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Automated Irrigation Driven Hydroponic Fodder Production in Rainfed Agro-Ecosystems

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Abstract: Hydroponic fodder production offers a climate-resilient solution to chronic green fodder shortages in water-scarce semi-arid regions. This study evaluated an automated automated irrigation–based hydroponic maize fodder system within a low-cost polyhouse (180 m^2) at Ananthapuramu, India during *Kharif* 2020. Three bedding materials control (no bedding), paddy straw, and sorghum stover were compared under manual and automated irrigation. One kilogram of maize grain (₹16 kg^{-1}) produced 2.65–4.40 kg green fodder within seven days, with sorghum stover achieving the highest yield (4.40 kg $tray^{-1}$) and a 66.04% increase over control. The water requirement was 2 L $tray^{-1}$ day^{-1} (14 L per cycle). Automation reduced irrigation labour by 12 man-days monthly (₹6,000 saving $month^{-1}$) compared to the manual system requiring 12 man-days $month^{-1}$ Water productivity ranged from 0.19–0.31 kg L^{-1} across treatments, with sorghum stover achieving the highest efficiency. Economic analysis revealed benefit–cost ratios of 0.37–0.87 per tray at market prices; however, system-level economics incorporating labour savings demonstrated a net annual return of ₹1,09,592, a payback period of 2.28 years, and a return on investment of 43.8%, indicating improved feasibility at the integrated system level. This research establishes that integrating automated irrigation with appropriate bedding materials improves viability under integrated system-level conditions and enhances resource-use efficiency for smallholder dairy systems.

Keywords: Hydroponics; Automated Irrigation; Water Productivity; Bedding Materials; Labour Economics; Maize Fodder; Semi-Arid Agriculture

1. Introduction

India faces a persistent and deepening deficit of green fodder, currently estimated at 35.6% of requirement, with the gap projected to widen as livestock populations increase and arable land diminishes under competing demands from food and cash crops [1,2]. This scarcity disproportionately affects small and marginal farmers, who constitute 86% of Indian agricultural households and often cannot maintain year-round green fodder availability for their dairy animals [2]. The situation is particularly acute in semi-arid regions such as Ananthapuramu district in Andhra Pradesh, where low and erratic rainfall (550–600 mm annually), high evapotranspiration, and groundwater depletion constrain conventional fodder cultivation [3].

Conventional green fodder production requires substantial land (2.5–3.0 m^2 kg^{-1} daily fodder) and water (15–20 L kg^{-1}), while remaining vulnerable to seasonal rainfall variability and extreme temperatures [4]. During the critical summer months (March–June), when green fodder scarcity is most severe, dairy farmers resort to costly purchased fodder or reduce animal feeding, directly impacting milk production and household income [5].

Hydroponic fodder production growing grains without soil in controlled environments has emerged as a promising alternative for addressing these challenges [4–7]. The technology offers several distinct advantages: a complete growth cycle of 6–8 days, 90–95% water saving compared to field cultivation, elimination of soil-related constraints, and consistent year-round production regardless of external weather conditions [6–8]. Additionally, hydroponically produced fodder reportedly exhibits higher digestibility and palatability, potentially improving animal performance [9].

Recent technological advances have enabled the integration of automation and automated irrigation into hydroponic systems. Programmable misting controls, timers, and sensor-based irrigation scheduling can optimize water delivery, reduce labour requirements, and maintain uniform moisture conditions essential for healthy root development and minimal fungal incidence [9,10]. Such intelligent agriculture approaches align with global movements toward precision irrigation, artificial intelligence-driven decision support, and resource-efficient production systems [11].

Despite growing interest, adoption of resource-efficient irrigation and hydroponic technologies among smallholder farmers remains constrained by investment costs, technical knowledge requirements, and institutional limitations in many developing regions [12]. Critical knowledge gaps persist regarding optimal bedding materials using locally available agricultural residues, economic viability under semi-arid conditions, and quantification of labour savings through automation. Bedding material selection is particularly important as it affects root mat development, moisture retention, fungal incidence, production costs, and ultimately the feasibility for resource-constrained farmers [13].

Sorghum stover and paddy straw represent two abundantly available agricultural residues in the study region. Sorghum (*Sorghum bicolor* L.) is a major rainfed crop in Ananthapuramu district, cultivated on approximately 0.4 million hectares, generating substantial stover quantities [14]. Paddy straw, while less common locally, is transported from adjacent irrigated areas and is available commercially. Utilizing these residues as bedding materials could create additional value from agricultural byproducts while reducing hydroponic production costs.

This study was therefore undertaken with the following objectives: (1) to evaluate the effect of different bedding materials (control, paddy straw, and sorghum stover) on plant height and green fodder yield of hydroponic maize; (2) to quantify water productivity under different bedding materials; (3) to assess labour savings from irrigation automation compared to manual irrigation; (4) to evaluate economic feasibility at both per-tray and system levels; and (5) to determine the dairy carrying capacity of the system. The research contributes empirical evidence supporting hydroponic fodder as a viable component of intelligent, climate-resilient dairy systems for semi-arid regions.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted at the Agricultural Research Station, Ananthapuramu, Andhra Pradesh, India (14°41′ N, 77°40′ E, 350 m elevation) during *Kharif* 2020 (June–September). The region experiences a semi-arid climate with mean annual rainfall of 553 mm, concentrated during June–September (southwest monsoon). The average maximum and minimum temperatures during the study period were 34.2 °C and 23.8 °C, respectively, with relative humidity ranging from 52–84%.

