CARRASCO, G.; FUENTES, M.; GAJARDO, J. M.; FUENTES-PEÑAILILLO, F. Pilot evaluation of a semiautomated vertical system for hydroponic oat fodder production. **Revista de Agricultura Neotropical**, Cassilândia-MS, v. 13, n. 1, e11337, 2026. ISSN 2358-6303. DOI: https://doi.org/10.32404/rean.v13i1.11337

Pilot evaluation of a semiautomated vertical system for hydroponic oat fodder production

Gilda Carrasco[1], Manuel Fuentes[1], José Manuel Gajardo[2], Fernando Fuentes-Peñailillo[3]

[1] Universidad de Talca, Talca, Maule, Chile. E-mail: gcarrasc@utalca.cl; fuentes.manuel.98@gmail.com

[2] Independent researcher, San Luis de Alico, San Clemente, Chile. E-mail: jomagaheagro@gmail.com

[3] Dirección de Investigación, Universidad de Talca, Talca, Maule, Chile. E-mail: ffuentesp@utalca.cl

Received: 08/24/2026; Accepted: 09/11/2026.

ABSTRACT

Hydroponic fodder can provide short-cycle fresh biomass in compact structures, but vertical systems perform best with adequate water distribution and light availability. This pilot study designed and implemented a four-tier semiautomated system for oat (*Avena sativa* L.) fodder and compared its crop performance with a simultaneously operated manual reference rack. Each system contained 12 trays, each with a cultivation area of 0.1326 m². The semiautomated unit integrated a 30-L reservoir, a 0.5-hp pump, recirculating water distribution and drainage, and tier-specific lighting conditions; the manual reference used hand irrigation and ambient light. Oat cv. Urano INIA was harvested 12 days after sowing. Fresh yield was 2.78 versus 4.84 kg m^{-2}, final height was 11.86 versus 13.96 cm, and crude protein was 15.04% versus 15.22%. Canopy-level photosynthetic photon flux density (PPFD) in the semiautomated rack ranged from 2.2 to 7.1 μmol m^{-2} s^{-1}. The prototype completed the crop cycle under very low photon supply but produced less fresh biomass than the manual reference. Because each system was represented by a single rack in a different environment, the results are interpreted as a technological pilot benchmark rather than a causal test of semiautomation.

Keywords: Controlled environment, LED lighting, Fresh biomass, Seedling emergence, Crude protein.

Avaliação piloto de um sistema vertical semiautomatizado para produção hidropônica de forragem de aveia

RESUMO

A forragem hidropônica permite produzir biomassa fresca em ciclos curtos e em estruturas compactas, mas o desempenho de sistemas verticais depende de uma distribuição adequada de água e da disponibilidade de luz. Este estudo piloto projetou e implementou um sistema semiautomatizado de quatro níveis para a forragem de aveia (Avena sativa L.) e comparou seu desempenho ao de uma estrutura de referência, operada simultaneamente com irrigação manual. Cada sistema continha 12 bandejas, cada uma com área de cultivo de 0,1326 m². A unidade semiautomatizada integrou reservatório de 30 L, bomba de 0,5 hp, distribuição e drenagem recirculantes de água e condições luminosas específicas por nível; a referência manual utilizou irrigação manual e luz ambiente. A aveia cv. Urano INIA foi colhida 12 dias após a semeadura. O rendimento fresco foi de 2,78 versus 4,84 kg m^{-2}, a altura final de 11,86 versus 13,96 cm e a proteína bruta de 15,04 versus 15,22%. A densidade de fluxo de fótons fotossintéticos (PPFD) variou de 2,2 a 7,1 μmol m^{-2} s^{-1} no sistema semiautomatizado. O protótipo completou o ciclo sob baixa disponibilidade de fótons, mas produziu menos biomassa fresca do que a referência manual. Como cada sistema foi representado por uma única estrutura em diferentes ambientes, os resultados constituem uma referência tecnológica piloto, e não um teste causal da semiautomatização.

Palavras-chave: Ambiente controlado, Iluminação LED, Biomassa fresca, Emergência de plântulas, Proteína bruta.

