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Alternative feed resources in the era of climate change: A review

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ABSTRACT

Climate change poses significant challenges to traditional feed resources, impacting livestock production and food security. In response, the search for alternative feed resources has gained momentum, aiming to enhance the resilience and sustainability of agriculture in a changing climate. This review explores a diverse array of alternative feed resources that show promise in mitigating the impacts of climate change on feed availability and quality. Drawing from a comprehensive analysis of industry reports, case studies, and articles from sources such as Elsevier, Scopus, PubMed, ScholarOne, PLUS One, Science Direct, and Google Scholar, this study covers a range of innovative options, including insect-based feeds, algae, seaweeds, microbial proteins, residues, by-products, aquatic plants and weeds, hydroponic fodder production, climate-resilient forage crops, agroforestry systems, high-value crop by-products, and silvopastoral systems. Each alternative feed resource is examined in terms of its nutritional value, environmental benefits, and potential challenges to adoption. The review underscores the importance of developing and implementing climate-resilient livestock feeding strategies to ensure food security and sustainability in a changing climate. In light of climate change, this study explores the effects of switching to other feed sources in livestock production. Further research and policy support are emphasized to facilitate the integration of these alternative feed resources into livestock production systems worldwide. By embracing these innovative approaches, the agricultural sector can build resilience, reduce environmental impacts, and secure food supplies amidst climate change challenges through insect-based feeds, hydroponic fodders, agro-industrial byproducts, aquatic plants and algae, among others can be used as substitutes in the era of climate change.

Introduction

Climate change is a long-term imbalance in the features of a region's temperature, wind, and rainfall that has affected livestock output in this period (Hidosa and Guyo 2017). According to Kassie *et al.* (2014), the impact of climate change is anticipated to increase vulnerability in livestock production systems by impairing feed intake, metabolic processes, and defensive mechanisms. One critical aspect affected by climate change is feed availability and quality for livestock (Escarcha *et al*., 2018). As changing weather patterns, extreme events, and shifting environmental conditions become more frequent, understanding the impacts of climate change on feed resources is crucial for ensuring sustainable livestock production and food security (Assan, 2014)

Significant worldwide changes have been experienced during the past 65 years, including global warming and the observed and expected climate changes for the twenty-first century (Assan, 2014). With its impact on many elements of the ecological, environmental, socio-political, and socio-economic disciplines, climate change is an inter-governmental complex problem worldwide (Feliciano *et al.* 2022). Temperatures are rising in many different regions due to climate change (Schuurmans, 2021) at the rate of 0.06°C per decade since 1850 resulting in changes to wetness and dryness, to winds, snow and ice, coastal areas and oceans. With the onset of the industrial revolution, the problem of earth climate was amplified

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manifold (Abbass *et al.* 2022). The issue of the earth's climate was greatly exacerbated with the start of the industrial revolution (Abbass *et al*., 2022).

The susceptibility to livestock feed in terms of quality and quantity has increased due to climate change. For several varieties of grass growing in low-land situations, the hot and dry seasons have caused the biggest drop in biomass output (Morton, 2007). According to the study, increases in temperature, carbon dioxide concentrations, and nitrogen deposition reduce pasture primary productivity. On the other hand, Hopkins (2000) predicts that many currently semi-arid regions would have less rainfall as a result of climate change. In many tropical regions, it is anticipated that the length of the pasture growing season will shorten. This may be accompanied by more unpredictability in rainfall patterns and more frequent droughts (Change, 2007). It has been noted that biodiversity and species richness in rangelands are impacted by climate change. According to research conducted in the Qinghai-Tibet Plateau region, a trend of warming and drying is causing a shift from highly productive alpine-adapted Kobresia communities to less productive grassland Stipa populations (Howden *et al*., 2008). Additionally, Nardone *et al.* (2010) stated that the trend toward environmental drying and warming is having a detrimental impact on the productivity of rangelands by reducing the amount and nutritional value of forages in addition to reducing water availability. When it comes to the composition of the range's forage species, changes in temperature and CO_2 levels also affect the ideal growth and dynamic of the range's species. A study conducted in Ethiopia showed that the Afar clans from Baadu have been driven 150 km west by the Issa from their traditional rainy season pastures. The invasion of the pasturelands by exotic species, such as Prosopis juliflora, has made the loss of the rainy season pastures even worse (Wilkes, 2008).

