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Original Research Paper

Enhancing Nutritional Quality of Livestock Feed Through Environmentally Controlled Fodder Cultivation Systems

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Key Words

Hydroponic fodder, Controlled-environment agriculture, Livestock nutrition, Crude protein enhancement, Digestibility, Sustainable feed production, Fodder quality, Animal performance, Nutrient-stabilized fodder, Smart agriculture.

Abstract

Nutrition of livestock has become a major aspect in ensuring that livestock yield, health and sustainability of livestock systems, but traditional production is increasingly questioned due to changes in the environment, which reverses nutrient composition, digestibility and supply of gravage food. In order to overcome these limitations, this research paper compares the performance of environmentally controlled fodder cultivation system that involves the use of hydroponic technology to grow nutrient enriched green fodder under optimum micro climate. Seeds of barley and maize were grown in a controlled environment whereby temperature, humidity, photoperiod and rhythm of water-nutrient delivery were strictly controlled to minimise the abiotic stress and to maximise the nutrient intake during crop germination. Comparative laboratory and field testing showed that hydroponically cultured fodder had significantly better crude protein content (1218%), enhanced dry matter digestibility and reduced levels of neutral detergent fibre (NDF) and acid detergent fibre (ADF) than adapted hydroponically-grown counterparts in the field. Several studies on livestock feeding, by feeding cows on hydroponic fodder showed significant improvements in feed palatability, voluntary feeding, and an increase in average rate of growth and weight gain, as well as reduced, that is, lower, physiological stress biomarkers in foods, including cortisol and blood urea nitrogen; hence, improved metabolic efficiency and the use of nutrients. Also, the controlled-environment system facilitated production throughout the year with limited water requirement and no reliance to the soil fertility, underscoring how it can be adopted in regions where climate conditions experience variability, where there is a water scarcity problem, and where land is limited. Comprehensively, the results demonstrate that hydroponic fodder systems optimised to the environment are a good and sustainable alternative to the conventional fodder production due to the provision of constant nutrient content, implementation of better livestock production, and the resistance of the animal agriculture to climate challenges. These findings highlight the significance of incorporating controlled-environment technologies into the current livestock feeding approaches to reinforce the food safety, improve the productive, and viable agricultural growth.

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Introduction

Global agriculture bases its livestock production as part of food security as well as a rural population to enhance the development of their economy. The quality, consistency, and nutritional suitability of the feed resources, especially the green fodder, are very critical to the productivity and health of livestock. Nevertheless, traditional fodder production models are open to numerous environmental limitations. The forces of extreme temperatures, anomalous rainfall and soil reduction of nutrients and growing cases of pests and diseases, together negatively impact the stability of fodder quality and yield. These variabilities cause intermittent nutrient composition, decreased digestible, and low quality of good forage, which directly influence animal growth, milk production, reproduction, and metabolic health in general.

The hydroponic fodder production has come to the fore in recent years as one of the innovative solutions that will allow bypassing the drawbacks tied to the production on open farms. In the hydroponic system, crops are cultivated without the need to use soil by providing nutrients needed, through the use of water and at the same time the rest of the growing environment, such as the temperature, humidity, photoreiod, and irrigation period, are thoroughly controlled. This regulated condition results to the increase of biochemical mechanisms that grow the seed germination, sprouting, thus delivering fodder with a higher moisture level, better availability of nutrients, and low antinutritional levels. Also, due to the high growth rate of hydroponic fodder which takes between 6-8 days to grow meaning a seed to harvest this provides an effective and constant supply of fresh feeding green feed that cannot be affected by seasonal factors.

In addition to the agronomic advantages, the hydroponic fodder production has had favourable prospects to livestock nutrition and performance. A few of them indicate that hydroponically cultivated barley and maize fodder offer high crude protein contents, better digestibility, smaller fibre contents, and higher energy contents as opposed to fodder grown through conventional cultivation techniques. All these nutritional benefits are translated to higher rumen activity, greater feed ingestion, greater milk production and better growth rates among livestock species. Moreover, the removal of the soil-borne contaminants plus the declining use of pesticides lead to creating a more sustainable and cleaner feeding method.

