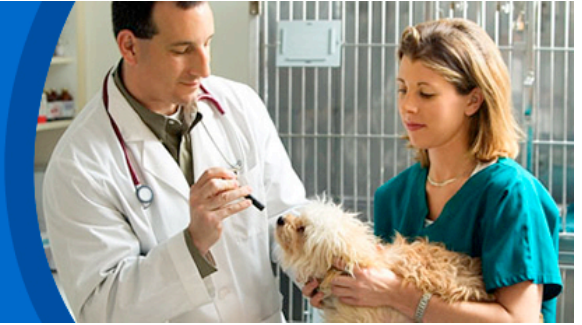




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Culled carrots (*Daucus carota* L.) as an alternative feed resource for sustainable livestock production

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ABSTRACT

The increasing competition between humans and livestock for conventional feed resources, rising feed costs, and environmental concerns have intensified the search for sustainable alternative feed ingredients. Among vegetable by-products, culled carrots (*Daucus carota* L.), generated during harvesting, grading, processing, transportation, and marketing, represent an abundant but underutilized biomass with considerable nutritional potential. Culled carrots contain soluble carbohydrates, dietary fibre, β -carotene, α -carotene, vitamins, minerals, and bioactive compounds such as polyacetylenes and phenolics. These constituents contribute to their nutritional value and antioxidant, immunomodulatory, hepatoprotective, and antimicrobial properties. Studies indicate that fresh, dehydrated, or ensiled carrot by-products can partially replace conventional feed ingredients without adversely affecting feed intake, nutrient digestibility, growth, milk production, or carcass characteristics in livestock. Their utilization also supports circular agriculture by reducing food waste and feed costs. However, information on optimum inclusion levels, preservation methods, long-term safety, and economic feasibility remains limited. This review evaluates the nutritional value, processing, feeding potential, and sustainability of culled carrots in animal nutrition.

Keywords: Carrot, Byproducts, Nutrition, Livestock, Sustainability

1. Introduction

Livestock production is an integral component of global agriculture, contributing substantially to food security, rural livelihoods, employment and economic development. In developing countries, livestock provide milk, meat, eggs, fibre and draught power while serving as an important source of income for smallholder farmers. However, sustaining livestock productivity is increasingly challenging because of the widening gap between the demand and availability of quality feed resources (Frontiers in Sustainable Food Systems Policy Research Group, 2025) [1].

Feed is the largest recurring expenditure in livestock production, accounting for approximately 60–70% of total production costs. The availability of conventional feed ingredients such as maize, barley, wheat, soybean meal and oilseed cakes is increasingly constrained by population growth, urbanization, industrialization and changing land-use patterns. These factors have intensified competition between humans and livestock for cereal grains and edible plant resources, increasing feed prices and reducing the profitability of animal production. India, despite having one of the world's largest livestock populations, continues to experience substantial shortages of green fodder, dry fodder and concentrate feeds (NIANP, 2013) [2]. Such deficiencies can adversely affect growth, reproductive efficiency, milk production, disease resistance and overall animal health. These challenges may become more pronounced under climate change because of drought, erratic rainfall and declining availability of cultivable land (Saha et al., 2024) [3].

Consequently, increasing attention has been directed towards alternative feed resources that can partially replace conventional ingredients without compromising animal performance. Agro-industrial by-products and fruit and vegetable residues are particularly promising because they are generated in large quantities throughout the food supply chain and often retain considerable amounts of digestible carbohydrates, protein, fibre, minerals, vitamins and bioactive compounds (Bakshi et al., 2013) [4]. Their utilization in livestock feeding can reduce feed costs while minimizing environmental problems associated with organic waste disposal (Bao et al., 1994; Sharma et al., 2012; Shyamala et al., 2010) [5, 6, 7]. Such utilization also supports circular bioeconomy principles by converting underutilized biological residues into valuable livestock products (Kaur et al., 2026; Pistol et al., 2024) [8, 9].

Among vegetable residues, culled carrots (*Daucus carota* L.) have considerable potential as an alternative feed resource. Carrots rejected during harvesting, grading, packaging, transportation and marketing because of irregular size, shape, cracking, bruising or other cosmetic defects retain much of the nutritional value of

marketable carrots. They contain readily digestible carbohydrates, moderate fibre, β -carotene and other carotenoids, vitamins, minerals and biologically active compounds, making them potentially useful as both a nutritive and functional feed ingredient (Saha *et al.*, 2024; Pistol *et al.*, 2024) [3, 9].