According to Roberts *et al.* (1975), unforeseen climate change causes nutritional stress, which lowers growth rates, lowers fertility, and increases death. In a similar vein, another investigation found that seasonal feed shortages brought on by climate change were to blame for the loss of weight increases performances gained during more advantageous times. According to a different study that focused on the feed consumption rate of chickens, rising temperatures have caused chickens to consume less feed as a result of climate change. Age-related increases in feed rejection during heat stress are seen in broilers (Menigistu, 2004). Through a comprehensive analysis of industry reports, case studies, and articles from sources such as Elsevier, Scopus, PubMed, ScholarOne, PLUS One, Science Direct, and Google Scholar, this study aim to explore alternative feed ingredients in livestock production in the era of climate change.

Impact of climate change on livestock

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report determined the "likely range" of rise in global average surface temperature by 2100, which is between 0.3ºC and 4.8ºC (IPCC, 2013), notwithstanding uncertainties in climatic variability. Changes in the production and quality of forage and feed crops, water availability for animal development and milk production, illnesses, reproductive issues (Nardone *et al*., 2010), and biodiversity (Reynolds *et al*., 2010) are just a few of the potential effects on livestock. According to Aydinalp and Cresser (2008), these effects are mostly caused by an increase in temperature, an increase in atmospheric carbon dioxide (CO_2) concentration, changes in precipitation, and a combination of these variables. Figure 1 displays the effects of climate change on the factors affecting production output. Most important aspects of livestock production, including water availability, animal productivity, reproduction, and health, are impacted by temperature. Variations in temperature, CO_2, and precipitation all have an impact on the amount and quality of forage. The primary effects of rising temperatures and changing precipitation on livestock diseases.

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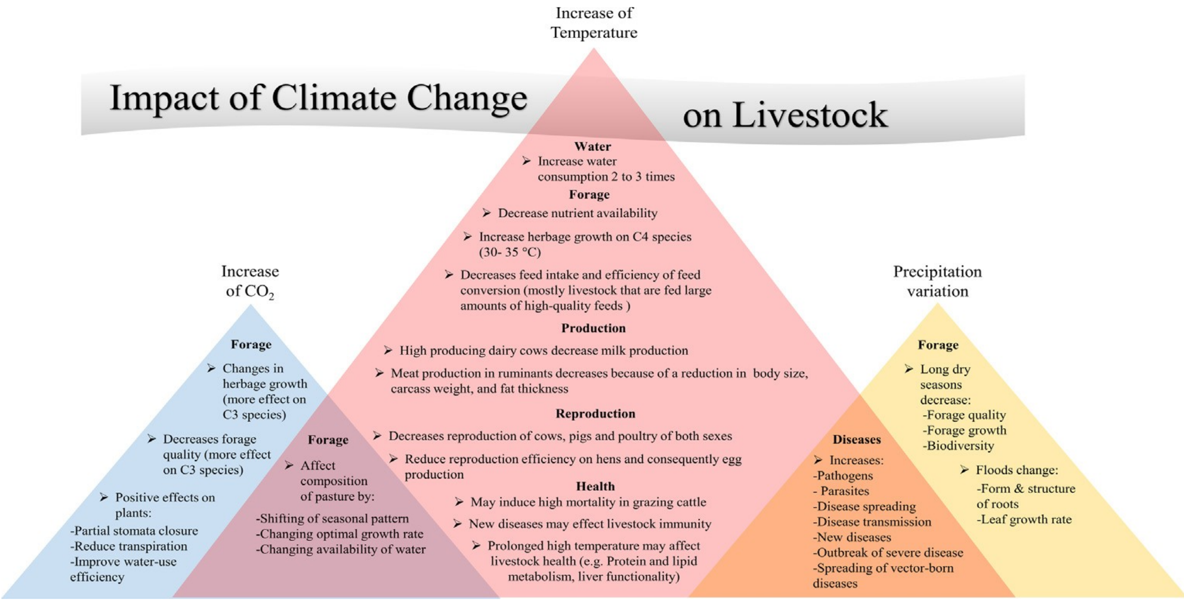

Figure 1. Impacts of Climate Change on Livestock (Source: Rojas-Downing *et al.*, 2017).

Impact on quantity and quality of feedstuff: C3 and C4 plants

The key factors affecting feed quantity and quality will be an increase in temperature and atmospheric CO2 levels (Chapman *et al.*, 2012). Location, livestock system, and species all affect how much and how well feeds are affected by climate change (IFAD, 2010). Among the effects on forage and feed crops are:

According to Thornton *et al.* (2015), an increase in CO2 concentration will cause changes in herbage development that will have a higher impact on C3 species than on grain yields (Figure 1). Due to the partial stomatal closure caused by CO2, decreased transpiration, and improved water usage efficiency in some plants, the impacts of CO2 will be favorable (Wand *et al.*, 1999).

