oleifera* leaf extract was enough to inhibit microbial spread in chicken sausages. Meanwhile, the addition of 0.75 and 1 g/100 g of *M. oleifera* leaf showed a negative impact on the sensory evaluation of chicken patties. More studies on the effect of *M. oleifera* fortification of meat on organoleptic traits and consumer sensory evaluation cannot be overemphasized. With respect to the increasing interest, exploiting the health prospects of *M. oleifera* to boost the nutritional worth of meat and its products is promising and needs further empirical research on the bioavailability and the bio-functional elements post-consumption of *Moringa* fortified meat products.

Potential of Moringa oleifera Lam as an Antioxidant and Enhancer of Meat Quality

Due to its reported nutritive components, the *M. oleifera* plant has been widely used in research as an animal feed additive. Various researchers (Moyo *et al*., 2012; Nkukwana *et al*., 2014b) who investigated *M. oleifera* as an animal feed additive concluded that the plant had antioxidant properties which were evident from the reduced lipid oxidation in the meat. The antioxidant activity of the *M. oleifera* leaves has been highly credited to its high amount of polyphenols (Moyo *et al*., 2012; Falowo *et al*., 2014). Phenolic compounds are the most important antioxidant compounds in plants because they can reduce oxidative damage of tissues indirectly or directly through enhancement of natural cell defense and scavenging of free radicals species respectively (Du *et al*., 2010). Phenolic compounds owe this ability to their hydroxyl groups that are joined with conjugated double bonds (Falowo *et al*., 2014).

Apart from retarding lipid oxidation, phenolic and flavonoid compounds affect meat quality parameters including chemical components, fatty acid structure and color stability (Lungu and Afolayan, 2022). Phenolic compounds specifically increase conjugated linoleic acid concentrations giving meat a brighter colour (Mapiye *et al*., 2011). Reports by Velasco and Williams (2011); Shah *et al*. (2014) also agree that plant-derived antioxidants can control and boost the color, pH, flavor and taste of muscle foods and products. Natural antioxidants like *M. oleifera* regulate meat color by inhibiting the degradation of heme pigments, thus slowing down metmyoglobin formation to stabilize color (Muthukumar *et al*., 2014). Meat treated with plant-derived antioxidants has been shown to have improved flavor and juiciness. The distinct bioactive compounds present in *M. oleifera* suggest that it can potentially be employed as an antioxidant in the meat industry.

Influence of Meat Fortification with Moringa oleifera Lam and Consumer Sensory Evaluation

Terms such as stale, cardboard-like, painty, or rancid (Lungu and Afolayan, 2022) have been used to describe the characteristics of WOF. These characteristics can be physically detected by consumers through smelling, visual appraisal, or tasting. Sensory analysis is an important tool in new product development because it bridges the lack of information between product features as well as consumer perception and acceptance (Yu *et al*., 2018). Consumer sensory studies are a useful tool in detecting characteristics such as warmed-over flavor which are not acceptable to consumers. Therefore, sensory analysis is a potent tool that gives insight beyond analytical testing. In recent research (Raikos *et al*., 2016; Amin and Edris, 2017; Alirezalu *et al*., 2019) consumer sensory analysis has been an important tool for determining the effects that natural antioxidants have on sensory attributes over time.

Studies have also reported the impact of *Moringa Oleifera* Lam Plants (MOLP) on consumer sensory evaluation for meat including pork, mutton, chevon, chicken and beef among others. Lungu and Afolayan (2022), in their study, revealed that the addition of 1% root powder of *Moringa oleifera* was acceptable by consumers compared to the leaf part and comparable to the control group without the inclusion of the plant. Khomola *et al*. (2021) also reported that the addition of 0.3% of MOLP on mutton patty samples had high sensory acceptance (aroma, taste, appearance and overall acceptability) and they were comparable in terms of sensory evaluation to those of the control group without any MOLP inclusion. In the study by Moyo *et al*. (2014), goat meal supplemented with a blend of sunflower (170 g) and MOLP (200 g) leaf diet had a positive influence on consumer sensory ratings of goat meat with greater first bite, flavor, aroma and juiciness ratings in comparison to the group that was not supplemented. Furthermore, the findings by Jaja and Tembela (2022) reported that the inclusion of 0.5% of *Moringa oleifera* leaf meal in chicken droëwors enhanced the sensory characteristics of the meat when compared to the control group without MOLM. Again, talking about the study on chicken, it was reported that the sensory panel found no variance in any sensory qualities in chicken patties fortified with 0.25 and 0.5% *Moringa oleifera* leaves compared to the control treatments (Jayawardana *et al*., 2015).

In addition, the study by Mashau *et al*. (2021), showed that the inclusion of *Moringa oleifera* Leaves Powder (MOLP) at 0.2 and 0.4% in ground beef was comparable to the control group (without *Moringa oleifera*). However, the study further reported that the inclusion of the plant at higher levels (0.6 and 0.8%) had significantly lower taste acceptability and sensory attributes by the sensory panelists. This observation of low sensory attributes was credited to the natural bitter taste in the MOLP due to the presence of glucosinolate-myrosinase in the plant (Mashau *et al*., 2021). Meanwhile, the bitter taste in *Moringa-fortified* meat could be reduced or removed from the product by soaking the plant in acidic solutions (such as tamarind water) before use or by mixing sweetener (such as aspartame) with the plant to improve consumer sensory acceptability (Chan *et al*., 2021). Conversely, the technique of reducing the effect of bitterness in the *Moringa* plant before the fortification of any food product (including meat) has not been widely adopted and studied. More research in this regard is highly recommended. Apart from meat, the inclusion of *the Moringa oleifera* plant at various levels has also been employed to improve the sensory attributes of other food derivatives including beverages, juice, dairy products (yogurt, cheese) and bread (Bourekoua *et al*., 2018; Govender and Siwela, 2020; Olusanya *et al*., 2020; Trigo *et al*., 2023).