However, their effective utilization is influenced by high moisture content, seasonal availability, storage stability, transportation costs and dietary inclusion level. Therefore, preservation methods such as dehydration and ensiling are important for improving storage life and facilitating year-round utilization (Pistol *et al.*, 2024; Šeregelj *et al.*, 2020) [9, 10]. The present review evaluates the nutritional composition, bioactive compounds, feeding value, processing methods, physiological effects and sustainability potential of culled carrots in livestock feeding, while identifying research gaps and future opportunities for their efficient utilization in sustainable livestock production systems.

2. Carrot production, generation of culled carrots and their availability as livestock feed

Carrot (*Daucus carota* L.), belonging to the family Apiaceae, is an important root vegetable cultivated widely in temperate, subtropical and tropical regions. It is valued for its pleasant flavour and nutritional properties, particularly its high content of provitamin A carotenoids. Global carrot production has increased with the adoption of improved cultivars and agronomic practices. China is the leading producer, while India is also an important producer, with cultivation concentrated in states including Haryana, Punjab, Uttar Pradesh, Karnataka and Tamil Nadu (Government of India, 2018) [11].

A considerable proportion of harvested carrots fails to reach consumers because of losses during harvesting, grading, transportation, storage, processing and marketing. Roots rejected because of irregular size or shape, cracking, bruising, branching or other cosmetic defects are commonly termed culled carrots. Despite their poor marketability, these carrots generally retain considerable nutritional value comparable to marketable roots (Saha *et al.*, 2024) [3]. Approximately 10–15% of carrot production may be rejected before reaching retail markets. Processing industries also generate carrot pomace, pulp, peel and trimming residues during juice extraction, canning and dehydration, providing additional sources of potentially valuable feed material (Bao *et al.*, 1994; Sharma *et al.*, 2012; Shyamala *et al.*, 2010) [5, 6, 7]. Culled carrots are generally seasonal and contain high moisture, which limits their storage stability and increases transportation costs. Dehydration, ensiling and incorporation into total mixed rations or complete feed blocks can improve their storage and facilitate year-round utilization (Saha *et al.*, 2024) [3]. Their relatively low cost and availability from markets and processing units further enhance their potential as an economical livestock feed resource. Utilization of these residues also supports circular bioeconomy principles by recovering nutrients and reducing organic waste disposal (NIANP, 2013) [2].

3. Nutritional composition of carrot

The nutritional value of an unconventional feed ingredient determines its suitability for livestock feeding. Culled carrots possess a favourable nutritional profile characterized by readily digestible carbohydrates, moderate fibre, low lipid content, vitamins, minerals and biologically active phytochemicals. Despite rejection from the human food chain because of cosmetic defects, their nutrient composition remains broadly comparable with that of marketable carrots (Saha *et al.*, 2024) [3]. However, chemical composition varies with cultivar, growing conditions, maturity, harvesting season, storage and processing.

Fresh carrots generally contain 85–90% moisture and approximately 10–13% dry matter. Gopalan *et al.* (1991) [12] reported 86% moisture, 0.9% protein, 0.2% fat, 10.6% carbohydrate, 1.2% crude fibre and 1.1% ash (Gopalan *et al.*, 1991) [12]. Holland *et al.* (1991) [13] reported 88.8% moisture, 0.7% protein, 0.5% fat, 6.0% carbohydrate and 5.6% crude fibre (Holland *et al.*, 1991) [13]. Bakshi *et al.* (2013) [4] reported 10.1% dry matter, 91.8% organic matter, 8.2% ash, 9.9% crude protein, 1.4% ether extract, 9.0% NDF and 8.0% ADF (Table 1) (Bakshi *et al.*, 2013) [4]. These characteristics indicate that carrot is primarily an energy-rich feed rather than a protein supplement.

Carrot contains appreciable concentrations of soluble carbohydrates, particularly sucrose, glucose and fructose, which contribute to palatability and provide readily available energy. Its relatively low lignification favours nutrient digestibility. Lardy *et al.* (2009) [14] reported 13% dry matter, 10.3% crude protein, 11% ADF, 82% TDN, 0.86 Mcal/lb NEm and 0.59 Mcal/lb NEg (Holland *et al.*, 1991) [13]. Dehydration increases dry matter concentration to approximately 90%, improving storage stability and facilitating incorporation into complete feeds.