1. Introduction

Short-cycle hydroponic fodder systems have received renewed attention because they can produce fresh cereal biomass without field soil in compact, protected, or controlled environments. However, their practical value depends on more than rapid germination. Seed cost, dry-matter recovery, water and energy demand, sanitation, environmental control, and system reliability all affect technical and economic performance (Ahamed et al., 2023; Pastorelli et al., 2024; Ebenezer and Gnanaraj, 2026).

Oat (*Avena sativa* L.) is one of the cereal species used for hydroponic fodder. Recent studies have shown marked differences among oat, maize, and wheat grown as hydroponic fodder (Upreti et al., 2022), while seeding density and harvest time affected hydroponic oat production (Núñez Torres et al., 2023). More recently, tray arrangement was also reported to modify dry-matter production of hydroponic oat in a multilevel recirculating system (Mautone Rodriguez et al., 2025). These findings indicate that crop performance is highly sensitive to establishment and environmental management.

Vertical stacking increases cultivation area per unit floor area, but it introduces additional engineering constraints. Water must be distributed uniformly across tiers, drainage must avoid localized saturation, and photon supply must reach all crop surfaces. Grigas et al. (2020) showed that tray slope can alter hydroponic cereal fodder productivity, and Mautone Rodriguez et al. (2025) reported that tray arrangement affected dry-matter production of hydroponic oat in a four-level recirculating rack. Lighting is also critical: in hydroponic barley, Yang et al. (2024) observed strong effects of photon flux on photosynthetic activity, growth, biomass accumulation, and nutritional composition.

The level of mechanization should also be defined precisely. Current controlled-environment fodder systems may integrate sensors, control logic, and actuators to monitor and regulate lighting, nutrient-solution conditions, temperature, and relative humidity; nevertheless, watering strategy and environmental control remain important engineering challenges (Ahamed et al., 2023). By contrast, a semiautomated unit may mechanize only selected operations, such as water delivery and recirculation, while environmental set points and operating schedules remain under manual control. Such intermediate systems may be relevant when the objective is modular, lower-complexity technology rather than full closed-loop automation.

The objective of this study was to design and functionally implement a semiautomated vertical system for hydroponic oat fodder and to characterize its crop performance, light environment, and crude protein concentration relative to a simultaneously operated manual reference rack. Because the original implementation used one rack per production system and the racks were exposed to different environments, the comparison was treated as a pilot technological benchmark intended to identify design constraints before replicated scale-up.

2. Material and Methods

2.1 Study site and experimental approach

The trial was conducted in March 2023 at research facilities in Talca, Maule Region, Chile (35°24′25″ S, 71°38′14″ W; 111 m above sea level). The semiautomated unit was installed inside a recycled 40-foot maritime container adapted for controlled-environment cultivation. The manual reference unit was placed immediately outside the container on a roofed, open-sided surface exposed to ambient outdoor conditions (Figure 1).



Figure 1. (A) Ambient outdoor conditions. (B) Four-tier rack used for outdoor oat production.

Two four-tier aluminum racks were used, with three cultivation trays per tier and 12 trays per rack. Each tray measured 26 × 51 cm (0.1326 m²). The production-system factor was therefore applied at the rack level,

with only one rack representing each system. Individual trays were treated as subsamples rather than independent system replicates. In addition, the two racks differed simultaneously in location, irrigation mode, and light environment. These characteristics precluded causal inference regarding semiautomation and were explicitly considered in interpreting the results.

2.2 Plant material and crop establishment

Commercial seed of oat cv. Urano INIA was used, with a reported minimum germination rate of 85% and purity of 98%. Foreign material, empty seeds, and seeds of other species were removed. Seed was washed three times, disinfected with a 0.5% sodium hypochlorite solution for 5 min, rinsed, and soaked in water for 24 h, following the general crop-establishment sequence described for hydroponic oat by Núñez Torres et al. (2023). Soaking water temperature was not recorded.

After soaking, the seed was distributed uniformly in the trays to form a layer approximately 1.5–2.0 cm thick. The experimental record indicated a nominal loading equivalent to 3 kg m^{-2}; because tray portions were weighed after soaking, and post-soaking seed moisture was not determined, this value is best interpreted as the operational seeding rate recorded for the experiment rather than an independently verified dry-seed rate. The day on which seedling emergence began was not recorded. Irrigation was performed with water through day 7 and subsequently with a 0.5% commercial water-soluble fertilizer solution (Ultrasol Multipurpose). The exact nutrient composition of the applied commercial formulation, electrical conductivity, and pH were not recorded in the experimental dataset. Fodder mats were harvested 12 days after sowing. Therefore, dry-seed conversion efficiency was not calculated.