Less than 1% of all plants on Earth are C4 species, which thrive in hotter climates and utilise water more efficiently than C3 plants. Increases in temperature between 30ºC and 35°C may promote the development of herbage, having a greater impact on C4 species. The location, production system, and plant species may all have an impact on the outcomes (Thornton *et al.*, 2009).

Because species competition dynamics are altered by changes in optimum growth rates, changes in temperature and CO2 levels will have an impact on the composition of pastures (IFAD, 2010). Seasonal variations in water supply have an impact on plant competition (Polley *et al.*, 2013). If temperatures, precipitation, and concomitant nitrogen deposition rise, changes in species composition may result in higher primary production in pastures (IPCC, 2007).

Increased heat and dry conditions may have an impact on the quality of feed crops and forage owing to changes in the concentrations of nitrogen and water-soluble carbohydrates. Temperature increases may result in higher levels of lignin and cell wall components in plants (Sanz-Saez *et al.*, 2012; Polley *et al.*, 2013), which lower digestibility and breakdown rates (IFAD, 2010; Polley *et al.*, 2013), reducing the availability of nutrients for cattle (Thornton *et al.*,

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2009). However, C3 plants will see greater fodder quality improvements than C4 plants when the CO2 concentration rises. In comparison to C4 plants, C3 plants have higher crude protein content and digestibility (Wand *et al*., 1999).

Extreme weather conditions, such as floods, can alter the shape and structure of roots, alter the rate at which leaves grow and reduce overall yield (Baruch and Mérida, 1995).

The geography and duration of the growing season have an impact on fodder quantity and quality (Polley *et al*., 2013). In arid and semi-arid environments, an increase of 2°C will have a detrimental effect on pasture and cattle productivity through drought while having a favorable effect in humid temperate zones. Because it affects the length and timing of the forage's availability, the length of the growing season is also a crucial element in determining the quality and amount of fodder. Methane emissions per unit of gross energy used may rise if pasture quality declines (Benchaar *et al*., 2001). To minimize increased methane emissions by animals, it may be necessary to reduce forage consumption and replace it with grain in amounts that avoid acidosis if forage quality diminishes (Polley *et al*., 2013).

Impact of climate change on feed resources

The impacts of climate change on feed supplies utilized in agricultural and animal production are important. The amount, quality, and accessibility of feed supplies can be impacted by climate change, changing precipitation patterns, and an increase in extreme weather events.

Reduced Forage Quality: As temperatures rise, nutrient content in forage plants may drop and lignin content may increase, decreasing the forage's nutritional value and digestibility for animals (Gornall *et al*., 2010). Animal production and performance may suffer as a result of the reduced nutrient content.

Modified Crop Yields: Variations in temperature and precipitation patterns can have an impact on the nutritional value and crop yields. According to studies, important feed crops including maize, wheat, and soybeans can produce less when temperatures rise (Lobell *et al*., 2011). Reduced yields can make it harder to find supplies for feed.

Changes in Feed Availability: According to According to Thornton *et al*. (2014), climate change may cause changes in the geographic distribution of plant species and land use patterns. The livelihoods of farmers and the sustainability of livestock production systems may be impacted by changes in the accessibility and availability of feed supplies for livestock as a result of this.

Climate change may make water shortage worse in many areas, which is important for drinking water and agricultural irrigation. Water shortage can restrict the development and production of forage and feed crops, reducing the total supply of feed for animals (FAO, 2020).

Increased danger of Feed Contamination: According to Milićević *et al*. (2019), climate change can provide circumstances that are favorable for the growth of fungi that produce mycotoxin, increasing the danger of mycotoxin contamination in feed grains. Mycotoxins can have a detrimental effect on an animal's performance and health - reduced productivity, increased disease incidence, chronic damage of vital organs, and decreased reproductive performance.

Impact of climate change on feed production, forage quality and nutritive value of feedstuffs

Livestock feed is majorly composed of forage, grains and oilseed crops or byproducts. Production of these materials are influenced by climate, water supplies, and soil moisture. Thus, changing climate indirectly imposes an effect on livestock production mainly through its impacts on feed supply and water (Saeed *et al*., 2019). Forage plants can be roughly divided into two large groups: grasses and legumes. Legumes are grouped into cool season (C3) and warm season categories (C4) based on leaf anatomy (Pearcy and Ehleringer, 1984). Increases in atmospheric CO2 and temperature can alter forage quantity and quality, with the magnitude depending on the livestock systems (Pearcy and Ehleringer, 1984), location, species, rainfall patterns and extreme climate events causing production variations.