Carrot also supplies essential minerals, including calcium, phosphorus, potassium, magnesium, sodium, iron, zinc and copper. Holland *et al.* (1991) [13] reported calcium, phosphorus, sodium, potassium and magnesium concentrations of 34, 25, 40, 240 and 9 mg/100 g, respectively (Holland *et al.*, 1991) [13]. Potassium was the predominant mineral.

Carrot is particularly recognized for its carotenoid content. Total carotenoids have been reported at 5.33–16.4 mg/100 g, including α -carotene and β -carotene, together with vitamin E, vitamin C, thiamine, riboflavin, niacin and folic acid (Alasalvar *et al.*, 2001) [15]. These compounds may contribute to antioxidant defence and immune function. Carrot also contains polyacetylenes such as falcarinol, falcarinol and falcarinol-3-acetate. Falcarinol has reported biological and antineoplastic activity, with concentrations of approximately 0.7–4.06 mg/100 g fresh weight (Christensen, 2013) [16].

The high moisture content of fresh carrot limits storage stability and increases the risk of microbial deterioration. Therefore, dehydration, drying and ensiling are useful preservation methods. Overall, the combination of readily available carbohydrates, digestible fibre, carotenoids, vitamins, minerals and bioactive compounds makes culled carrot a potentially valuable energy-rich feed ingredient for livestock. Variation in chemical composition should, however, be considered when formulating diets and determining appropriate inclusion levels.

Table 1. Chemical composition of carrot

Source	DM (%)	Ash (%)	CP (%)	EE (%)	NDF (%)	CF (%)	ADF (%)
Bakshi and Wadhwa (2013) ⁴	10.1	8.2	9.9	1.4	9.0	–	8.0
Feedipedia, carrot root, fresh ¹⁸	10.7	7.4	9.1	1.0	11.8	10.0	9.1
Feedipedia, carrot root, dry ¹⁹	90.0	6.4	11.1	2.2	19.0	9.3	12.4
Goby and Gidenne (2008) ²⁰	89.3	21.2	12.9	–	19.5	–	13.8
Rust and Buskirk (2008) ²¹	12.0	8.2	9.9	1.4	–	–	–

DM: dry matter; CP: crude protein; EE: ether extract; NDF: neutral detergent fibre; CF: crude fibre; ADF: acid detergent fibre.

4. Bioactive compounds and functional properties of culled carrots

Beyond their nutritional value, culled carrots contain several bioactive compounds that may contribute to their potential as functional feed ingredients. Carotenoids, phenolic compounds, vitamins and polyacetylenes exhibit antioxidant, immunomodulatory, antimicrobial and anti-inflammatory activities, which may complement the nutritive contribution of carrot-based diets (Sharma *et al.*, 2012; Pistol *et al.*, 2024) [6, 9].

4.1 Carotenoids

Carrots are particularly rich in carotenoids, mainly β -carotene and α -carotene, with smaller amounts of lutein and other carotenoids depending on cultivar. β -Carotene serves as an important precursor of vitamin A, which is essential for vision, epithelial integrity, reproduction and immune function. In livestock, adequate carotenoid status may support reproductive performance and immune responses. β -Carotene also possesses antioxidant activity through scavenging reactive oxygen species and protecting cellular components from oxidative damage (Alasalvar *et al.*, 2001) [15].

4.2 Polyacetylenes

Polyacetylenes, particularly falcarinol, falcarinol and falcarinol-3-acetate, are characteristic phytochemicals of carrots. These compounds have demonstrated antimicrobial, anti-inflammatory and cytoprotective activities in experimental studies (Sharma *et al.*, 2012; Šeregelj *et al.*, 2020; Zaini *et al.*, 2011) [6, 10, 17]. Falcarinol has also attracted attention because of its reported effects on cellular proliferation and oxidative stress. However, much of the available evidence is derived from in vitro and biomedical studies, and further livestock-specific research is required to establish their physiological significance in animal feeding (Pistol *et al.*, 2024; Šeregelj *et al.*, 2020) [9, 10].

4.3 Phenolic compounds and antioxidant vitamins

Carrots contain phenolic acids and flavonoids that can scavenge free radicals and reduce lipid oxidation. These compounds, together with vitamin C and vitamin E, contribute to antioxidant protection and may improve cellular resilience during environmental and metabolic stress. Vitamin C functions mainly as a water-soluble antioxidant, whereas vitamin E protects membrane lipids from oxidative damage. Their combined activity may support normal physiological and immune functions in livestock (Sharma *et al.*, 2012; Pistol *et al.*, 2024; Šeregelj *et al.*, 2020) [6, 9, 10].

