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Article *in* Annals of Animal Science · July 2023

DOI: 10.2478/aoas-2023-0075

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ANNALS OF ANIMAL SCIENCE
ISSN: 2300-8733, https://sciendo.com/journal/AOAS

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Received date: 15 December 2022

Accepted date: 26 June 2023

To cite this article: (2023). Pastorelli G., Serra V., Turin L., Attard E. (2023). Hydroponic fodders for livestock production – a review, Annals of Animal Science, DOI: 10.2478/aoas-2023-0075

Hydroponic fodders for livestock production – a review

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Running Head: Hydroponics in Livestock Feeding
DOI: 10.2478/aoas-2023-0075

Abstract

The human population is expected to reach 9.7 billion by 2050. One of the main challenges will be the demand for food and food security. With time farmland is being lost especially due to environmental change and anthropogenic activities. There is huge competition for the utilisation of farmland for human food production, animal feed production, energy production and other sectors that are utilising the farmland. To minimize the competition between human food and animal feed production, in terms of land use, alternative growing systems, such as hydroponics, may serve to address this problem. Hydroponics is a technology of sprouting grains or growing plants in a soilless environment, with only water or nutrient-rich solution. The present review aims to provide an evaluation of hydroponically-sprouted maize and barley in food producing animals, underlining benefits and limitations in its application.

Key words: hydroponic fodder, ruminants, non-ruminants, sustainability, performance

The term "hydroponics" is derived from the Greek phrase 'hydro' which means water and 'ponos' meaning labour, hence referred to as water working. This is also known as a technology of sprouting grains or growing plants in a soilless environment, with only water or a nutrient-rich solution.

In such a soilless agricultural system, the soil is replaced by an inert substrate, which is irrigated by nutrient solutions that contains all the necessary elements required for growth (Gericke 1929). To date, this system has been used, worldwide, for several leafy vegetables and fodder crops. Such fodder crops include mainly those from the *Fabaceae* family, leguminous species such as alfalfa, clover, or cowpeas, and those from the *Poaceae* family, grain species such as barley, oats, wheat, sorghum and corn (Ghorbel et al., 2022).

Hydroponic fodder crops are produced from seeds or grains that are sprouted and grown under optimum conditions in a closed, controlled system within a short period of time. The concept of hydroponic fodder production is relatively old and detailed scenario of the history of hydroponics was recently reviewed by Akkenapally and Lekkala (2021).

The utilization of sprouted fodder was developed in 1699 by an English scientist, Woodward who tried to sprout plants using several water sources (Withrow and Withrow, 1948). Later, in 1800, French scientists De Saussure and Boussingault discovered the importance of elemental substances required for the physiological functioning and growth of plants. Such substances include carbon, hydrogen, oxygen, and nitrogen, and as autotrophs plants can convert these elemental substances into carbohydrates, fats, proteins (including enzymes). In 1860, Sachs and Knop discovered that other macro elements such as phosphorus, sulfur, potassium, calcium and magnesium are also essential and added them to the list previously mentioned by De Saussure and Boussingault. They managed to grow several plant species that were sensitive to deficiencies caused by the lack of the mentioned macro elements (Schwarz, 1995).

Between 1920 and 1930, Gericke further developed techniques for upscaling of such systems with plants in nutrient solutions coining the term "hydroponic" (Butler and Oebker 1962). Since 1950, hydroponic germination chambers have spread from Europe to the United States and, since then, despite contradicting scientific findings on the validity of such a cultivation system, the hydroponic technique has become a reality in many countries around the world (Rodríguez-Muela et al., 2005).

Table 1 reports the increased attention to the hydroponic sector documented by European Union (EU) funded projects (https://cordis.europa.eu/projects/en) in the last 40 years and relative area of application.

Table 1. Area of research and their allocation share (adapted from https://cordis.europa.eu/projects/en)

Area of research	Percentage allocation
Agriculture	67.14%
Aquaponics	11.42%
Energy	4.29%
Other	17.15

The hydroponic fodder system is a potential solution in areas where arable land is scarce and where pasture land is either limited or non-existent. According to the Food and Agriculture Organization of the United Nations, it is predicted that by 2050, the world population will reach nine billion people with two thirds of the population residing in urban settlements. One of the main challenges will be the demand for food and food security. With time farmland is being lost to environmental changes partly due to anthropogenic activities. Climate change, water scarcity, soil and water pollution, desertification are amongst the other factors. Hence, alternative growing systems, such as hydroponics, may serve to address this problem. The production of green fodder using hydroponic systems is a highly efficient process in terms of water saving, as such a system requires only about 2-3% of that water used under field conditions to produce the same amount of fodder (2-3 litres of water vs 55-75 litres of water to generate one kilogram of green fodder) (Al-Karaki and Al-Hashimi, 2012; Velázquez-González et al., 2022). Furthermore, water is often recycled and used several times. This aspect is particularly important in areas suffering from chronic water shortages or where there is no irrigation infrastructure.