Summary and Future Perspectives/Recommendations

The profitability of the meat industry highly depends on the satisfaction of consumers. Consumer perceptions about products are of importance because they determine the relatedness of product purchasing. The warmed-over flavor is a known aspect that negatively affects consumer acceptance of muscle foods and meat derivatives and this has negatively affected the profitability of the meat sector. Lipid oxidation and the development of WOF in muscle food and meat derivatives are inevitable and hinder the introduction of new ready-to-eat muscle food and meat derivatives in the market since they mostly affect the shelf-life of such products. WOF is more prominent in cooked, ready-to-eat, or processed meats that are kept under refrigerated storage. Currently, consumer demand for ready-to-eat meats and their derivatives that are made with little or no artificial (synthetic) antioxidants is high. Science and innovation play a strategic influence in equipping the industry to respond to such consumer concerns and expectations. In this light, scientists have been trying to come up with new innovations such as the utilization of natural/orthodox antioxidants in muscle foods and its product formulations. Various researchers have reported that natural antioxidants have been shown to have antioxidant and antimicrobial potentials that can improve the shelf-life of meat and its derivatives. *M. oleifera* plant has been reported to be a potential replacer of synthetic/artificial antioxidants in the meat industry. Not only does *M. oleifera* have a potential role as an antioxidant, but it also possesses nutritional and health benefits that can contribute to the production of functional meat derivatives. However, its utilization in the muscle food industry is still limited. Therefore, there is still a need for more research to quantify the exact amounts and parts of the plant that can be practically applied to produce functional foods. Regardless of the seemingly extensive use of *M. oleifera* plant to improve livestock products (meat and its derivatives), a holistic approach for incorporating the plant into livestock diet to boost meat quality (antioxidant and antimicrobial activities) is still a challenge due to the anti-nutritional agents which could limit their performance. Notwithstanding, further study on the use of phytases, lignin and cellulose (as enzyme supplements) to encapsulate *M. oleifera* plants should be considered in the future. Furthermore, inventions on effective techniques to detoxify *the Moringa oleifera* plant (to lessen/remove the bitter taste) and effective methods of application of the plant in meat and its products.

Conclusion

The utilization of plant resources as natural/orthodox antioxidants has an immense antimicrobial prospect to preserve muscle food and its derivatives from oxidative spoilage. The inclusion of natural antioxidants is hypothetical essential to improve the endogenous antioxidant against oxidative stress in livestock and avert lipid-protein oxidation in muscle food and meat derivatives. Conversely, because the impact of oxidative stress on muscle food nutritive attributes has not been sufficiently studied, it is imperative to explore this aspect of research to curb the problems of quality losses as a result of oxidation. The likelihood of obtaining a practical answer to this challenge undoubtedly bowls down to the effective utilization of medicinal-plant-rich antioxidants to sustain the functionality of meat and guarantee the production of muscle food derivatives with nutraceutical traits. The present study revealed that *M. oleifera* is a vital bio-functional natural resource that can be utilized to improve meat quality and production. The addition of *M. oleifera* in meat and its derivatives is considered safe and healthy for meat consumers when compared to the use of synthetic additives in meat. The prospect of *M. oleifera* has gained significance as a prospective feed constituent in the farm animal diet and agro-feed sector. The inclusion and fortification of meat and its derivatives with *M. oleifera* as impactful natural antimicrobial and antioxidant phyto-substance to boost meat and its shelf life during storage and processing is capable of providing a new remedy against the use of synthetic antioxidant and anti-microbial agents which has been shown to be unhealthy for meat eaters. However, one area of critical interest to look at, is the indirect inclusion (e.g. amount/ rate of inclusion) of *M. oleifera* in livestock feed (due to the challenge of anti-nutritional factors of the plant) and how this can affect meat and its products from livestock. Conversely, further research work on the utilization of enzymes as additives (e.g., phytases) to boost the nutrient utilization and efficient digestibility of the plant for livestock when *M. oleifera* is used as a diet should be considered with respect to improving meat and its products. Meanwhile, some studies have reported some limitations in the area of sensory acceptability of meat (in terms of taste and color) fortified with *the Moringa oleifera* plant (powder) by consumers.

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Author's Contributions

Nobuhle Sharon Lungu: Conceptualized the study, contributed to written the manuscript, proofread and edited the final drafted of the study.

Emrobowansan Monday Idamokoro: Contributed to written the manuscript, proofread and edited the final draft of the study.

Ethics

This manuscript is the original work of the authors and does not contain unpublished material. The corresponding author confirms that all the authors read and approved this study and no ethical matters are involved. In addition, the study adhered to all ethical guidelines and was approval by the institutional review board of the university.

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