CO2 affects crop growth (Rust, 2019). C3 crop (soybeans, cotton, and wheat) yields increase under increased CO2 concentrations (Figure 1), while yields of C4 crops (corn and sorghum) do not directly respond to the elevated CO2 but may indirectly benefit under drought. Other climatic factors that affect livestock feed supply quantity are precipitation; temperature; and extreme events, such as drought. Increased precipitation is beneficial to corn, sorghum, rice, and soybean (Hatfield *et al*., 2011; Cho and McCar, 2017). As for temperature, C4 species enjoy greater benefits from temperature rise, but such effects depend on location, plant species, and production system (Hadi *et al*., 2020). Drought causes significant crop yield reductions, especially in hot regions (Hummel *et al*., 2018; Ray *et al*., 2018). A recent study in Europe found that drought stress is the main driver of losses for corn and winter wheat, especially in low-yielding years (Webber, 2018). These climatic factors are often confounded, and their effects on vegetation growth are not easy to isolate. For example, higher temperatures at lower latitudes may be associated with higher water stress, while higher temperatures at higher latitudes may increase suitability for cropping and expand the length of the growing season.

Grass forage supplies are also affected by climate change. In terms of grassland and pasture, increases in average temperature bring significant changes in pasture composition, patterns, and biome distribution. Changes in precipitation patterns and more frequent droughts may lead to shorter pasture growing periods (Webber, 2018). Some research has indicated that changes in temperature, CO2 levels, and nitrogen deposition decrease the primary production in pasture (Hopkins and Prado, 2007), while some argue that higher temperatures favor grasses over forbs and legumes.

A balanced and sufficient nutrition is vital to weight gain, productive efficiency, and reproduction. Forage is a critical nutrition component for ruminants while grains are important for monogastrics. As forage and grain quality varies greatly within and between forage crops and nutritional needs vary among animal species, providing suitable feed to animals requires a balance. Most forage quality or nutrition studies have focused on productive performance, nutritive value, voluntary intake, and the effects of anti-nutritional factors (Ball *et al*., 2001). Feed and forage of higher digestibility supply more energy and protein per unit dry matter intake. Nutritive values reported by forage analysis usually include neutral detergent fiber (NDF); acid detergent fiber (ADF); crude protein (CP); and minerals, such as calcium (Ca), phosphorus (P), magnesium (Mg), and potassium (K) (Collins *et al*., 2017), while those of monogastric animal focus on proximate composition and chemical constituents like CP, crude fibre, ether extract, ash, nitrogen free extract and metabolizable energy.

Quality can be influenced by climate via elevated temperatures and dry conditions, which gives rise to variations in concentrations of water-soluble carbohydrates and nitrogen (Hopkin and Prado, 2007). Forage quality may also increase due to an increase in nonstructural carbohydrates resulting from elevated CO2 levels (Dumont *et al*., 2015) for ruminants. However, quality may also decrease since rising temperatures can increase lignin within plant tissues and therefore reduce digestibility (Polley *et al*., 2013). Lee *et al*. (2017) suggest that increasing temperature reduces forage nutritive values and correspondingly may lead to higher methane production.

Seasonal patterns, resource availability and crop outcome (Konapala *et al*., 2020) is affected by the changing climate and impose more impact on livestock production. Apart from heat stress, seasonal changes have been reported to affect beef quality with better beef in spring and worse pastures coinciding with worse beef quality in summer linked to muscle glycogen. Also, fluctuations in seasons' pattern influences forage availability and bring additional challenges for grazing management and livestock management (Bai *et al*., 2019). The risk of drought threatens forage quantity, while melting snow alters water patterns, and precipitation indirectly influences feed supply (Konapala *et al*., 2020). Thus, adaptation strategies are required to cope with such extreme events (Hajek and Knapp, 2021).

Adaptation of animals during climate change

Animals may modify in a variety of ways, whether behavioral, physiological, or morphological, to adapt to the consequences of climate change. These changes are essential for improving an animal's capacity for survival and success in shifting environmental conditions.