Fodder production on agricultural land is a conflicting issue in countries with food shortages. There is continued competition for the utilisation of land for various agricultural activities. The utilisation of land for fodder crop production may be placed second to the utilisation of land for cereal grains, rice, oilseeds, and pulses, used as crops to feed the ever increasing population and to ensure food security. As a result, hydroponic systems have been developed for the production of fresh forage from oats, barley, wheat, and other grains (Rodríguez-Muela et al., 2005). An advantage in terms of land use is that hydroponics production requires only 10 x 5 m to grow 600-650 kg of fodder/day, while one hectare of land would be required under traditional cultivation system to produce the same quantity.

In order to investigate the state of the art and the potential of hydroponic systems in livestock, a preliminary literature search was performed using Scopus database and the web.

Hydroponic" AND (as Boolean operators) "Fodder" restricted to the last ten years were chosen and 92 papers were retrieved. Among them, only one study was a review article and not focused on the use of hydroponic fodders in livestock (Gautam et al., 2021). The web search showed results referred to specific geographical areas (e.g., India, Ethiopia) or focused on a single species, mostly ruminants (Naik et al., 2015; Girma and Gebremariam, 2018; Kumar et al., 2018; Salo, 2019; Suma et al., 2020; Akkenapally and Lekkala, 2021; Hassen and Dawid, 2022).

The present review aims to focus on hydroponically-sprouted maize and barley and to provide a quantitative evaluation of hydroponic fodder in food-producing animals reporting the main effects.

Nutrient changes with sprouting

The seed is packed with numerous nutrients required for the development and growth of the embryo inside, during germination. However, the nutritional value of such grains would increase significantly once germination is triggered. Under such conditions complex proteins, carbohydrates and fats are converted to essential amino acids, sugars, and essential fatty acids, respectively. These changes are triggered by an increase in enzyme levels. During germination, the activation of enzymes, such as amylase and lipase, also increases the sugar and essential fatty acid content of grains (Chavan and Kadam, 1989).

During germination, the seed dry matter content decreases by 7-47%, which is attributed to the physiological and metabolic functions (Suma et al., 2020). Once sown, seeds lose some of the nutrients as imbibition is triggered. Although, this stops after a day, the dry matter (DM) continues to decrease up to 6 to 7 days of growth, mainly due to respiration during the sprouting process (Dung et al., 2005; Fazaeli et al., 2012).

There are several factors that affect the fresh yield and dry matter content of hydroponically-grown fodder. Such factors include those that pertain to the plant species, such as variety, quality and vigour of seed and others related to environmental conditions such as water quality and quantity (pH, frequency of irrigation, nutrient medium), light, temperature, humidity and hygiene (free from pests and diseases) within a controlled environments such as a greenhouse (Molla and Birhan, 2010).

In a study by Islam and co-workers (2016), it was observed that at different time intervals (8th, 9th and 10th day), there were significant differences in the dry matter percentage yield of maize plant and root. For instance, in maize root the yield of DM at 10th day was significantly ($p < 0.01$) higher than those of the other days (Islam et al., 2016).

Consequently, in cereal grains grown under a hydroponic system, the nutrient content may vary over time. In fact, when the starch content decreases in the seed, the total organic matter content and dry matter content also decrease. At this stage, starch is converted into a simpler and more readily available carbohydrate source that is required for the physiological, metabolic and energy processes within the growing plant, leading to cell development, cell wall synthesis, and respiration. Consequently, the utilisation of the starch source is expressed as a decrease in dry matter content. During sprouting the gross energy, metabolizable energy, and total digestible nutrient content decreases, mainly due to the respiratory processes of the plant (Fazaeli et al., 2011).

On the other hand, the components constituting the ether extract of hydroponic fodder (structural lipids and chlorophyll) increase as the plant grows (Hassen and Dawid, 2022). The increase in crude protein (CP) content may be attributed to breakdown of carbohydrates reflected as a loss in dry matter, through respiration during germination. Consequently, the increase in protein content and the decrease in dry matter content are affected significantly with longer sprouting times (Brown et al., 2018).

Several studies have shown that during sprouting, several nutrients, such as amino acids and soluble carbohydrates, become readily available due to the activity of hydrolytic enzymes (Plaza et al., 2003). The progressive decline in the breakdown of dry matter in the sprouting grains takes place during the 7 to 8 day growth cycle for barley and maize. This may be due to an increase in fiber content with age (Islam et al., 2016). According to Peer and Leeson (1985), in barley grain, the amino acid content increased to 70% from day 4 to day 7 after seed germination. Barley fodder protein increases from 2 to 4 per cent in the barley grain seed as a percent of dry matter.

Chavan and Kadam (1989) reported that sprouting cereal grains showed an increased nutritional quality due to an increased availability of essential nutrients, hence increasing the functional properties.

The mineral content may also be affected during this physiological process. Sprouted barley has been reported to contain more Ca, Fe, and Zn than other cereals (Peer and Leeson, 1985). Total digestible nutrients (TDN) as a percent of dry matter can decrease by 10% from the barley grain.

Unlike Dung and co-workers (2010a), Hafla and co-workers (2014) indicated that the benefits of sprouting may be rendered negligible when the total dry matter is lost, leading to no improvement in the concentration or digestibility of nutrients. In the analysis of hydroponic fodder, the apparent increase in nutrient concentrations with a decrease in total dry matter, may be attributed to dry matter exchanges within the sprouting seed.