2.3 Production systems

Both racks were approximately 2.0 m high, 0.9 m wide, and 0.6 m deep. In the manual reference system, trays were perforated at one end to remove excess water and were irrigated by hand using a 500-mL perforated bottle. The rack was surrounded by Raschel shade mesh that could be opened for irrigation and crop assessment.

The semiautomated system (Figure 2) incorporated a 30-L reservoir, a 0.5-hp peripheral pump, PVC supply lines, valves serving each tier, and a gravity return line that collected drainage and returned it to the reservoir. This configuration mechanized water distribution and recirculation but did not include sensor-based closed-loop control. Pump operation and environmental management remained manual.

Commercial 5-m LED strips were mounted on aluminum profiles above three tiers. The four nominal light environments were ambient container light, red LED, blue LED, and white LED. Spectral power distribution was not measured, and each nominal light environment corresponded to a fixed physical tier; therefore, spectral setting, photon flux, and vertical position were confounded. Air temperature inside the container was manually maintained at approximately 20–25 °C. During the trial, the daily minimum outdoor temperature was approximately 8–15 °C, and the maximum temperature was 25–31 °C. Tier-level temperature and relative humidity were not continuously recorded.

Table 1. Main configuration of the semiautomated vertical system and manual reference rack.

Component	Semiautomated vertical system	Manual reference rack
Location	Inside the controlled-environment 40-ft container	Roofed outdoor, open-sided area
Rack	4 tiers; 3 trays per tier	4 tiers; 3 trays per tier
Tray area	0.1326 m²	0.1326 m²
Water delivery	30-L reservoir; 0.5-hp pump; PVC distribution	Manual irrigation with a perforated 500-mL bottle
Drainage	PVC gravity return line to the reservoir	Drainage holes at tray end
Light	Ambient container light; nominal red, blue, and white LED settings by tier	Ambient/natural light
Temperature	Approximately 20–25 °C; manually adjusted	Daily minimum approximately 8–15 °C; maximum 25–31 °C during trial

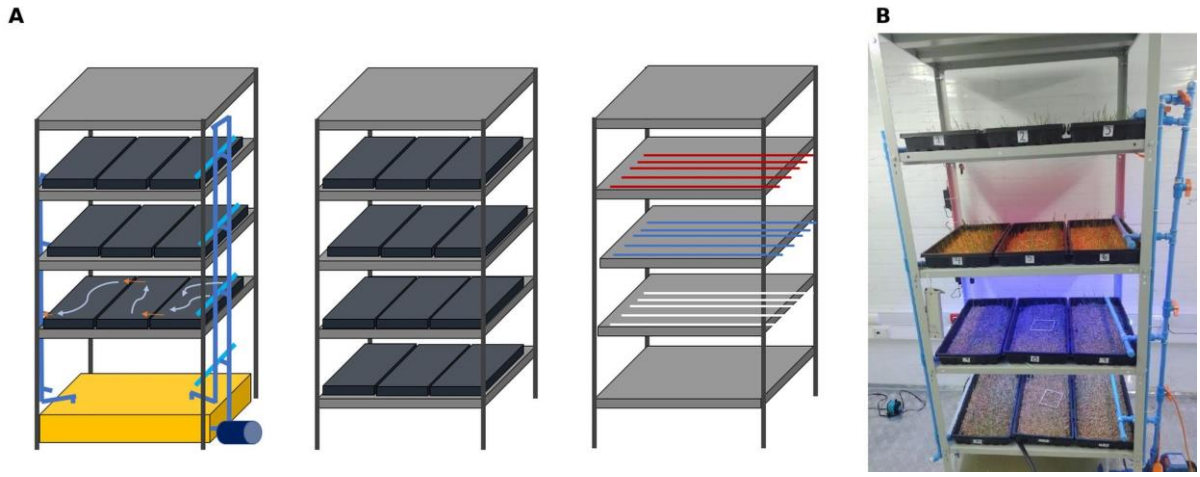


Figure 2. Semiautomated vertical hydroponic fodder prototype. (A) Functional layout of water distribution, trays, and tier lighting; (B) four-tier unit during oat production.