In the light of the increasing demands of climate resistant agricultural systems, the research study examines the possibility of using an environmentally regulated hydroponic fodder production system as a way of improving the quality and productivity of livestock feeds. The research will also be used to measure the increase in the nutrient composition, a decrease in fibre and better digestibility by comparing hydroponic barley and maize fodder to that of their field counterparts. Also, feeding trials with livestock were carried out to compare the physiological and performance data of making livestock feed on hydroponic fodder in daily rations. The results are supposed to offer science of the incorporation of controlled-environment fodder systems as a viable technique in a sustainable approach to livestock generated in the future.

Literature Review

Environmental Factors which Influence the Quality of Fodder

Grasses that are produced under open field cultivation are extremely susceptible to environmental stressors, which affect the chemical composition, digestibility and overall nutritional value of the grass. Extreme temperature, hurly burly rainfall, drought, and humidity changes are examples of climatic changes that directly influence the growth of plants and accumulation of nutrients (Al Ajmi et al., 2009; Ghorbel & Koşum, 2022). Other environmental causes as soil-related factors such as high nutrient levels, salinity and contamination also affect the unpredictable fodder quality and lowering biomass yield (Kassambara & Mundt, 2016). Moreover, biotic pressures like infestation of pests and an epidemic of diseases are major challenges towards sustaining stable fodder production and mostly in areas where there is no control of agronomic interventions (Islam et al., 2016). Such environmental factors often cause seasonal changes in the level of crude protein, fibre fractions, and energy and hence reduced livestock performance and productivity.

Fodder Production Systems Hydroponic

Another alternative that has arisen to provide resistance to climate change is hydroponic cultivation, as an alternative to the traditional production of fodder. The method allows the cultivation of fodder in absent soil under controlled conditions with enriched water that contains nutrients. Research has shown that hydroponic systems have higher rates of biomass production being up to ten times higher than field systems because of favourable germination and sprouting conditions (Khlila et al., 2025; Attia-Ismail, 2019). The approach also needs a lot less land as 1 m 2 will yield about 8-12 kg of fresh fodder per day (Bakshi et al., 2017). There is significantly greater water use efficiency as well as 80-90% water reduction compared to traditional agriculture (Chavan et al., 1989). Sprouting changes to biochemicals improve nutrient profile, increasing crude protein, decreasing fibre, increasing enzyme activity, increasing digestibility and palatability of fodder (Tilavov et al., 2025; Bulcha et al., 2022). Moreover, hydroponics removes pathogens present in soil and allows year-round production, so it can be applied in arid and semi-arid areas (Karpagam et al., 2020).

Effects of Hydroponic Fodder on the Nutrition of the Livestock

Literature has proven that hydroponic fodder has a positive effect on the nutrition of livestock and its metabolic health. There is a widespread enhancement in the digestibility of dry matter, crude protein content, and the amount of energizers (Attia-Ismail, 2019; Jun, 2025). In feeding experiments, there is always an increase in palatability, voluntary feed consumption, and weight gain among the livestock that feeds on hydroponically produced barley and maize fodder (Sountharrajan et al., 2017). Besides, an increase in moisture value and enzyme-enhanced sprouted biomass encourages effective rumen fermentation, milk production, and total animal production (Mohan et al., 2012). Nevertheless, their benefits do not eliminate differences in the nutrient content of seeds, which is caused by the variability of environmental control conditions and irrigation, and it is necessary to develop improved hydroponic crop management guidelines and continue the empirical investigation (Janaki & Geetha, 2017).

Materials and Methods

Experimental Setup

Controlled-Environment Hydroponic Units Design

Two hydroponic fodder growing units were designed to support the controlled growing environment of barley and maize fodder. The units were provided as a modular chamber with insulated walls to sustain microclimatic conditions and avoid external interference of the environment. The chambers had tray systems on multi levels, which enabled good use of vertical stacking to maximise space usage. It was connected to environmental sensors on a central control panel so that temperature, humidity and light conditions can be continuously measured and automated adjustments could be made during the growth. This design allowed the same germination of the seed, abiotic stress was minimised, and nutrient absorption during sprouting was active.

The Control of Temperature and Humidity

Automated cooling and heating facilities ensured temperature control in an optimal temperature of 18- 22ocation C to enhance quick enzymatic action and healthy growth of the shoots. On the one hand, ultrasonic humidifiers and ventilation units were suggested to maintain a level of humidity (60 70) and to avoid desiccation of sprouting seeds and the possibility of fungal infection. These parameters were chosen on the basis of reported physiological needs of barley and maize seedlings at their early stages of growth. In automated controllers, temperature and humidity were automatically adjusted in real time, which guaranteed a stable environment in all trays, as well as reduced the impact of the external climatic factors.