Chemical composition and nutritive value

The nutrient contents of hydroponics fodder are similar to those of leguminous fodders but superior to certain common non-leguminous fodders (Naik et al., 2014).

Tables 2 and 3 list the hydroponic barley and maize chemical composition expressed on DM basis for a snapshot comparison, respectively.

Table 2. Proximate composition and fiber fractions of hydroponic barley (on DM basis)

DM	CP	OM	CF	EE	Ash	ADF	NDF	Starch	NFE	Reference
18.3	19.8	-	10.4		3.6	11.9	35.4	-		Saidi and Omar (2015)
21.25	10.77	-	-	-	4.21	16.53	33.83	-		Yurtseven et al. (2019)
16.38	23.03	-	-	4.17	3.97		-	-		Abouelezz et al. (2019)
15.83	12.00	-	-	0.51	2.17	5.76	12.73	-		Agius et al. (2019)
-	15.60	-	3.7*	3.30		17.40	34.40	25.80		Soder et al. (2018)
15.40	15.60	-	3.7	3.30	3.60	17.40	34.40	25.80		Heins (2017)
18.00	19.00	-	10.9	-	3.9	11.00	36.00	-		Badran et al. (2017)
15.00	17.50	96.90	1.2 (L)*	-	-	25.80	56.80	-	-	Guerrero-Cervantesa et al. (2016)
15.30	22.50	-	11.4	3.20	-	13.10	32.50	-	-	Ata (2016)
16.00.	14.16	95.25	-	2.42	4.75	17.35	43.68	-	-	Shipard (2005)
15.45	13.72	95.89	16.33	3.72	4.11	-	-	-	-	Reddy et al. (1988)

16.91	-	95.00	19.2	-	-	-	-	-	-	Salo (2019)
14.61	15.58	92.60	-	3.25	4.15	8.45	36.35	-	-	Al-Saadi and Al-Zubiadi (2016)
19.80	-	-	8.00	-	3.60	11.00	35.00	-	-	Abd Rahim and Omar (2015)
14.20	14.44	-	13.50	5.67	3.40	-	-	-	64.66	Weldegerima (2015)
12.00	16.20	95.70	14.50	3.42	4.30	21.00	32.50	-	-	Devendar et al. (2020)
10.21	17.46	95.99	23.26	-	4.01	37.15	67.40	-	52.25	Ansari et al. (2019)
13.64	13.86	-	13.50	5.67	-	-	-	-	63.57	Kide et al. (2015)
19.26	13.69	96.35	-	2.25	3.65	14.35	31.25	-	-	Fazaeli et al. (2011)
13.98	12.76	96.35	-	-	-	-	31.25	-	-	Fazaeli et al. (2021)

ADF: acid detergent fiber; CF: crude fiber; CP: crude protein; DM: dry matter; EE: ether extract; NDF: neutral detergent fiber; NFE: nitrogen free extract; OM: organic matter.

Table 3. Proximate composition and fiber fractions of hydroponic maize (on DM basis)

DM	CP	CF	EE	Ash	ADF	NDF	NFE	Reference
-	13.59	14.14	3.53	3.89	-	-	66.78	Indira et al. (2020)
18.25	14.56	10.00	4.67	2.83	-	-	-	Gebremedhin (2015)
14.80	17.10	-	-	-	-	-	-	Lazo and Gonzabay (2020)
14.01*	13.03	10.40	3.55	1.75	-	-	56.58	Zainab et al. (2020)
16.38	23.03	-	4.17	3.97	-	26.70	-	Abouelezz et al. (2019)
18.00	13.57	14.07	3.49	3.84	-	-	-	Naik et al. (2012)
18.48	16.15	12.46	4.67	2.30	-	-	68.47	Weldegerima (2015)
18.48	12.88	9.31	3.47	2.79	-	-	71.55	Rani et al. (2019)
12.39	12.55	-	-	-	23.16	47.04	-	Upreti et al. (2020)
25.00	13.75	14.77	3.55	3.33	-	-	60.72	Adebiyi et al. (2018)
18.25	14.56	10.00	4.67	-	-	-	68.47	Kide et al. (2015)

18.30	13.30	3.37	3.27	1.75	-	-	75.32	Naik et al. (2015)
23.25	10.55	5.51	4.62	-	-	-	77.52	Jemimah et al. (2018)

ADF: acid detergent fiber; CF: crude fiber; CP: crude protein; DM: dry matter; EE: ether extract; NFE: nitrogen free extract; NDF: neutral detergent fiber.