2.4 Environmental and crop measurements

Plant height was measured daily from a fixed reference point with a 30-cm steel ruler. Emerged seedlings were counted in a 10 × 10 cm frame placed in the central tray of each tier, and the counts were expressed as seedlings per 100 cm². Thus, emergence counts were obtained from one tray per tier. Canopy-level photosynthetic photon flux density (PPFD) was measured with an SM206-PAR meter at three positions above each tray (both ends and the center), and the three readings were averaged for that tray.

At harvest, the complete fresh fodder mat, including shoots, roots, and residual seed material, was weighed for each tray. Fresh yield was expressed as kg m^{-2}. The shoot-to-root-mat fresh-mass ratio was calculated after separating the aboveground fraction from the root mat; the root-mat fraction included residual seed material. Crude protein was determined by the Kjeldahl method using eight composite samples, one for each tier × system combination, each composite consisting of material from the three trays in that tier. Carotenoid concentration was not measured in this pilot study.

2.5 Data treatment

The rack was the experimental unit for the production-system factor. Because only one rack represented each system, inferential testing of a system effect would constitute pseudoreplication. Accordingly, system contrasts were summarized descriptively using observed means and relative differences, and no p-values were used to infer an effect of semiautomation. Tier responses within the semiautomated rack were also treated descriptively because each nominal light setting occurred only in a single fixed tier. Daily plant-height values are presented as observed rack means. This analytical approach was chosen to separate useful prototype-performance information from causal claims that the design could not support.

3. Results and Discussion

3.1 Prototype operation and light environment

The semiautomated unit completed the 12-day crop cycle with pumped water distribution, return drainage, and tier lighting functioning together within an integrated rack. This demonstrated functional operation of the integrated hydraulic architecture over one complete crop cycle using commercially available components. It did not demonstrate superior efficiency because water consumption, electricity use, labor time, pump duty cycle, and irrigation uniformity were not quantified.

Photon supply was the main measured design limitation identified during operation. Mean PPFD within the semiautomated rack was 2.2 µmol m^{-2} s^{-1} under ambient container light, 2.6 under the nominal red LED setting, 7.1 under the nominal blue setting, and 5.7 under the nominal white setting. PPFD was not measured in the manual reference rack; consequently, a numerical light comparison between systems cannot be made. The prototype values were substantially below the 100, 200, and 300 µmol m^{-2} s^{-1} PPFD treatments evaluated by Yang et al. (2024) in hydroponic barley; under their experimental conditions, the most favorable overall response occurred at 200 µmol m^{-2} s^{-1}. Although this value should not be transferred directly from barley to oat, approximately 200 µmol m^{-2} s^{-1} could serve as an initial design benchmark for subsequent oat trials, which should then determine the species- and system-specific optimum.

The measured PPFD values do not, by themselves, establish a causal explanation for the lower biomass because photoperiod and daily light integral were not recorded, and the nominal LED colors differed in both intensity and fixed tier position. Nevertheless, the measurements identify photon delivery as a priority variable for redesign. Future versions should target and validate canopy-level PPFD near the 200 µmol m^{-2} s^{-1}

benchmark identified in hydroponic barley, record photoperiod, calculate daily light integral, and independently randomize or replicate spectral treatments. Bhat et al. (2023) reported the highest hydroponic maize fodder yield under combined red–blue LED lighting and fogger irrigation, illustrating the importance of considering lighting and water-delivery conditions together.

Table 2. Observed crop performance at harvest (12 days after sowing).

Variable	Semiautomated	Manual reference	Relative difference vs. manual (%)
Final plant height (cm)	11.86	13.96	-15.0
Emerged seedlings (seedlings 100 cm^{-2})	82.75	499.75	-83.4
Fresh mass (g $tray^{-1}$)	369.75	643.15	-42.5
Fresh yield (kg m^{-2})	2.78	4.84	-42.5
Shoot:root-mat fresh-mass ratio	0.124	0.161	-22.8
Crude protein (%)	15.04	15.22	-1.2

3.2 Emergence and early growth

Plant height increased throughout the evaluation period in both racks (Figure 3). At harvest, the observed mean height was 11.86 cm in the semiautomated unit and 13.96 cm in the manual reference, a 15.0% lower value in the prototype.