Behavioural modification: Animals can alter their behavior to adapt to variations in temperature, precipitation, and the availability of food. For instance, migratory habits may change to follow shifting resource availability or to steer clear of severe weather occurrences (Parmesan, 2006). To coincide with the ideal climatic circumstances, certain species may alter their foraging tactics or the timing of their reproduction (Visser, 2008).

Physiological adaptation: Numerous animals may modify their physiological systems to cope with temperature fluctuations. For instance, to protect cells from heat stress, certain species may change metabolic rates or the creation of heat-shock proteins (Hoffmann and Sgro, 2011). In addition, certain animals may cope with water shortages in dry environments by altering their electrolyte and water balances (Storz, 2016).

Range shifts: Some species may relocate to regions with better environmental circumstances as climate conditions change (Chen *et al*., 2011). This may entail traveling to higher latitudes or elevations where it is cooler or where there are more feed and water supplies.

Response of animals to feed intake during climate change

One reaction to high ambient temperatures is decreased feed intake. Under increasing heat stress, ruminants exhibit decreased hunger, gastrointestinal motility, and rumination (Yada *et al*., 2013). As ambient temperatures increase over 25–26OC and more quickly above 30OC, lactating dairy cows show a decrease in feed consumption (Kadzere *et al*., 2002). Compared to other ruminants, goats are less vulnerable to heat stress. However, when the surrounding temperature is more than 10ºC above their thermal comfort zone, their voluntary feed intake decreases (Lu, 1989). When temperatures rise from 20ºC to 35ºC, pigs under heat stress show an increase in body temperature and a decrease in feed intake of 10.9% (Lopaz *et al*., 1991). Such effects last after the hogs have been subjected to heat stress. As a result, it is indicated that feeding in the morning might aid in preventing decreased feed intake (Cervantes *et al*., 2018). In addition, poultry birds consume less feed when exposed to high temperatures. Birds' feed intake was shown to decrease by 9.5% from the post-hatch period to six weeks of age when the ambient temperature increased from 21.1 to 32.2ºC (Syafwan *et al*., 2011). Decreased feed conversion efficiency and daily weight increase the results of the feed intake reduction (Herbut *et al*., 2019). More broadly, lower feed intake caused by heat stress in all livestock species results in decreased milk, meat, and egg production, which in turn causes additional economic losses.

Studies show that compared to other U.S. livestock sectors, the dairy business has more economic losses as a result of heat stress (St-Pierre *et al*., 2003). Dairy cows who are under heat stress consume less dry feed, which accounts for around 35% of the drop in milk output (Rhoads *et al*., 2009). The most prolific breeds also show greater vulnerability to heat stress since they are bigger and produce more metabolic heat than lower-producing dairy cow types (Rojas-Downing *et al*., 2017). As a result, milk production decreases when metabolic heat generation driven by heat stress rises (Kadzere *et al*., 2002). Heat and humidity have impacts on milk composition in addition to milk output. According to Gorniak *et al*. (2014), nursing cows begin to experience heat stress at a temperature-humidity index of 72, and when the index rises over this point, milk protein and milk fat content decrease. Identical modifications to milk composition have been found for dairy goats (Seerapu *et al*., 2015) and buffaloes (Gonzalez-Rivas *et al*., 2020) but have only been narrowly studied.

For all of the main commercial livestock varieties, heat stress has been proven to have an impact on meat output (Gonzalez-Rivas *et al*., 2020). Ruminants under heat stress had smaller bodies, lighter carcasses, thinner fat layers, and worse meat quality (Summer *et al*., 2019). According to research by Berihulay *et al*. (2019), small ruminants like goats and sheep have been proven to be better suited to hot and humid climates. However, because they are grown with increased exposure to abrasive radiant surfaces and given high-energy diets, feedlot cattle have been proven to be more sensitive (Silanikove 2000). Pigs demonstrate decreased carcass weight and meat quality when exposed to high temperatures, much like ruminants do (Pearce *et al*., 2013). Under high ambient temperatures, they have also been found to exhibit reduced average daily gain of 9.8% when compared to thermoneutral animals (da Fonseca de Oliveira *et al*., 2019). When compared to thermoneutral animals, they have been discovered to have a lower average daily growth of 9.8% at high ambient temperatures (da Fonseca de Oliveira *et al*., 2019).