4.4 Dietary fibre and gut health

Although carrots are not considered high-fibre feeds, they contain both soluble and insoluble fibre. Soluble fibre can provide fermentable substrates for intestinal microorganisms and promote pro-

duction of short-chain fatty acids, whereas insoluble fibre supports gastrointestinal motility and normal digestive function. In ruminants, carrot fibre may influence ruminal fermentation, while in monogastric animals it can contribute to intestinal health and nutrient utilization (Bao *et al.*, 1994; Sharma *et al.*, 2012; Shyamala *et al.*, 2010) [5, 6, 7]. Overall, the combination of carotenoids, polyacetylenes, phenolic compounds, antioxidant vitamins and dietary fibre gives culled carrots functional properties in addition to their basic nutritive value. Nevertheless, the magnitude of these effects depends on cultivar, processing, inclusion level and animal species, and further in vivo studies are required to establish their practical significance in livestock production.

Despite their nutritional potential, further research is needed on long-term feeding, large-scale utilization, rumen microbial interactions, methane emissions, cultivar-related nutrient variation and optimum inclusion levels. Addressing these gaps will support the wider use of culled carrots as a sustainable livestock feed resource (Saha *et al.*, 2024) [3].

5. Feeding value of culled carrots in ruminants

Culled carrots have potential as an unconventional energy feed because of their high palatability, readily fermentable carbohydrates, low structural fibre and β -carotene content. Experimental studies indicate that carrot roots and their by-products can be incorporated into ruminant diets without adversely affecting animal performance when used at appropriate levels (Bakshi *et al.*, 2013; Forwood *et al.*, 2021; Dentinho *et al.*, 2023) [4, 18, 19] (Table 2).

5.1 Feed intake and palatability

Culled carrots are readily consumed by ruminants because of their high moisture content, sweetness and palatability. In lambs, unsaleable carrots included at approximately 45% of dietary dry matter supported satisfactory feed intake and animal performance when incorporated into a complete ration²¹. Similarly, carrot-based silage included at about 50% of dietary dry matter maintained dry matter and crude protein intake in lambs (Dentinho *et al.*, 2023) [19]. These findings indicate that carrots can be included at relatively high levels when diets are properly balanced.

5.2 Nutrient digestibility

The low structural fibre and high concentration of soluble carbohydrates in carrots contribute to their good feeding value. Carrot pulp has been reported to contain appreciable water-soluble sugars with relatively low NDF and ADF, indicating high potential digestibility (Saha *et al.*, 2024) [3]. Feeding studies in lambs have further shown that inclusion of carrot-based feeds can maintain nutrient intake and animal performance without detrimental effects on carcass traits (Forwood *et al.*, 2021; Dentinho *et al.*, 2023) [18, 19]. However, the optimum inclusion level depends on the form of carrot, basal diet and animal species.

5.3 Effects on rumen fermentation

The readily fermentable carbohydrates of carrots provide substrates for rumen microorganisms and can support microbial fermentation and volatile fatty acid production. Carrot-based silage has been successfully used in lamb diets without adverse effects on animal performance or in vitro methane production (Dentinho *et al.*, 2023) [19]. However, because of their high concentration of readily fermentable carbohydrates, excessive inclusion should be avoided, particularly when dietary physically effective fibre is inadequate.

5.4 Milk production and milk quality

Carrots are particularly important as a source of dietary carotenoids for dairy animals. Supplementation with fresh carrots has been reported to increase the vitamin and carotenoid content of milk, while studies on ruminant carotenoid metabolism demonstrate that dietary β -carotene can be absorbed and transferred into milk (Esfiokhi *et al.*,

2025; Nałęcz-Tarwacka *et al.*, 2003) [20, 21]. Thus, carrot feeding may be useful for increasing the carotenoid concentration of dairy products, although effects on milk yield and composition depend on dietary inclusion and overall nutrient supply.

5.5 Animal health and metabolic status

The β -carotene, phenolic compounds and antioxidant vitamins present in carrots may contribute to antioxidant protection. However, evidence for direct health and metabolic benefits in ruminants is less extensive than evidence for their nutritional value. Therefore, potential improvements in antioxidant status or blood biochemical parameters should be interpreted cautiously and require further controlled studies (Sharma *et al.*, 2012; Šeregelj *et al.*, 2020) [6, 10].