The largest observed contrast was in seedling emergence. Emergence reached 82.75 seedlings 100 cm^{-2} in the semiautomated rack and 499.75 seedlings 100 cm^{-2} in the manual reference. PPFD was not measured in the manual reference. Accordingly, the emergence gap should not be attributed to light availability alone, particularly because cereal germination can proceed before photosynthetic carbon gain becomes important. Water distribution, oxygen availability within the dense seed layer, local temperature and humidity, drainage, seed health status, and the effective seeding load could all have contributed. None of those seed-zone variables was quantified at sufficient resolution to isolate the mechanism.

From an engineering perspective, the emergence result indicates that hydraulic uniformity should be verified before scale-up. Bhat et al. (2023) found that water application method materially affected hydroponic maize fodder performance, while Ahamed et al. (2023) identified watering strategy and environmental control as key unresolved engineering issues in controlled-environment fodder production. For the present prototype, measuring discharge per tier, drainage volume, tray moisture distribution, and dissolved oxygen would be more informative than attributing establishment failure to a single environmental factor.

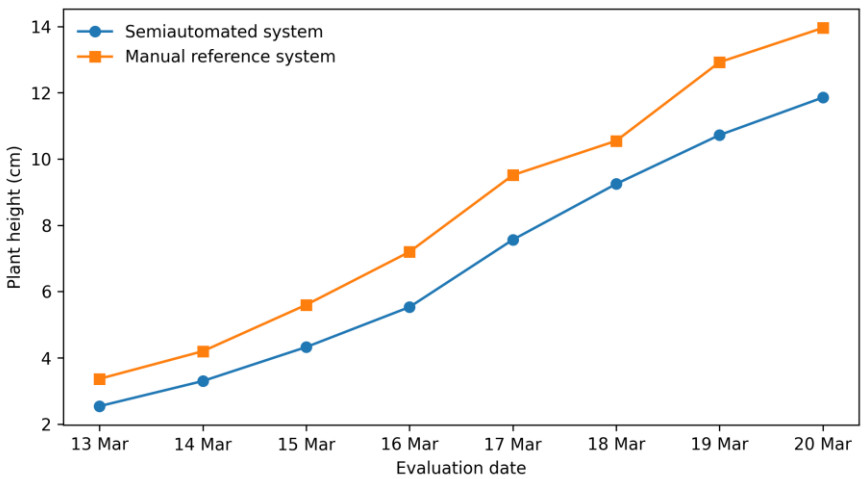


Figure 3. Observed mean plant height of hydroponic oat fodder during the evaluation period in the semiautomated and manual reference racks.

3.3 Fresh yield and biomass allocation

Fresh yield at 12 days was 2.78 kg m^{-2} in the semiautomated rack and 4.84 kg m^{-2} in the manual reference, corresponding to a 42.5% lower yield in the semiautomated rack. Fresh mass per tray followed the same pattern, with 369.75 and 643.15 g $tray^{-1}$, respectively. Because dry-seed mass was not independently verified, seed-to-fodder conversion efficiency and direct per-seed comparisons were not considered.

Within the semiautomated rack, fresh yield ranged from 2.56 to 2.93 kg m^{-2} among the four tiers, while measured PPFD ranged from 2.2 to 7.1 µmol m^{-2} s^{-1}. This pattern should not be interpreted as an absence of a light response, because each light setting occurred in a single fixed tier, the intensities were all low, and the trial did not independently manipulate light spectrum and tier position. Mautone Rodriguez et al. (2025) showed that tray arrangement itself can modify dry-matter production of hydroponic oat in a multilevel recirculating system, illustrating why vertical position and hydraulic configuration must be separated from lighting in future experiments.

The shoot-to-root-mat fresh-mass ratio was 0.124 in the semiautomated rack and 0.161 in the manual reference. Because the root-mat fraction included residual seed material, this index describes fresh-mass partitioning within the harvested mat rather than root biomass alone. The lower value in the prototype is consistent with reduced shoot development, but the present design cannot distinguish whether the difference arose from establishment, light environment, irrigation, or their interaction.

Table 3. Light environment and observed crop response among tiers of the semiautomated vertical rack.