According to Zaboli *et al*. (2019), chickens under heat stress need more energy to maintain thermoneutral circumstances at the price of development. According to Shakeri *et al*. (2018), heat-stressed broilers had lower weight gains, feed conversion rates, protein concentrations, and breast muscle weight. According to Mignon-Grastaeu *et al*. (2015), laying hen features that are more responsive to heat stress include eggshell strength, daily feed intake, egg mass, and egg output. Breeders are also showing major losses in egg output and eggshell quality, according to Oguntunji and Alabi (2010). Changes in dietary calcium can influence the decline in egg quality and production brought on by heat stress (He *et al*., 2018).

Both sexes are affected by how much heat is present. Heat stress affects females differently than men, reducing the estrous cycle and fertility while raising the risk of anestrous and fetal mortality. Semen quality, testicular size, and the amount of viable sperm all drop in males. According to Ross *et al*. (2017), there are notable seasonal changes in reproductive performance in both sexes. Heat stress has an impact on poultry reproduction as well, however, birds may perform differently than mammals. According to Nawab *et al*. (2018), male broilers are more susceptible to heat-related infertility than female broilers. According to Ayo *et al*. (2011), environmental stress in layers may cause ovulation to take longer, diminish the quality of the yolk, and impact hatchability.

Alternative feed resources mitigating the impacts of climate change on feed availability and quality

Mitigating the impacts of climate change on feed availability and quality requires exploring alternative feed resources that are more resilient to changing environmental conditions. Farmers are exposed to the effects of climate change, including unpredictable weather patterns, droughts, and diminishing pasture production. These difficulties have caused a shortage of feed and an increase in feed prices, endangering cattle production and livelihoods. It is possible to increase these farmers' adaptability and resilience by utilizing non-traditional feed supplies (FAO, 2018).

Insects as feed: Black soldier fly's larvae and mealworms, among other insects, are two examples of insects that provide a viable alternative source of protein and minerals for livestock. They offer a possible alternative protein source for the manufacturing of animal feed. They may be raised on a variety of organic waste streams to promote a circular economy (Newton *et al*., 2005). Belhadj *et al*., (2023) reported that grasshoppers, houseflies, beetles, silkworms, earthworms, and crickets, are in the sustainability spotlight as important sources of animal proteins for poultry. They meet the required nutrient requirements: protein, and amino acid, easily digested and accepted. They have a low carbon footprint and good feed conversion efficiency (van Huis *et al*., 2013). The use of insect-based feed can ease the strain on conventional feed crops, resulting in more sustainably produced feed. Edible insects need processing methods to increase their application for food/feed and they are insects are becoming more accepted as potential protein sources for feed since they are sustainable (Lange, 2021). High or low-temperature, drying, fermentation and proteolysis methods are being used for processing (Liceaga, 2021). The crude protein of some insect meal are as shown in Table 1.

Aquatic plants and algae as a supplement to nutrition: Duckweed and spirulina are two examples of aquatic plants and algae that are high in protein and other necessary minerals. They may be grown in ponds and other bodies of water, offering animals in places with little arable land a sustainable supply of food (Van der Spiegel *et al*., 2013). The quality of animal feed can be increased by supplementing animal diets with marine and freshwater algae, which are both high in vital nutrients (Wan *et al*., 2019). Algae are a climate-resilient alternative feed choice since they can be grown on little area and with little water. Proximate composition of water hyacinth is shown in Table 2.

Agro-industrial byproducts: Using agro-industrial byproducts as animal feed, such as maize stover, wheat bran, and rice bran, can decrease waste and enhance the supply of food (Zahari and Wang 2009). These wastes can serve as a sustainable supply of feed components and frequently include significant nutrients. For example, the use of brewery waste (Rachwał *et al*., 2020), rice bran (Fabian *et al*., 2011), wheat bran (Prueckler *et al*., 2014), palm kernel cake (Ojediran *et al*., 2020), biscuit waste dough (Shittu *et al*., 2016; Ojediran *et al*., 2019), cashew kernel waste meal (Ojediran *et al*., 2021; Ojediran *et al*., 2022b), cassava vinass (Ojediran *et al*., 2019), cassava distillers waste (Ojediran *et al*., 2022a) and other agro-industrial byproducts have the potential to be used as alternative feed sources. These materials can be utilized as supplemental feed to promote animal nutrition and are easily accessible in many areas (Devendra and Leng, 2011). The proximate composition of some agro-industrial byproducts is shown in Table 3.