Biomass yield

Hydroponic technology takes only 8 days to develop seed into fodder, compared to the 45 days required for the conventional growing of forage. The hydroponic cycle is very short, i.e. within seven days the sprouts can be harvested and on the eighth day fed to the dairy cattle (Fazaeli et al., 2011; Dung et al., 2010a; Dung et al., 2010b; Molla and Birhan, 2010; Naik et al., 2012; Agius et al., 2019; Jeton, 2016; Jemimah et al., 2015; FAO 2001). Forage production is accelerated by up to 25% by bringing nutrients directly to plants without developing large root systems exhibited by forage crops (Shit, 2019). A study conducted by Elmulthum and co-workers (2023), evaluating the economic feasibility of hydroponic and conventional green barley forage production, showed that the yield of fodder produced using the hydroponic system has largely exceeded the yield of the forage under the conventional cultivation system by approximately 7.5 fold (411.8 kg/m^2 vs 5.6 kg/m^2). Several studies provide information on the biomass yield and germination cycle for a number of fodder species grown under hydroponic conditions (Table 4).

Table 4. Biomass yield of different hydroponic fodders and corresponding germination cycle length

Fodder species	Biomass yield (kg per kg grain)	Germination cycle (days)	Reference
Barley	8	8 days	Badran (2017)
Barley	8.45	8 days	Sánchez et al. (2013)
Barley	5.21	7 days	Mekonnen et al. (2019)
Barley	5.06	5 days	Murthy et al. (2017)
Oats	6.32	7 days	Mekonnen et al. (2019)
Oats	2.50	7 days	Rahman et al. (2020)
Maize	2.74	7 days	Rahman et al. (2020)
Maize var. BH661	6.63	8 days	Assefa et al. (2020)
Maize	4.82	5 days	Murthy et al. (2017)
Wheat	3.50	7 days	Rahman et al. (2020)
Wheat	5.88	8 days	Sánchez et al. (2013)
Cowpea	7.20	5 days	Murthy et al. (2017)
Maize	4.67	14 days	Ningoji et al. (2020)
Barley	6.62	7 days	Abouelezz et al. (2019)

Palatability

No universally-recognized definition of the term “palatability” exists, but the concept of palatability has been considered as an important factor that affects the potential utilisation of a fodder crop (Marten, 1976).

The term "palatability" typically refers to the qualities of a feed that elicit an animal's sensory response and is thought to be a corollary of the animal's appetite for the feed. Furthermore, it has been demonstrated that physical traits play a role in the sensory response that the feed elicits (Baumont, 1996). The intake rate when the animal is given no choice and the feed preferences when given a choice are two ways that the sensory response elicited by a feed is conveyed.

According to FAO (2001), hydroponic green forage is described as extremely appetizing sprouts that are created by soil-free germination of cereal grains and using water with a mineral nutrient solution. Their heights range from 15 to 20 cm. Hydroponic fodders are highly digestible, appetising and savoured by the animals as sprouts are enzyme-rich feeds (Shipard, 2005). Palatability quality of hydroponic fodder makes it highly competitive for livestock farming. Besides, there is no nutrient wasting as the shoots and roots of the plant are consumed together.

According to Arif and coworkers (2023), the higher DM intake in the goat group fed hydroponic-based diets was due to the high palatability of these feeds, as opposed to the basal diet, which contained 20% of low-digestible wheat straw and may have reduced the diet palatability. The study was conducted on goats fed with different diets containing increasing percentages of hydroponic barley and maize fodders. Similar to this, Ibrahim and colleagues (2001) attributed the better palatability to the higher DM intake in groups fed hydroponic barley fodder. The entire mat, including roots and green sprouts, was eaten by animals. Sprout mat was appealing and edible, which greatly reduced the leftovers when compared to the baseline diet.

Growing Konkan Kanyal goats fed mixed maize and barley hydroponic fodder (20%:20%) reported the highest dry matter intake compared to other treatment groups, mainly attributed to the higher palatability of the diet with the hydroponic fodder (Kide et al., 2015).

The palatability of the hydroponic maize fodder may be due to the high leafy and succulent nature of the hydroponic green fodder, which is low in CF and high NFE content (Jemimah et al., 2020).

However, it has been pointed out by several researchers that hydroponically-grown fodders are susceptible to moulding and to a loss in dry matter content when compared to raw grains. This may be due to the high-water content present in hydroponic fodder. On the other hand, the water content of raw grains is generally low while the subsequent dry matter content is high. Therefore, animals may gain benefit from a balance between the two fodder types and as suggested by Tudor and co-workers (2003) a combination of straw and hydroponic fodder would lead to a decrease in moisture and an increase in dry matter content.

Dosage of hydroponic fodder

The production of hydroponically-grown fodder seems to be suitable for small ruminants as these animals have less dry matter requirements.

As opposed to dry fodder (hay and straw) and concentrates, the fresh hydroponic fodder is more succulent and animals can consume 1-1.5 per cent of their body weight (Jeton, 2016) or 15-25, 0.25-2.0, 1.5-2.0 and 0.1-0.2 kg per animal per day in large ruminants, adult pigs, small ruminants and rabbits, respectively (Jemimah et al., 2015). Table 5 lists doses reported in the FAO Manual (FAO, 2001).