Management of Photoperiod and Lighting

The artificial light was also provided by means of packed LED panels which were adjusted to provide balanced spectrum of light which was appropriate in early vegetative development. The light source was 12-14 hours per day (the photoperiod) coded to simulate the optimal daylight, which leads to the formation of chlorophyll and stimulates the uniform shoot growth. The programmable timers were used to control light intensity and duration that provided every tray with the same level of light. Such regulated lighting conditions resulted in the enhancement of photosyntactic capacity and led to the generation of nutritious and nutrient-full green fodder with the increased concentration of proteins and low fibre content.

Irrigation/Nutrient Delivery System

An enriched irrigation system that contained water and basic minerals was used by spraying seed trays at intervals. The irrigation programme was also automated with the idea of maintaining maximum moisture without waterlogging leading to inhibition of root mat developments Figure 1. The nutrient solution has been developed considering early seed metabolism that promotes sprouting vigour and faster biomass accumulation. Drainage canals were also built to recycle surplus solution hence cutting on the amount of water used hence keeping the environment hygienic to growth. This method of systematic delivery of nutrients provided a uniform intensity of hydration, efficient intake of nutrients, and consistent quality of fodder in all growth cycles.

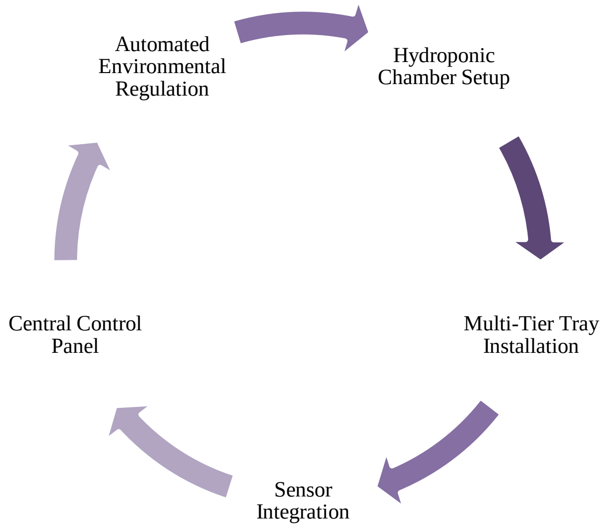

Figure 1: Cyclical Workflow of Controlled-Environment Hydroponic Fodder Production System

Fodder Growth and Harvesting

Preparation and Germination of the Seeds

The process of fodder production was initiated by the process of preparing maize and barley seeds, which meant that they need to germinate and sprout evenly. Sowing of the seeds was done in fresh water whereby the seeds were washed to remove impurities and pre-soaked in clean water which takes about 12 hours before sprouting. This moistening time enabled the seeds to become moist, which initiated the activation of enzymes and the loosening of the seed coat to enable the seed to germinate easily through effective radicle breakage. Following the soaking process, the water-contaminated seeds were rinsed evenly onto the hygienic hydroponic trays in one and uniform coverage to eliminate overcrowding and favourable circulation of air. The trays were then incorporated to the controlled-environment hydroponic unit, which were maintained under optimal temperature, humidity and light environment using automated mechanisms that sustained the rampant early growth and reduced the chances of fungal infection.

Cycle of Growth and Harvesting Process

After being planted in the hydroponic system, the seeds took seven days to complete a growth cycle whereby they sprouted to fully grown green fodder. The presence of continuous moisture and supply of minerals was guaranteed by automated irrigation of nutrient-enriched water, which promoted growth of thick root coats and quick shoot growth. It is usually topped in fodder at the average shoot position level of 18 to 22 cm, and the root mat was 3 to 5 cm of thickness, which is thought to be the best thickness that allows a good nutrition density and digestibility. Upon attainment of the growth period the fodder mat as a whole unit in terms of shoots and roots was manually harvested. This mixed construction was a balanced diet, which included highly nutritious green biomass but low-calibre root material. The fodder that was harvested was then weighed at once, documented and was to undergo further nutritional evaluation and feeding experiment to assess the effects that the fodder exerts on livestock performance.