Overall, available evidence indicates that culled carrots can be effectively incorporated into ruminant diets, particularly in lambs and dairy cattle, when inclusion levels are adjusted according to moisture content, nutrient composition and the basal ration.

Table 2. Reported effects of carrot and carrot by-products in ruminants

Species	Carrot product	Inclusion level	Major response	Reference
Lambs	Unsaleable fresh carrots	45% of dietary DM	Satisfactory feed intake, growth performance and carcass characteristics; meat quality was maintained	Forwood <i>et al.</i> (2021) ²²
Lambs	Carrot-based silage	50% of dietary DM	Maintained DM and CP intake, growth performance, carcass traits and meat quality; no adverse effect on methane production	Dentinho <i>et al.</i> (2023) ²³
Ewes and lambs	Carrot pulp	20 and 40% of dietary DM	Improved feed intake, postpartum performance, colostrum and milk yield at higher inclusion; improved antioxidant status of ewes and lambs	Esfiokhi <i>et al.</i> (2025) ²⁴
Dairy cows	Fresh carrots	5 kg/day	Increased vitamin A and carotenoid concentration in milk	Nałęcz-Tarwacka <i>et al.</i> (2003) ²⁵
Dairy cows	Carrot silage	Not specified	Increased β -carotene concentration in blood plasma and milk	Nonaka <i>et al.</i> (1994) ²⁷
Japanese Black cows	Dry carrot preparation	138 mg β -carotene/day	Increased plasma β -carotene and colostral IgA	Nishijima <i>et al.</i> (2017) ²⁸
Ruminants	Carrot pulp/cannery waste	Not specified	High water-soluble sugars and relatively low NDF and ADF, indicating good feed potential	Bakshi and Wadhwa (2013) ⁴

Abbreviations: DM = dry matter; CP = crude protein; NDF = neutral detergent fibre; ADF = acid detergent fibre.

6. Preservation and utilization in ruminant feeding systems

The high moisture content of fresh carrots limits their storage life and increases transportation costs. Therefore, suitable preservation methods are essential for their efficient utilization in ruminant feeding systems.

6.1 Fresh feeding

Fresh culled carrots can be fed directly after proper cleaning and chopping. This approach is particularly suitable for farms located near vegetable markets or processing units, where transportation distances are short. Fresh carrots can be mixed with the basal ration or incorporated into TMR (Saha *et al.*, 2024) [3].

6.2 Dehydration

Dehydration reduces moisture content and improves storage stability while lowering transportation requirements. Dried carrot meal can be incorporated into concentrate mixtures and pelleted feeds, allowing utilization throughout the year. Proper drying conditions are important to minimize nutrient and carotenoid losses (Esfiokhi *et al.*, 2025) [20].

6.3 Ensiling

Ensiling is an effective method for preserving carrot by-products because of their high moisture content. Chopped carrots can be mixed with dry roughages such as hay, straw or other crop residues to improve dry matter content and fermentation. Properly prepared carrot silage can provide good palatability and facilitate year-round utilization (Kaur *et al.*, 2026; Pistol *et al.*, 2024) [8, 9].

6.4 Economic significance

Culled carrots generated by vegetable markets and processing industries can provide a relatively low-cost source of nutrients for livestock. Their local utilization may reduce dependence on conventional energy feeds and simultaneously decrease waste disposal problems (Saha *et al.*, 2024) [3]. However, economic feasibility depends on the cost of collection, transportation, processing, dehydration and storage. Therefore, utilization is likely to be most advantageous in areas with concentrated carrot production and nearby livestock farms (Kaur *et al.*, 2026; Pistol *et al.*, 2024) [8, 9].

7. Feeding value of culled carrots in non-ruminants

Culled carrots and their by-products have potential as alternative feed ingredients for non-ruminants because of their readily fermentable carbohydrates, moderate fibre, carotenoids and other bioactive compounds. Their utilization has been investigated mainly in rabbits and poultry, while information in pigs and horses is comparatively limited (Sharma *et al.*, 2012; Pistol *et al.*, 2024) [6, 9] (Table 3).

7.1 Rabbits

Rabbits can efficiently utilize vegetable materials because of their hindgut fermentation. Fresh carrots, carrot tops and dried carrot meal are generally well accepted and can contribute to feed intake and nutrient utilization. Dried carrot products have been evaluated at approximately 10–30% of the diet, with satisfactory performance reported at moderate inclusion levels. Carrot tops may also partially replace conventional forage because of their fibre and protein content (Saha *et al.*, 2024; Bao *et al.*, 1994) [3, 5]. The appropriate inclusion level depends on the nutrient composition of the carrot product and the overall diet.