Tier light environment	PPFD (µmol m^{-2} s^{-1})	Final height (cm)	Fresh yield (kg m^{-2})	Shoot:root-mat ratio
Ambient container light	2.2	11.97	2.56	0.123
Nominal red LED	2.6	12.63	2.91	0.143
Nominal blue LED	7.1	10.50	2.72	0.120
Nominal white LED	5.7	12.33	2.93	0.110

Note: Nominal light setting, PPFD, and physical tier position were not randomized or replicated independently; values are descriptive.

3.4 Crude protein concentration

Crude protein concentration was similar between the two racks: 15.04% in the semiautomated system and 15.22% in the manual reference. These values are close to the 14.79% crude protein reported by Fuentes et al. (2011) for hydroponic oat harvested at 10 days under desert conditions. However, differences in harvest age and production environment limit direct comparison. Salvador-Castillo et al. (2022) also demonstrated that nutrient solution and sampling time can modify the nutritional composition of hydroponic oat and barley.

Protein concentration alone is insufficient to establish feed value or nutrient productivity. Dry-matter yield, neutral detergent fiber, acid detergent fiber, digestibility, mineral composition, and protein yield per unit area were not quantified. Hydroponic fodder can exhibit higher concentrations of certain nutrients while losing seed dry matter through respiration during germination (Pastorelli et al., 2024; Vastolo and Cutrignelli, 2025). Consequently, future validation should report fresh and dry biomass together and express nutrient output per unit of seed used, cultivation area, water, energy, and time. Future studies should also quantify carotenoids and other bioactive compounds to determine whether production conditions alter attributes relevant to fodder quality and the subsequent quality of animal products.

3.5 Technical implications and study limitations

The prototype met the engineering objective of integrating a compact four-tier rack, pumped water distribution, recirculating drainage, and artificial lighting. The crop response suggests a practical optimization sequence: increase and standardize canopy-level photon supply; quantify irrigation uniformity and drainage by tier; log nutrient-solution electrical conductivity, pH, and temperature; and characterize air temperature and relative humidity at each level. Only after these variables are controlled should full rack-level replication be used to test whether mechanization itself changes crop performance.

The absence of independent rack-level replication was the principal limitation of the experiment. The semiautomated and manual racks also differed in location, temperature regime, irrigation mode, and light source, so the observed performance gap cannot be assigned specifically to semiautomation. The four nominal light environments in the prototype were

additionally confounded with vertical position. For these reasons, the study is best interpreted as a pilot engineering-and-crop assessment that identified measurable design priorities for a second-generation system.

No measurements of water use, irrigation frequency, electricity consumption, labor requirements, or production costs were available; therefore, water consumption cannot be estimated reliably for either system from the experimental record. Claims of improved sustainability, water-use efficiency, energy efficiency, or economic advantage are consequently not supported by this dataset. This distinction is important because hydroponic fodder can achieve high water-use efficiency yet remain economically unfavorable under certain production conditions (Elmulthum et al., 2023). Subsequent replicated trials should measure input and drainage volumes for each irrigation event, reservoir replenishment, evapotranspirative losses, energy use, seed use, labor, and operating costs, together with biomass and feed quality.

4. Conclusions

The four-tier semiautomated prototype completed a 12-day hydroponic oat fodder cycle, demonstrating functional operation of its integrated recirculating hydraulic and lighting architecture over one complete production cycle. Under the tested configuration, observed fresh yield was 2.78 kg m^{-2} compared with 4.84 kg m^{-2} in the manual reference, whereas crude protein concentration was similar in magnitude (15.04 versus 15.22%). Its recirculating water circuit and four-tier configuration offer potential sustainability gains through drainage recovery and increased cultivation area per unit floor area. These potential gains were not quantified because water, energy, and labor use were not measured. The low PPFD, unquantified hydraulic uniformity, and absence of rack-level replication identify the key priorities for a replicated redesign and validation study.

Authors' Contribution

Gilda Carrasco: Conceptualization, Methodology, Resources, Funding acquisition, Formal analysis, Supervision, Project administration, Writing – review & editing. Manuel Fuentes: Investigation, Methodology, Data curation, Visualization, Writing – original draft. José M. Gajardo: Validation, Formal analysis, Writing – review & editing. Fernando Fuentes: Conceptualization, Methodology, Formal analysis, Writing – review & editing.