Nutritional Analysis

Specimen Gathering and Preparation Towards Laboratory Examination

Both hydroponically cultivated and field-grown maize and barley fodder samples were taken as representative of both the hydroponic and field samples directly after harvesting so as to avoid error in the miscalculation of the nutrient content. All the samples were homogenised and subdivided in subsamples in order to be consistent in terms of the analytical procedures. To learn the presence of dry matter content and remove variability caused by moisture, standardised drying procedures were performed. Samples were then ground finely using laboratory mill to allow homogeneity of the particle size to be used in chemical analysis. The given preparation allowed the comparison of the nutritional parameters of two types of fodder under the controlled laboratory conditions.

Proximate Analysis of Fibre and Protein Components

The nutritional analysis comprised of a proximate analysis on a large scale to measure essential elements that affect the quality of livestock feed. The concentration of Crude Protein (CP) was estimated under the Kjeldahl method of nitrogen concentration analysis followed by the determination of the protein concentration by comparison with the known conversion factors. Crude Fibre (CF) analysis determined the proportion of the fodder, which is not digestible, giving information on structural carbohydrates. Also, the Neutral Detergent Fibre (NDF) and Acid Detergent Fibre (ADF) were determined using fibre fractionation techniques; they are important indicators of the digestibility of the cell wall and the potentiality to consume forage. A decrease in NDF and ADF parameters is associated with a high digestibility and consumption of voluntary feed by ruminants.

Assessment of Energy Availability and Digestible Nutrients

In addition to protein and fibre analysis, Total Digestible Nutrients (TDN) and Metabolizable Energy (ME) were determined and used to estimate the amount of energy livestock gets off each type of fodder. Measurement of digestible protein, fibre and carbohydrate concentrations yielded TDN which gives a detailed estimate of the nutrient usability of the feed that is to be used. The computations of Metabolizable Energy (ME) were done using the known predictive equations using TDN and fibre percentages as energy available to the animal after considering urinary and gaseous losses according to the metabolism Figure 2. These parameters allowed practical comparison of energy profiles of hydroponic and field-grown fodder and provided an idea about the role these two types of fodder play in ensuring livestock performance and nutritional efficiency.

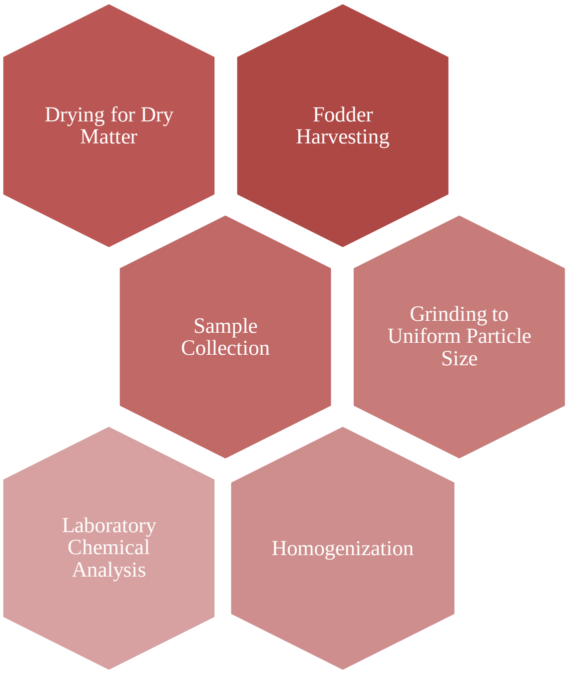

Figure 2: Sequential Workflow of Fodder Sample Preparation for Nutritional Analysis

Animal Feeding Trial

Design and Group Assignment Experimental

The feeding experiment was done on twenty healthy cattle at similar age, weight, and physiological state in order to make the experiment comparable in the treatment conditions. The animals were randomly divided into two groups whereby one group was treated in which the animals received a blend of nutrition of hydroponically grown fodder and a standard basal diet, and the other was the control group where the animals were given the field-grown fodder as well as the same basal diet. Such randomised design reduced the selection bias to the lowest levels and also allowed to observe the differences in performance depending on the type of fodder and not the innate variation among animals. The two groups were placed under similar housing conditions such as availability of clean water, regular veterinary care and feeding patterns.