Table 1. Crude protein content of some insect meals

Name	Scientific name	Crude protein (%)	References
Black soldier fly	*Hermetia illucens*	32-61	Chu *et al.* (2020); Liu *et al.* (2021)
Grasshoppers	*Orthoptera*	48-65	Amobi *et al.* (2020)
Silkworm	*Bombyx mori*	46-72	Jintasataporn (2012)
Earthworm	*Eisenia fetida*	41-66	Janković *et al*., 2020; Heuzé *et al*., 2020)
Housefly	*Musca domestica*	40-64	Elahi *et al.* (2020)

Table 2. Proximate composition of water hyacinth and Botryococcus braunii algae.

Proximate composition	Crude protein (%)	Ether extract (%)	Crude fibre (%)	Ash (%)	Moisture (%)	Reference
Hyacinth (*Eicchornia crassipes*)	8.20	2.21	21.42	18.10	89.21	Suleiman *et al.* (2020)
Algae (Botryococcus braunii)	25-56	2-22	-	-	-	Tavakoli *et al.* (2021)

Table 3. Proximate composition of some agro-industrial byproduct.

Agro-industrial byproducts	Crude protein (%)	Ether extract (%)	Crude fibre (%)	Ash (%)	Moisture (%)	Reference
Brewery waste	24.30	5.20	19.66	5.77	79.19	Yitayew *et al.* (2022)
Rice bran	17.50	13.10	23.33	4.92	4.30	Mansoor *et al.* 2023)
Wheat bran	17.10	2.11	11.25	6.11	3.10	Prueckler *et al.* 2014
Palm kernel cake	15.75	12.23	21.42	1.40	9.42	Ojediran *et al.* (2020)
Biscuit waste dough	19.4	3.87	4.18	7.00	9.91	Shittu *et al.* (2016); Ojediran *et al.* (2019)
Cashew kernel waste meal	21.10	35.09	6.83	4.10	9.20	Ojediran *et al.* (2021); Ojediran *et al.* (2022b)
Cassava distillers waste	11.82	2.83	34.86	3.54	10.10	Ojediran *et al.* (2022a)
Cassava vinnase	19.26	3.72	7.96	9.33	5.68	Ojediran *et al.* (2019)

Hydropogenic feed production:

Fodder produced hydroponically is made by sprouting grains in a small amount of water and soil. For animals, it offers a year-round supply of fresh, wholesome feed (Biswas and Goswami 2019). During droughts or when traditional forage supply is constrained owing to the effects of climate change, hydroponic fodder can be very beneficial. The proximate composition of hydroponically produced maize fodder is shown on Table 4.

Table 4. Proximate composition of hydroponically produced maize fodder.

Hydroponically produced	Crude protein (%)	Ether extract (%)	Crude fibre (%)	Ash (%)	Moisture (%)	Reference
Maize fodder	12.42	2.67	9.50	2.77	83.22	Rachel *et al.* (2020)

Breeding and growing climate-resilient forage crops, such as specific types of grasses and legumes, can increase the availability and quality of feed in the face of changing climatic circumstances (Shaoo 2018). These plants are able to endure changes in humidity and temperature.

Silvopastoral systems: According to Sinclair *et al.* (2019), silvopastoral systems mix trees, forage crops, and livestock grazing to provide feed in a sustainable and climate-resilient manner. To boost feed growth and cattle welfare, trees offer shade, lessen heat stress, and enhance soil quality.

Climate-resilient livestock feeding strategies

Climate-resilient livestock feeding strategies are essential to mitigate the impacts of climate change on feed availability and quality while ensuring the well-being and productivity of livestock by ensuring a consistent supply of nutritious feed, reducing heat stress, and maintaining hydration, which supports overall health and productivity.

Improved Grazing Management: Rotational grazing and intensive grazing techniques can boost soil health, encourage better plant development, and increase fodder consumption, making grazing systems more robust (Teague *et al.*, 2011).

Drought-Tolerant Forage Species: Cultivating drought-tolerant forage species in animal diets can assist preserve feed availability during times of water shortage. Examples of such species include several types of grasses and legumes such as sorghum, pearl millet, Rhodes grass, leucaena, buffel grass, alfalfa, and teff grass (Koura *et al.*, 2022)

Supplemental nutrition: Improving livestock resistance to shifting environmental circumstances by balancing animal diets with the right nutritional supplements. Animal health and production can be increased by supplementing with minerals, vitamins, and vital nutrients (NRC, 2000) and amino acids with low crude protein diet.

Utilization of byproducts: According to Jayasuriya *et al.* (2012), using agro-industrial byproducts and crop residues such as groundnut shells, pineapple waste, citrus pulp, and so on as feed resources can help minimize the reliance on conventional feed crops and offer other sources of nutrition for livestock.