Table 5. Recommended doses according to animal species (FAO, 2001)

Species	Dose, kg/100 kg BW	Note
Dairy cattle	1–2	To be administered as a supplement with barley straw or other source of fibers
Dry cow	0.5	To be administered with good quality fiber
Beef	0.5–2	Supplemented with fiber
Pig	2	Faster growing and better reproductive performance
Horse	1	Add fiber and complete feed. Improvement of performance
Sheep	1–2	Add fiber
Poultry	25 kg / 100 kilos of dry feed	Improvement of feed conversion ratio
Horse	1	Add fiber and complete feed. Improvement of performance
Rabbit	0.5–2*	-

*fattening rabbits accepted up to 180-300 g HF/day (10-12% of live weight); intake of dams in lactation = up to 500 g HF/day.

As a general rule, the ration is increased gradually over a period of 4-5 days as animals need to get used to the fodder gradually (Mijena et al., 2021).

Cost of production

The cost of a hydroponic system can vary, depending on the size, technical features, geographical location, and water and electricity costs.

The cost of hydroponic fodder also depends on the growing area and land availability. In fact, hydroponic systems are advantageous in areas where land availability is limited or is costly. In situations where land is readily available, either as arable land or pasture land, hydroponic fodder is considerably more expensive than conventional feedstuffs and grazing. Economic viability of hydroponic fodder production depends on the type of sprouting system and quality of the grain, which in turn is determined by the germination rate, culturing condition and management (Jemimah et al., 2017).

The cost of hydroponic fodder depends to a great extent (around 90%) on the cost of the seed, which is not normally the case when the seed is cultivated on the farmers' land (Abdula, 2022).

To the best of our knowledge, there is little information on cost/benefit analysis of hydroponic systems applied in animal nutrition in general and no one in Europe.

As the most important aims in agricultural production are increasing the biomass yield and reducing cost of production, it is necessary to manage energy use to decrease environmental footprints of inputs consumption and operating costs. In terms of water productivity, it has been showed that this index in hydroponic forage is very high, as about 287 kg of hydroponic forage is produced per each m^3 of water consumed; this aspect represents one of its important advantages (Ghasemi-Mobtaker et al 2022).

Since electricity is one of the main non-renewable inputs in hydroponic fodder production, the use of solar panels to generate electricity is recommended as sustainable strategy for reducing of electricity consumption and accordingly hydroponic systems' environmental impact (Martinez-Mate et al 2018; Ghasemi-Mobtaker et al 2022).

A study conducted in Greece evaluated the feasibility of a hydroponic greenhouse farm focused on tomatoes production through a cost-benefit analysis during a period of five years (Michalis et al 2022). The analysis showed that the economic viability of the farm is achieved after 4 years from the beginning of its operation, as in the 4th year the initial invested capital of 110.000 € as well as the annual operating costs are fully compensated by the revenues of the farm. This demonstrates that the installation of the greenhouse farm is an economically viable investment option (Michalis et al 2022).

A study performed in USA analysing the costs of production of hydroponic fodder system (dry matter exchange in sprouting the seed, fixed investment cost of purchasing the fodder system, labor needs, seed cost) showed that per lb. of DM produced, the fodder system had a $0.045 cost for investment; $0.23 cost for labor; $0.12 cost for seed; and $0.01 cost for water, electrical and other for a total cost of $0.40 per lb. of DM produced (Tranel, 2013).

In the experiment conducted by Devendar and colleagues (2020) in India, the replacement of concentrate mixture with hydroponic barley fodder in the ration of growing lambs reduced the production cost, as the cost per kg gain was significantly ($p < 0.05$) lower in the lambs fed hydroponic barley when compared to the control group (1.42 vs 1.56 €). This decrease in feed cost per kg gain in lambs fed hydroponic barley could be due to its higher nutrient digestibility, in particular CP digestibility, compared to the concentrate mixture. Similarly, replacement of the concentrate mixture at 25 and 50% levels with hydroponic maize fodder resulted in lower cost of production per kg gain in growing goats compared to control group (1.85 vs 2.05 €) (Dhawale et al., 2018). In the study conducted by Abdel-Wareth and co-workers (2023) on growing rabbits whose diet was replaced with 25% dried hydroponic barley, the cost of total feed was dropped by 7.39%. This decrease was mainly due to the lower price of 1 kg of diet containing hydroponic barley compared with the control diet (0.67 vs 0.72 €).

Supplementation of hydroponic fodder to animal's diets

More recently, several studies performed on animal nutrition reported the following doses of supplementation (Table 6) and relative effects.

Table 6. Doses and main results of hydroponic fodder included in animal diet on performance and quality of derived product

Animal species	Source	Dose	Performance Results	Product Results	Reference
Rabbit	HM	76.78 g and 156 g	Better performance in both HM diet	-	Jemimah et al. (2018)
Ewes	HW	2 kg as fed gestation/lactation	No effect on reproductive parameters; no effect of DMI during trial	-	Guerrero-Cervantesa et al. (2016)
Dairy cow	HB	7.9 kg as fed	↑ CP and CF digestibility and milk yield		Naik et al. (2014)