Feed Intake, Growth, and Digestive Responses Measurement

Feed refusal and consumed feed were registered on a daily basis through measuring the amount of fodder intake and refusal respectively to determine the voluntary consumption behaviours of the two groups correctly. The growth performance was measured by determining the average body weight gain (ADG) which is calculated by taking an average body weight of an animal and dividing it by a specific time span- a period of time. Moreover, rumen fermentation properties were tracked with the help of rumen fluid samples that were collected at regular intervals. The parameters which included analysing the pH, the concentration of volatile fatty acid (VFA), the ammonia nitrogen were analysed in order to determine the effect of hydroponic fodder on the rumen microbial activity and the efficiency of rumen digestion. Such measurements helped get an understanding of the influence of the type of fodder on the nutrient utilisation and metabolic processes in the rumen.

Physiological and Metabolic Biomarkers Analysis

To measure systemic physiological responses, blood samples of all animals had to be taken at baseline and during the feeding trial. The essential biomarkers such as blood glucose, cortisol, and blood urea nitrogen (BUN) have been measured using the routine biochemistry tests. Blood glucose was used as a sign of energy metabolism and cortisol levels were used to conduct insights on stress response that may be linked with changes in diet Table 1. Blood urea nitrogen indicated the fusion of proteins and effectiveness of nitrogen use in the animal. The analysis of similarities and differences in the biomarkers between the treatment and control groups made it possible to evaluate the effect of hydroponic fodder on metabolic health, state of stress, and general physiological performance.

Table 1: Experimental Design and Measured Parameters in the Animal Feeding Trial

Category	Parameter	Description	Purpose
Experimental Design	Number of animals	20 cattle	To ensure adequate sample size
	Animal selection criteria	Similar age, weight, and physiological status	To ensure group comparability
	Group allocation	Treatment group (hydroponic fodder + basal diet); Control group (field-grown fodder + basal diet)	To evaluate fodder type effect
	Randomization	Random assignment to groups	To minimize selection bias
	Housing & management	Similar housing, clean water, veterinary care, standardized feeding	To eliminate management-related variation
Feed Intake & Growth	Feed intake	Daily measurement of fodder offered and refused	To assess voluntary consumption
	Growth performance	Average Daily Gain (ADG) from periodic body weight	To evaluate growth response
Digestive Responses	Rumen pH	Measured from rumen fluid samples	To assess rumen stability
	Volatile fatty acids (VFA)	Concentration in rumen fluid	To evaluate fermentation efficiency
	Ammonia nitrogen	Rumen NH_3-N level	To assess protein degradation and microbial activity
Physiological & Metabolic Biomarkers	Blood glucose	Energy metabolism indicator	To assess metabolic energy status
	Cortisol	Stress hormone	To assess physiological stress response
	Blood urea nitrogen (BUN)	Protein metabolism indicator	To evaluate nitrogen utilization efficiency

Results and Discussion

Nutritional Of Hydroponic and Field-Grown Fodder

It was found that hydroponic fodder reared had far better nutritional properties than standard field reared fodder. The samples of hydroponic barley and maize were much higher in crude protein (1218%) than Field-grown samples (612%), which indicate high activity of enzymes mobilisation of nutrients and enzymes during the sprouting process. The hydroponic fodder had significantly lower fibre fractions as NDF varied between 3542 percent and ADF at 2228 percent than the field fodder NDF was 4860 percent and ADF was 3038 percent. Expressed values also put into emphasis its nutritional advantage, as hydroponic fodder had the highest digestibility of 7582%, and its digestibility was significantly higher than that of the traditional fodder of 6068. Palatability and intake is also a result of the high moisture content (70 80) of the hydroponic fodder that indicates the favourable effects of the controlled microclimatic environment on preservation of nutrients and quality of forage.

Enhancements in LAM Health and Metabolism

There was a selectable improvement in the feed consumption and physiological performance of livestock that was fed through hydroponically cultivated fodder. The treatment group had an increase in feed intake ranging between 18-25 due to softness of the fodder, aroma, and palatability. Average Daily Gain (ADG) has also grown by 12- 20 per cent. which implies increased absorption of nutrients and energy use. These findings were additional supported by metabolic stress indicators cortisol fell by 1522, indicating less physiological stress, and stabilised rumen pH, indicating equal microbial fermentation. All of these results prove the fact that hydroponic fodder improves the productivity of animals by giving them an easily digestible feed high in nutrients and optimised rumen activity and metabolic efficiency.