7.2 Poultry

Carrot by-products provide carotenoids, carbohydrates and antioxidant compounds that may contribute to poultry nutrition. Moderate dietary inclusion generally maintains growth performance when diets are properly balanced. Carotenoids from carrots can increase yolk pigmentation and may contribute to antioxidant protection of eggs and tissues. However, excessive inclusion may increase dietary fibre and reduce nutrient digestibility, particularly in broilers (Sharma *et al.*, 2012; Pistol *et al.*, 2024) [6, 9].

7.3 Pigs

Carrot-derived products contain soluble fibre, carotenoids and phenolic compounds that may support intestinal function and antioxidant defence. Their potential use is particularly relevant in young pigs dur-

ing periods of dietary stress. However, compared with rabbits and poultry, experimental information on culled carrots in pigs is limited. Further studies are required to determine suitable inclusion levels and their effects on growth, nutrient utilization and gut microbiota (Pistol *et al.*, 2024; Šeregelj *et al.*, 2020) [9, 10].

7.4 Horses

Fresh carrots are highly palatable and are commonly used as supplementary feeds for horses. They provide readily available carbohydrates, moisture and β -carotene. Carrots should be offered in moderate quantities and should not replace good-quality forage. Appropriate ration formulation is particularly important for horses requiring dietary control of rapidly fermentable carbohydrates (Sharma *et al.*, 2012) [6].

8. Effects of culled carrots on growth performance and nutrient utilization

The effects of carrot supplementation on growth performance vary with animal species, product form and dietary inclusion level. In rabbits, carrot products can provide readily available energy and fibre while supporting growth and feed utilization. In poultry, moderate inclusion can maintain growth performance when diets are adequately balanced (Saha *et al.*, 2024; Sharma *et al.*, 2012) [3, 6].

In ruminants, feeding trials with unsaleable carrots and carrot-based silage have shown that substantial inclusion can maintain growth performance and carcass characteristics in lambs (Forwood *et al.*, 2021; Dentinho *et al.*, 2023) [18, 19]. Overall, available evidence indicates that culled carrots can contribute to nutrient supply and reduce dependence on conventional feed ingredients when included at appropriate levels.

9. Blood biochemical profile and antioxidant status

Carrots contain β -carotene, phenolic compounds and antioxidant vitamins that may contribute to antioxidant defence. Dietary carrot products have been associated with increased circulating carotenoids and favourable antioxidant responses in experimental studies (Sharma *et al.*, 2012; Šeregelj *et al.*, 2020) [6, 10]. Some studies have also reported changes in blood biochemical parameters, particularly those related to lipid metabolism.

However, these responses may vary with species, physiological status, carrot product and inclusion level. Therefore, further controlled studies are required to establish the effects of culled carrots on antioxidant enzymes, haematological parameters and metabolic health under practical livestock production conditions.

Table 3. Reported effects of carrot and carrot by-products in non-ruminants

Species	Carrot product	Inclusion level	Major response	Reference
Rabbits	Dried carrot meal	10–30% of diet	Maintained growth performance and feed utilization at moderate levels	Saha and Rathod (2024) ³
Rabbits	Carrot tops	Partial forage replacement	Supported feed utilization and productive performance	Saha and Rathod (2024) ³
Poultry	Carrot meal/by-products	Moderate inclusion	Maintained growth performance and feed efficiency	Sharma <i>et al.</i> (2012) ⁶
Poultry	Carrot products	Moderate inclusion	Increased yolk pigmentation and carotenoid deposition	Sharma <i>et al.</i> (2012) ⁶ ; Pistol <i>et al.</i> (2024) ⁹
Pigs	Carrot-derived products	Not established	Potential support for gut health and antioxidant status	Šeregelj <i>et al.</i> (2020) ¹⁰ ; Pistol <i>et al.</i> (2024) ⁹
Horses	Fresh carrots	Supplementary feeding	High palatability and supply of β -carotene and readily available carbohydrates	Sharma <i>et al.</i> (2012) ⁶

10. Immunomodulatory, antioxidant and health-promoting mechanisms of culled carrots

The importance of functional feed ingredients in modern livestock production has increased considerably owing to restrictions on antibiotic growth promoters, increasing consumer preference for naturally derived feed additives and growing concern regarding oxidative stress associated with intensive animal production. Among vegetable by-products, culled carrots have emerged as a promising functional feed because they contain bioactive compounds capable of improving antioxidant defence, modulating immune responses and supporting animal health. These properties may extend their value beyond basic nutrient supply and contribute to improved productivity and product quality (Sharma *et al.*, 2012; Pistol *et al.*, 2024; Šeregelj *et al.*, 2020) [6, 9, 10].