Integrated crop-livestock systems: Livestock can graze crop leftovers and gain from cover crops and intercropping methods in integrated crop-livestock systems, which can increase feed availability (Gómez-Mason *et al.*, 2015).

Efficient feed conversion: Increasing feed efficiency by enhancing management techniques, genetic selection, and precision feeding can lessen the demand for feed resources as a whole (Arche *et al.*, 1999).

Climate-resilient forage crops: In the face of climate change, feed supply and quality may be improved by choosing and developing forage crops that are more resistant to heat, drought, and pests (Tester and Langridge, 2010).

Isolated positive impact of climate change to livestock farmers

The implications of climate change on agriculture, particularly livestock farming, are generally negative, notwithstanding the possibility that there may be a few small gains for livestock producers in some places or under particular circumstances. Farmers who raise livestock face a variety of difficulties as a result of climate change, such as increased heat stress in animals, altered precipitation patterns, and changes in the distribution of pests and diseases (Thornton *et al.*, 2014). However, there may be some beneficial impacts, though isolated:

Extended grazing seasons: Livestock farmers may see extended grazing times in areas where warmer temperatures and changed precipitation patterns result in longer growing seasons and postponed frosts (Derner *et al.*, 2018). This could lessen the demand for stockpiled feed at specific seasons of the year.

Extension of areas with sufficient climate for specific types of livestock farming: In some locations, climate change may result in the extension of areas with sufficient climate for specific types of livestock farming (Thornton and Gerber, 2010). For instance, in some locations, warmer temperatures and more rain may encourage the development of novel fodder species or enable farmers to cultivate cattle breeds that were previously unsuitable for those environments.

It is important to understand that any possible advantages of climate change for livestock producers are likely to be isolated and may be exceeded by the general negative effects on agriculture, such as decreased feed quality, increased animal heat stress, and water shortages. The long-term sustainability of cattle production and global food security are also seriously threatened by climate change (Fonta *et al.*, 2011).

Socio-economic implications of adopting alternative feed resources in the era of climate change

The livestock sector significantly contributes to greenhouse gas emissions through feed production, processing, and animal digestion, which is a pressing worldwide concern (Gerber *et al.*, 2013). In addition to promoting livelihoods and food security, the use of alternate feed resources may assist reduce the sector's negative environmental effects (Herrero *et al.*, 2016).

Reduced emissions of greenhouse gases: It has been demonstrated that alternative feed sources, such as insects, algae, and byproducts from the food and biofuel sectors, emit fewer greenhouse gases than conventional feed sources (Makkar and Ankers, 2014). Emissions can be decreased and so help with efforts to mitigate climate change by incorporating these alternative feeds into animal operations (FAO, 2019).

Improved livelihood possibilities: For small-scale farmers and business owners, the use of alternate feed supplies may open up new economic prospects. As an illustration, insect farming can offer job and income diversification in rural regions (van Huis 2013). According to McMichael *et al.* (2007), this economic diversification can improve local economies and lessen their susceptibility to climate-related shocks.

Sustainable land use: The burden on land usage for feed production can be eased by employing alternative feed supplies, such as food waste or agricultural byproducts (Karimi *et al.*, 2018). This might result in better ecosystem services and biodiversity preservation, as well as more sustainable land management techniques including reforestation and afforestation (Haase 2021).

Challenges in adopting alternative feed resources

Technological and infrastructural constraints:

Alternative feed resource systems sometimes involve new infrastructure and technology, which can be expensive and difficult to obtain, particularly for small-scale farmers (Spranghers *et al*., 2017). To make these technologies more available and inexpensive, governments and development organizations need to spend money on research and development.

Consumer acceptance and purchasing patterns:

Market acceptability and customer behavior also have an impact on how well alternative feed is adopted. The industry's expansion depends on consumers' readiness to accept novel protein sources, such insect-based diets (Siddiqui *et al*., 2022). To encourage consumer adoption of alternate feed sources, awareness-building and benefit promotion are crucial.

Conclusions

Exploring alternative feed resources is becoming increasingly crucial in the era of climate change, therefore, by embracing these innovative approaches, the agricultural sector can build resilience, reduce environmental impacts, and secure food supplies amidst the challenges of climate change. Furthermore, insect-based feed, hydroponic fodders, agro-industrial byproducts, aquatic plants and algae, among others can be used as substitutes in the era of climate change.

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