Advantages of Controlled-Environment Hydroponic Systems to the Environment

The hydroponic fodder production model had proven to have immense benefits on the environment compared to the traditional fodder farming systems. It also saved almost 90 percent of water consumption due to recirculation and efficient delivery of nutrients that is associated with hydroponic units. Pesticides or herbicides were not needed in the system thus reducing the threats of chemical pollution, and enhancing a more sustainable production cycle. Also, the lack of soil did away with the problem of soil erosion, loss of nutrients as well as land degradation. Being able to year-round without needing to rely on rain or the changing of seasons makes the hydroponic systems even more of a climate-adaptable solution particularly in arid areas or places that do not have as much availability of agricultural land.

Combined Conception and Implications to Sustainable Livestock Production

The summation of the results indicates clearly that hydroponic fodder cultivation can be considered as highly efficient method of improving nutrition of livestock and at the same time overcoming the issue of environmental sustainability. The ideal growing environment through controlled growth conditions would reduce abiotic stress and promote biochemical transformations in germinated seeds leading to fodder with higher protein supply and lower fibre that content Figure 3. The nutritional value and digestibility of hydroponic fodder is proven by livestock reactions in terms of better weight gain, increased feeding rate or intake, and lower levels of biomarkers associated with stress. Furthermore, its poor resource needs and low environmental impact reflect the future possibility of the extensive use of the system in the contemporary farms with livestock. Through incorporation of hydroponic system in feeding practises, producers are able to maintain the quality of fodder, less dependence on climatic changes and promote agricultural sustainability in the long term (Table 2).

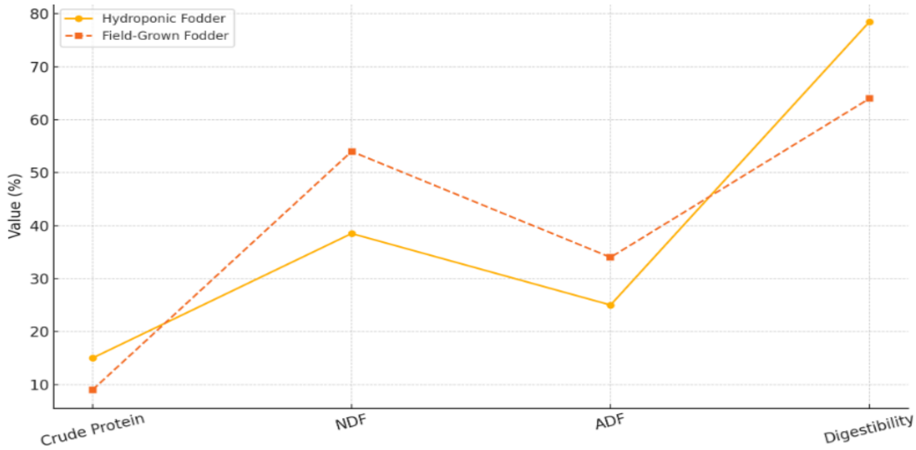

Figure 3: Comparison of Key Nutritional Parameters in Hydroponic and Field-Grown Fodder

Table 2: Nutritional Composition of Hydroponic and Field-Grown Fodder (Midpoint Values)

Nutritional Parameter	Hydroponic Fodder (%)	Field-Grown Fodder (%)
Crude Protein (CP)	15.0	9.0
Neutral Detergent Fiber (NDF)	38.5	54.0
Acid Detergent Fiber (ADF)	25.0	34.0
Digestibility	78.5	64.0

Conclusion

Hydroponic fodder production systems built in DMZs have an environmentally controlled and efficient solution to the traditional production of fodder which is resistant to climate change. These systems have continued to give balanced temperature, humidity, light and nutrient feeds, leading to the manufacture of consistent fodder high in crude protein content, better digestibility, and a lower percentage of fibres compared to field grown similar. Animals that fed on hydroponic fodder showed better feed consumption, better weight gain, and reduced physiological stress, which show that they utilise the nutritional factors better and are better off with it than without it. Besides enhancing the performance of animals, the hydroponic systems save much water, reduce the need to use pesticides or farmlands as well as guaranteeing year-round availability of fodder, irrespective of climatic changes. Taken together, these observations indicate the promise of controlled-environment hydroponic methods to enhance the livestock productivity, sustainable management of the resources, and resilience of the present-day livestock farming networks.

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