10.1 Antioxidant mechanisms

Oxidative stress occurs when the production of reactive oxygen species (ROS) exceeds the antioxidant defence capacity of tissues. Excessive ROS can damage lipids, proteins and nucleic acids, resulting in impaired cellular function, inflammation and reduced productivity. Livestock are exposed to oxidative stress during rapid growth, pregnancy, lactation, transportation, weaning, vaccination, thermal stress and disease challenges. Therefore, dietary antioxidants are important for maintaining normal cellular function.

Culled carrots are rich in β -carotene, α -carotene, vitamins C and E and phenolic compounds, which possess antioxidant properties (Sharma *et al.*, 2012; Pistol *et al.*, 2024) [6, 9]. These compounds may scavenge reactive oxygen species, prevent lipid peroxidation, protect cellular DNA and proteins, preserve enzyme activity and support endogenous antioxidant defence systems. Carotenoid supplementation has been associated with increased antioxidant enzyme activity and reduced oxidative stress biomarkers such as malondialdehyde (MDA), suggesting a possible role of carrots in improving physiological resilience during metabolic stress.

10.2 Immunomodulatory effects

Efficient immune function is essential for maintaining animal health and productive performance. Carrot-derived carotenoids may influence both innate and adaptive immune responses. β -carotene has been associated with improved macrophage activity, neutrophil function, phagocytosis and pathogen-killing capacity, thereby supporting the first line of defence. It may also influence lymphocyte proliferation, antibody production, T-helper cell activity and cytokine regulation. Such effects indicate the potential role of carrot-derived carotenoids in supporting immune responsiveness, although direct evidence in livestock remains limited (Hughes, 1999) [22].

10.3 Anti-inflammatory activity

Chronic inflammation can negatively affect feed efficiency, growth, health and reproductive performance. Carrots contain polyacetylenes, particularly falcarinol and falcariindiol, which possess anti-inflammatory and other biological activities (Sharma *et al.*, 2012; Šeregelj *et al.*, 2020) [6, 10]. These compounds may help regulate inflammatory signalling, reduce oxidative tissue damage and support cellular protection. However, much of the available mechanistic evidence is derived from laboratory studies, and further livestock-based research is required.

10.4 Effects on lipid metabolism

Carrot dietary fibre and antioxidant compounds may influence lipid metabolism through several mechanisms. Soluble fibre can bind bile acids in the gastrointestinal tract and increase their excretion, thereby promoting cholesterol utilization for bile synthesis. Antioxidant compounds may also reduce oxidative modification of lipoproteins. These effects suggest a possible beneficial influence on lipid metabolism and metabolic health, particularly in high-producing animals (Bao *et al.*, 1994; Sharma *et al.*, 2012; Shyamala *et al.*, 2010) [5, 6, 7].

10.5 Hepatoprotective effects

The liver plays an important role in nutrient metabolism, detoxification and synthesis of plasma proteins. Experimental studies indicate that carrot-derived compounds may provide hepatoprotective effects by reducing lipid peroxidation, enhancing antioxidant enzyme activity and stabilizing hepatocyte membranes. Reductions in hepatic biomarkers such as ALT and AST have been reported following carrot supplementation in experimental models. However, evidence under livestock production conditions remains limited (Al-Thubaiti *et al.*, 2023) [23].

10.6 Effects on reproductive performance

β -carotene is an important precursor of vitamin A, which is essential for normal reproductive function. Adequate carotenoid and vitamin A status may support ovarian function, corpus luteum development, embryonic survival, spermatogenesis and placental integrity. Carrot supplementation can increase circulating carotenoid concentrations in dairy cattle, suggesting a possible role in reproductive nutrition. However, direct causal relationships between carrot feeding and improved fertility require further controlled studies (Sharma *et al.*, 2012; Pistol *et al.*, 2024) [6, 9].