Dairy cow	HB	11 kg as fed	-	↑ fat milk content	Agius et al. (2019)
Dairy cow	HB	6.2 kg as fed	↓ FI	-	Fazaeli et al. (2011)
Konkan Kanyal goat	HM and HB	CON (finger millet straw) (T0) CON + HM 20% (T1) CON + HB 20% (T2) CON + HM 40% (T3) CON + HB 40% (T4) CON + HM 20% + HB 20% (T5)	↑ DMI (T3 and T5) ↑BWG (T3 and T5) ↑ DM digestibility (T3 and T5) ↑ feed conversion efficiency (T3 and T5)	-	Kide et al. (2015)
Holstein dairy heifers	HB	Substitution corn meal 1.5%–4.5% expressed as DM	No difference; no adverse effects	-	Kim et al. (2020)
Crossbreed piglet	HM	10%, 20 % in the diet	No effects on DWG, FW, FCR 10% HM: highest FW	-	Upreti et al. (2020)
Weaned pig	HM	50%, 100%	↓ FW and WG better FCR in HM 50%	-	Adebiyi et al. (2018)
Dairy cow	HM	1–7 kg	-	↑ Milk protein, fat and lactose	Barwant and Barwant (2020)
Goat kids	HHG and HSH	50% of concentrate mixture	No differences on growth performance; lower cost of feeding		Jemimah et al. (2017)
Laying Japanese quail	HB	CON ad libitum CON ad libitum + HB (100 g) CON restricted + HB	HB did not compensate feed restriction; ↓ daily egg mass, fertility and hatchability; ↑ ad libitum fed: egg laying, as weights of gizzard and testis, fertility and number of hatched chicks/female	No effect on eggs quality	Abouelezz et al. (2019)
Sheep	HB and HO	PH ad libitum; PH ad libitum + 300 g (concentrate mix); PH + 1 kg HB (50% DM) PH + 948 g HO	↑ DMI in HB and HO; All supplemented treatments produced better BWG and feed conversion efficiencies than CON	-	Mekonnen et al. (2019)

		PH + 150 g concentrate mix + 250 g HB + 237 g HO			
Dairy cattle	HB	10 kg as fed	-	No difference in physical-chemical milk analyses	Kaouche-Adjlanea et al. (2016)

BWG: body weight gains; CF: crude fiber; CP: crude protein; DMI: dry matter intake; FCR: Feed conversion ratio; FW: final weight; HB: hydroponic barley; HHG: hydroponic horse gram; HM: hydroponic maize; HO: hydroponic oat; HSH: hydroponic sun hemp; HW: hydroponic wheat; PH: pasture hay; WG: weight gain; (↑): increase; (↓): decrease.

Ruminants

Determination of DM intake is very important in feed evaluation, so as to prevent the deficiency or excess intake of nutrients and to support the use of nutrients efficiently (NRC, 2001). Some researchers have argued that the sole feeding of animals with green fodder does not support the expected production traits in these animals. However, results on performance are discordant. According to Abd Rahim and Omar (2015), hydroponic barley fodder (HBF) exhibited favorable impacts on ewe's health, mortality, conception rate, and abortion rate but no changes in feed consumption, body weight change, milk yield, or milk composition. In a study, it was reported that the effect of partially replacing corn (at 10% or 15%) with hydroponic barley fodder in Holstein heifer feed was insignificant on the heifer’s live body weight (Kim et al., 2020). Abd Rahim and Omar (2015) noted that in feedlot cattle and dairy cattle, the intake of green fodder by was low due to its high moisture content, when compared to the control ration with a high dry matter content.

When cows were given diets containing hydroponic barley green fodder, in proportions ranging from 40 to 60 percent of the maize silage portion on a DM basis, Fazaeli et al. (2021) discovered that the average DM consumption, CP intake, and net energy intake were not influenced by dietary treatment. Results showed that when employed up to 60% of maize silage in the diet, barley green fodder generated by a hydroponic system might be comparable to corn silage. Similar results were obtained in other studies with the incorporation of hydroponic green fodder in ruminants’ diets (Fazaeli et al., 2011; Marsico et al., 2009; Naik et al., 2017).

There was also a report which indicates a decrease in the DM intake of the animals consuming hydroponic fodder (Heins, 2017). Similarly, Naik et al. (2014) reported lower DM intake when hydroponic fodder was supplemented to the diet of dairy cows. Two fodders were compared in this study, fresh hydroponic maize fodder (HMF) and the conventional Napier bajra hybrid green fodder (NBH), in the diet of lactating cows for 68 days. The authors reported that maize fodder intake was lower (0.59 kg DM/d) than the latter (1.19 kg DM/d) with a comparable total DM intake in both groups.

The lower DM intake linked with the feeding of hydroponics green fodder may be associated with the high-water content of the hydroponics green fodder that might increase the fresh bulk hence limiting the DM intake by the animals (Fazaeli et al., 2011).

Conversely, Nugroho and Permana (2015) disagree on this point and in their studies performed on hydroponic maize fodder in the diets of lactating cows, reported that DM intake was increased by the animals receiving the diets containing hydroponic fodder. In detail, Nugroho and Permana (2015) added in the treated group of dairy cows maize hydroponic fodder produced in a hydroponic system using bioslurry as a fertilizer, replacing napier grass and concluded that dairy cows receiving 7% maize hydroponic fodder increased DM intake.