Acknowledgments

The authors acknowledge the technical and infrastructural support provided by Universidad de Talca.

Funding

This study was funded by the FIC-R project of the Gobierno Regional del Maule, BIP 40.036.334-0.

Bibliographic References

Ahamed, M.S., Sultan, M., Shamshiri, R.R., Rahman, M.M., Aleem, M., Balasundram, S.K., 2023. Present status and challenges of fodder production in controlled environments: a review. Smart Agricultural Technology, 3, 100080. https://doi.org/10.1016/j.atech.2022.100080

Bhat, A.G., Jinu, A., Sathian, K.K., 2023. Optimization of water use efficiency of hydroponic maize fodder production system under different microclimatic conditions. International Journal of Environment and Climate Change, 13(9), 3354–3367. https://doi.org/10.9734/ijecc/2023/v13i92588

Ebenezer, R.J., Gnanaraj, P.T., 2026. Hydroponic fodder production and utilization in sustainable livestock and poultry feeding. Discover Agriculture, 4, 164. https://doi.org/10.1007/s44279-026-00652-x

Elmulthum, N.A., Zeineldin, F.I., Al-Khateeb, S.A., Al-Barrak, K.M., Mohammed, T.A., Sattar, M.N., Mohmand, A.S., 2023. Water use efficiency and economic evaluation of the hydroponic versus conventional cultivation systems for green fodder production in Saudi Arabia. Sustainability, 15(1), 822. https://doi.org/10.3390/su15010822

Fuentes, F., Poblete, C., Huerta, M., Palape, I., 2011. Evaluación de la producción y calidad nutritiva de avena como forraje verde hidropónico en condiciones de desierto. Idesia, 29(3), 75–81. https://doi.org/10.4067/S0718-34292011000300011

Grigas, A., Kemzūraitė, A., Steponavičius, D., Steponavičienė, A., Domeika, R., 2020. Impact of slope of growing trays on productivity of wheat green fodder by a nutrient film technique system. Water, 12(11), 3009. https://doi.org/10.3390/w12113009

Mautone Rodriguez, W.A., Carrossio Escudero, A.A., Rodriguez Padron, R.A., 2025. Optimizing of tray arrangement for the production of hydroponic green fodder from Avena sativa. Revista de Ciências Agroveterinárias, 24(1), 179–187. https://doi.org/10.5965/223811712412025179

Núñez Torres, O.P., Guerrero López, J.R., Leiva-Mora, M., Almeida Secaira, R.I., 2023. Producción de avena en corte e hidropónica sembrada a diferentes dosis y tiempo de cosecha. Revista Bionatura, 8(3), 6. https://doi.org/10.21931/RB/2023.08.03.6

Pastorelli, G., Serra, V., Turin, L., Attard, E., 2024. Hydroponic fodders for livestock production – a review. Annals of Animal Science, 24(3), 645–656. https://doi.org/10.2478/aoas-2023-0075

Salvador-Castillo, J.M., Bolaños-González, M.A., Cedillo-Aviles, A.K., Vázquez-Chena, Y., Varela-de Gante, S.A., Meza-Discua, J.L., 2022. Efecto de la aplicación de soluciones nutritivas en la calidad bromatológica del forraje verde hidropónico de Avena sativa y Hordeum vulgare. Terra Latinoamericana, 40, e996. https://doi.org/10.28940/terra.v40i0.996

Upreti, S., Ghimire, R.P., Banskota, N., 2022. Comparison of different cereal grains for hydroponic fodder production in locally constructed polyhouse at Khumaltar, Lalitpur, Nepal. Journal of Agriculture and Natural Resources, 5(1), 27–33. https://doi.org/10.3126/janr.v5i1.50378

Vastolo, A., Cutrignelli, M.I., 2025. Hydroponic forage in ruminant nutrition: a systematic review of nutritional value, performance outcomes, and sustainability. Animals, 15(24), 3544. https://doi.org/10.3390/ani15243544

Yang, J., Sun, J., Wang, X., Zhang, B., 2024. Light intensity affects growth and nutrient value of hydroponic barley fodder. Agronomy, 14(6), 1099. https://doi.org/10.3390/agronomy14061099