10.7 Gut health and product quality

Carrot-derived soluble fibre can serve as a fermentable substrate for beneficial microorganisms. Its fermentation produces short-chain fatty acids such as acetate, propionate and butyrate, which provide energy to intestinal epithelial cells, support gut barrier integrity and influence immune responses. Thus, carrot supplementation may contribute to improved gastrointestinal health, although further microbiome-based studies are required (Esfiokhi *et al.*, 2023) [24].

Carotenoids absorbed from the diet may also be deposited in milk, eggs and meat, potentially improving natural pigmentation, antioxidant capacity and nutritional value while reducing lipid oxidation. Therefore, culled carrots may have value as both feed ingredients and functional components for improving the quality of animal-derived foods (Saha *et al.*, 2024) [3].

Culled carrots show antioxidant, immunomodulatory and health-promoting potential, but livestock-specific evidence remains limited. Bioactive compounds vary with cultivar, maturity, processing and storage. Further controlled studies are needed to establish bioavailability, optimum inclusion levels, long-term effects and practical benefits under livestock production conditions.

11. Practical feeding considerations and diet formulation

The practical value of culled carrots depends on their nutrient composition, moisture content and method of incorporation into the ration. Fresh carrots contain high moisture and relatively low dry matter; therefore, ration formulation should be based on dry-matter contribution rather than fresh weight. This is particularly important in high-producing dairy animals.

Culled carrots should be considered mainly as an energy and functional feed ingredient rather than a protein supplement. Their inclusion may require adjustment of dietary protein and mineral supply. In ruminants, gradual introduction is recommended when large quantities are fed because of their readily fermentable carbohydrates.

Fresh roots, dried carrot meal and ensiled material are the major forms suitable for feeding. Fresh carrots are useful where local supplies are available, whereas drying improves storage stability and facilitates ration formulation. Ensiling can preserve seasonal carrot residues, but fermentation quality and hygienic conditions should be monitored (Bao *et al.*, 1994) [5], (Shyamala *et al.*, 2010) [7].

12. Safety, quality control and limitations

Culled carrots are a heterogeneous feed material. Carrots rejected because of size, shape or superficial damage may be suitable for feeding, whereas material showing mould, advanced decay, chemical con

tamination or abnormal spoilage should be avoided. Visual inspection for mould, odour and foreign material is therefore essential.

Nutrient composition varies with cultivar, maturity, growing conditions and processing. Washing, trimming, drying, juice extraction and storage may further alter nutrient and carotenoid concentrations. Published values should therefore be considered reference values rather than fixed formulation values (Sharma *et al.*, 2012; Shyamala *et al.*, 2010) [6, 7].

Evidence for antioxidant, *anti*-inflammatory and antimicrobial effects is largely derived from laboratory and experimental studies. Therefore, these findings should not be directly interpreted as production responses in livestock. Further controlled feeding studies are required.

13. Economic and environmental significance

Utilization of culled carrots can convert discarded biomass into useful animal feed and contribute to circular resource utilization. Carrot residues provide carbohydrates, fibre, minerals and phytochemicals and therefore have potential value in sustainable livestock production (Kaur *et al.*, 2026; Pistol *et al.*, 2024) [8, 9]. However, transportation, drying and preservation costs may reduce economic and environmental benefits. Local utilization near production and livestock areas may therefore be more advantageous.

14. Research gaps and future directions

Standardized feeding recommendations are required for different livestock species. Existing studies differ in carrot type, processing method, inclusion level, basal diet and animal characteristics, limiting direct comparison. Future studies should report chemical composition and inclusion levels on a dry-matter basis.

Long-term studies are needed to evaluate nutrient utilization, production performance, reproductive efficiency, product quality, methane emission and health responses under practical livestock conditions. Further research should also examine the effects of processing and storage on carotenoid retention and feed quality.

15. Conclusion

Culled carrots have considerable potential as an alternative feed resource in livestock production, as their rejection is often associated with physical appearance rather than poor nutritional quality. They provide readily fermentable carbohydrates, fibre, carotenoids, vitamins, minerals and other bioactive compounds. Their utilization can help reduce feed costs, diversify conventional feed resources and minimize vegetable waste. However, high moisture content, variation in nutrient composition, storage and preservation requirements and limited livestock-specific research remain important constraints. Therefore, culled carrots should be properly evaluated for quality and incorporated into balanced rations based on dry-matter contribution. Further research is needed to establish suitable inclusion levels, processing methods, long-term animal responses and economic feasibility for their wider use in sustainable livestock production.

Conflict of interest

The authors declare that there is no conflict of interest

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