Such differences between the results obtained by Nugroho and Permana (2015) and Fazaeli and co-workers (2021) could be due to the higher DM content (18.3%) of hydroponic maize fodder than the hydroponic barley green fodder (13.98%).

An indicator of the positive impacts of the incorporation of hydroponic grass in a dairy cow's diet, is milk yield. This was reported as an increase in a milk yield of 13.7% by Naik and co-workers (2014). In another study, Reddy and co-workers (1988) observed an increase of 7.8% in milk production when cows were supplemented with hydroponic barley, concluding that this was due to high protein content in the fodder resulting from the maize fodder. Kaouche-Adjlanea and co-workers (2016) reported that the milk yield was significantly increased with hydroponic fodder registering a volume of 3.49 litre/day more in dairy cows. Abd Rahim and Omar (2015) observed a slight improvement in milk protein and milk fat in dairy goat but were not significant in sheep.

Naik and Singh (2013) reported that milk yield was increased by 0.5-2.5 l/animal/day when dairy animals were supplemented with hydroponic fodder. In a study by Agius and coworkers (2019) relating the incorporation of hydroponic grass in the feed ration, demonstrated that this incorporation increased the percentage of milk fat and pH. Mincera and co-workers (2009) reported an improvement in welfare and milk yield in Comisana sheep feed on hydroponically-germinated oats. In another study, the daily milk yield was 8.0-14.0% higher in animals fed total mixed ration containing hydroponic maize or barley fodder than those fed conventional green fodder (Jemimah et al., 2015). From these studies, it transpires that hydroponic fodder improves milk yield, improves fat content, prolongs the lactation period and improves the general health of the herd.

Therefore, studies on milk production showed that there was an improvement in the animals fed on the hydroponic fodder compared to those fed on cereal grains, hay or silage. Salo (2019) reported that Canadian dairy farmers who used hydroponic fodder as feed experienced an increase in feed intake by their cows and an improvement in milk yield by 3.6 kg per day over the lactation period. In fact, this improvement has been linked to the possible good palatability of maize hydroponic fodder which is believed to have stimulated the increased consumption of other types of feed (Singh and Chaudary, 2007).

An increase in the milk production by 0.5 to 2.5 l/animal/day and net profit by $0.33-0.67/animal/day due to feeding of hydroponics, has been reported by a dairy cattle farmer of a district in India. Additionally, other positive observations, include an increase in fat and SNF content of the milk, improvement in health and conception rate of the dairy animals, reduction in cattle feed requirement by 25%, increase in taste (sweetness) of the milk, whiter milk, reduction in labour cost, lower space and water requirements, freshness and high palatability of the hydroponics fodder amongst others (Naik and Singh, 2013). Furthermore, South African farmers reported 3.6 l less milk production after discontinuing feeding of 6.8 kg per day (Shit, 2019; Mooney, 2005).

No significant difference in live weight gain or feed conversion efficiency between a fodder diet and a control diet (barley grain) was found in calves (Fazaeli et al., 2011). Tudor and co-workers (2003) stated that steers supplemented with hydroponic barley sprouts performed higher than expected for a period.

Kim and co-workers (2000) reported no significant changes in blood metabolites such as total protein, total cholesterol, albumin, BUN, CK, or creatinine in Holstein heifers fed a diet supplemented with 10% and 30% HSB as compared with those fed the CON diet (only corn) indicating that the replacement did not adversely affect their carbohydrate, lipid and protein metabolism.

Nutrient digestibility may be increased by using sprouted grains in the ruminant diet. Fayed (2011) determined that the addition of sprouted barley with rice straw and *Tamarix mannifera* increased DM, OM, CP, EE, CF, NDF and ADF digestibility. This may be due to the presence of bioactive enzymes which increases digestion and absorption of nutrients and enhance the release of energy. Similarly, Ibrahim and co-workers (2001) and Sharif and co-workers (2013) reported on the increase in digestibility with the incorporation of sprouted grains increases nutrient digestibility. Sharif et al. (2013) observed an increase in digestibility by the addition of sprouted grains in the diet of ruminants, broilers and large animals. Al-Saadi and Al-Zubiadi (2016) showed that treated groups particularly those fed with a 30% sprout supplementation, recorded significantly ($p < 0.05$) higher values for DM, OM, CP and EE digestibility respectively than those fed with a 10% sprouts supplementation and the control group, respectively.

Helal (2015) reported that digestibility coefficients of all nutrients were significantly higher in sprouted barley supplemented sheep. In general, feeding of hydroponic fodder increased the digestibility of the nutrients of the ration, which could be attributed to the tenderness of the fodder (Reddy et al., 1988). In the study conducted by Naik and co-workers (2014), there was a significant increase in the digestibility of CP and CF of cows when hydroponic maize fodder was added. It seems that the increase digestibility is due to high content of leafy and root portions in sprouts, which is easily digested and hydrolysed by the enzymes of rumen microflora, as well as enzymatic digestion (proteases) present in the lytic vacuoles of plant cells (Laredo and Mison, 1975). Other researchers observed that particle size of sprouts feed affected the formation of microbial colonies in the rumen leading to efficient digestion and passage rate of feed (Laredo and Mison, 1975; Ehle, 1984).

Concerning small ruminants, Gebremedhin (2015) reported 37.52 to 61.93 g per day increased body weight of goat fed with finger millet straw used as control diet (CON) as compared to supplementation with hydroponic maize fodder (CON:HMF, 80:20) and a supplementation of a combination of HMF and HBF (CON:HMF:HBF, 60:20:20). Better body weight gain was reported on other studies on cross-bred calves (Rajkumar et al., 2018), goat (Kide et al., 2015) and Awassi lambs (Ata, 2016) fed with HMF and HBF.

Maize and barley hydroponic fodder supplemented in different percentages (20%, 40% or 20% HMFM + 20% HBF) were assessed in feeding goats (Arif et al., 2023). Hydroponic fodder groups showed improved diets digestibility, performance and growth, and FCR compared to the control diet. The higher increase in BWG of group fed with equal percentage of HMF and HBF than control might be attributed to the higher ability of hydroponic fodder to provide essential nutrients that maximize growth and performance.

Raeisi and co-workers (2018), Dung and co-workers (2010a) and Fayed (2011) reported an increase in dry matter intake (DMI) with hydroponic barley fodder. The effect is attributed to the release of soluble carbohydrates and nitrogen from HBF that stimulated microbial growth and colonization, and improved degradation of the low protein forage used in their experiments. An improvement of body weight was also registered by Tudor and co-workers (2003) in lambs. The increase in body weight also reflects microbial activity in rumen and enhanced nutrient digestibility which is attributed to increased live weight gain. Beef cattle fed with hydroponics green fodder showed an average of 200 g higher daily gain when compared to those fed with a maize control diet (Fazaeli et al., 2011).

Non-ruminant species

Jemimah and co-workers (2018) performed a study on New Zealand white rabbit kits by replacing the concentrate mixture with 25 and 50 per percent hydroponic yellow maize fodder in their diet. The feed conversion ratio, expressing feed intake and body weight, was significantly higher in the group receiving the highest maize fodder integration. This result may be attributed to the enhanced nutritional value of sprouted grain, mainly due to the modification of heterogeneous compounds into an essential form during sprouting process (Chavan and Kadam, 1989) and the increase in quantity and quality of protein, sugars, minerals and vitamin during sprouting (Lorenz, 1980).

Thus, the study of Jemimah and co-workers (2018) suggested that, half of the rabbit diet may contain the hydroponic yellow maize fodder without any deleterious effect on their growth and profitability. This is also substantiated in a study by Chakravarthi and co-workers 2020 with New Zealand White rabbits. They reported that the complete replacement of the rabbit conventional diet with hydroponic maize fodder led to a lower weight gain than when half of the conventional diet was replaced.

Mohsen and co-workers (2015) reported that the inclusion of hydroponic barley at 30% in the diet of rabbits has no adverse effect on the initial and final live body weight and total and daily weight gain. Similarly, no adverse effect was noticed on ADG and FCR in goat kids and rabbit kits fed hydroponic horse gram or sun hemp fodder replacing 50% of a concentrate mixture (Jemimah et al., 2015).

Hydroponic barley sprouts were reported to have a promising application in organic, intensive, and small-scale animal and poultry enterprises with a sustainable product quality (Tranel, 2013). Within the poultry industry, hydroponic fodder improved weight gains, resulted in high quality carcass, decreased feed costs and improved overall health (Jemimah et al, 2015).

The existing research on poultry and sprouted grain is scarce. However, the use of hydroponic fodder in poultry farming is proposed since roughage material is often recommended as a supplement to improve animal welfare and behaviour, reducing incidences of egg pecking, feather pecking and cannibalism (Abouelezz et al., 2012; Abouelezz et al., 2019; Mohammed et al., 2013). Fresh fodder is also believed to improve the quality of meat and eggs in broilers and layers, respectively (Abouelezz et al., 2012; Blair, 2008).

Conclusions

Several studies have reported the positive correlation between the use of hydroponic fodder and its beneficial effect on the quality of life of farm animals, however the commercial potential of dietary inclusion has not been fully exploited.

The present review underlines that hydroponic fodder has high nutritive value due to the conversion of complex compounds into a simpler and essential form, and the activation of enzymes during germination. In ruminants, improvements in digestibility and intake of nutrients results in increased milk yields and milk fat. In general, the substitution of part of feed ration with hydroponic fodder is more effective than the sole feeding of hydroponic fodder as reported in studies on ruminants and non-ruminants.

In spite of all the benefits of hydroponically-grown fodder, there are still some issues that need to be addressed. Some of these are attributed to the growing process particularly the loss in dry matter during the sprouting process. Parameters that need further investigation include nutrient management, improvement in the day/night cycle and a reduction in mould contamination. Issues related to feeding management for various livestock production systems should be addressed too. Parameters that need further investigation include the incorporation of hydroponic fodder within the feed ration, the adaptive feeding approach, the effects on the physiology and health of the farm animals and the effects on animal products.

Further studies are needed for hydroponic production and animal feeding management for a holistic farm economic benefit.

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Received: 15 XII 2022

Accepted: 26 VI 2023