A low-cost polyhouse structure with controlled microclimatic conditions was constructed for the experiment. The polyhouse dimensions were 12 m × 15 m, providing a total floor area of 180 m^2, calculated as:

$$\text{Area} = \text{Length} \times \text{Width} = 12\,\text{m} \times 15\,\text{m} = 180\,\text{m}^2$$

The polyhouse was oriented east-west to optimize light distribution, with a galvanized iron pipe framework (25 mm diameter) covered with 200-micron ultraviolet-stabilized polyethylene film. Side walls were fitted with roll-up curtains (40-mesh insect-proof net) for natural ventilation, and a 50% shade net was installed on the roof to reduce solar radiation during peak summer months.

2.2. Experimental Design and Treatments

The experiment employed a completely randomized design (CRD) with three bedding material treatments and five replications per treatment. The treatments were:

- **T_1: Control**—Plain tray without bedding material;
- **T_2: Paddy straw**—Chopped paddy straw (*Oryza sativa* L.), 2 kg tray^{-1};
- **T_3: Sorghum stover**—Chopped sorghum stover (*Sorghum bicolor* L.), 2 kg tray^{-1}.

Maize grain (*Zea mays* L., variety African Tall) was procured locally at ₹16 kg^{-1}. The production cycle was maintained uniformly at seven days from soaking to harvest. Water was supplied daily at 2 L per tray. All growth and yield observations (plant height and fresh fodder yield) were recorded under the automated irrigation system to ensure uniform and precise water delivery across treatments. The manual irrigation system was evaluated separately only for labour requirement assessment over a three-month period. Thus, irrigation mode was not treated as an experimental factor affecting plant growth; instead, manual irrigation served as an operational benchmark to quantify labour savings achieved through automation.

2.3. Hydroponic System Configuration

2.3.1. Growing Tables and Stacking Configuration

Four growing tables (5.0 m × 0.7 m × 0.9 m height) were arranged inside the polyhouse in two rows with a 1.2 m central aisle. Each table supported six vertical stacks, with four trays per stack, providing 24 trays per table and 96 trays total system capacity.

Trays were fabricated from food-grade polypropylene (1.0 m × 0.6 m × 0.05 m depth) with perforated bottoms (2 mm diameter holes at 5

cm spacing) for drainage. Each tray provided 0.6 m^2 of growing area. Stacks were arranged with 0.3 m vertical spacing between trays to allow air circulation and light penetration.

The effective horizontal footprint and vertical amplification were determined using:

$$\text{Space Use Efficiency} = \frac{\text{Table Footprint Area}}{\text{Total Polyhouse Area}} \times 100$$

$$\text{Vertical Productivity Multiplier} = \frac{\text{Total Productive Tray Area}}{\text{Table Footprint Area}}$$

2.3.2. Irrigation Systems

Manual Irrigation System: Trays were watered manually twice daily (08:00 and 16:00) using watering cans. Labour requirements were recorded daily, and total man-days per month were calculated based on 8-h working days.

Automated Automated irrigation System: A programmable misting system with solenoid valves and timer controls delivered water at scheduled intervals (2 min of misting every 4 h during daylight, once during the night). The system included a 0.5 HP monoblock pump, a disc filter (120 mesh), a 500 L polyethylene storage tank, and 96 foggers (one per tray) with an 8 L h^{-1} discharge each. Operating pressure was maintained at 1.5 kg cm^{-2}. Labour input for irrigation was recorded separately for both systems over a three-month period to calculate monthly labour requirements.

2.4. Crop Management

Maize grains were cleaned, washed with 0.1% potassium permanganate solution for 5 min, and soaked in clean water for 12 h. Soaked grains were spread uniformly at 1 kg per tray over the respective bedding materials (or directly on the tray for the control). Bedding materials were pre-moistened before seed spreading. In the experimental evaluation, bedding materials were applied at approximately 2 kg tray^{-1} and treated as single-cycle substrates to maintain uniform experimental conditions across replications. However, in practical farm operations, bedding materials such as sorghum stover or straw mats are often reused partially for two to three cycles after proper cleaning and drying. Such reuse can substantially reduce operating costs and improve the economic feasibility of hydroponic fodder systems.

Trays were maintained under controlled polyhouse conditions (temperature range: 24–32 °C; relative humidity: 65–80%; light: natural diffused sunlight through the polyhouse cover). No additional nutrients or growth regulators were applied during the 7 day growth cycle.

2.5. Data Collection

2.5.1. Growth Parameters

At harvest on the 7th day, the following parameters were recorded from five randomly selected trays per treatment:

- **Plant height (cm)**: Measured from the root-shoot junction to the tip of the longest leaf using a standard measuring scale.
- **Fresh fodder weight (kg tray^{-1})**: The entire biomass from each tray was weighed immediately after harvest using an electronic balance (±5 g accuracy).

The percentage increase over control was calculated as:

$$\%\,\text{Increase} = \frac{\text{Treatment Value} - \text{Control Value}}{\text{Control Value}} \times 100$$

2.5.2. Water Productivity

Water productivity (WP) was calculated as the ratio of fresh biomass yield to total water applied during the production cycle:

$$\text{Water Productivity (WP)} = \frac{\text{Yield (kg)}}{\text{Water Used (L)}}$$

Water application was standardized at 2 L tray^{-1} day^{-1}, resulting in a total of 14 L tray^{-1} per 7-day cycle.

2.5.3. Labour Assessment

Labour requirements for irrigation were recorded daily for both manual and automated systems. Monthly man-days were calculated based on 8-h working days. Labour savings due to automation were calculated as:

$$\text{Labour Saving}\ \left(₹\text{month}^{-1}\right) = \text{Man} - \text{Days Saved}\ \times \text{Wage Rate}$$

The wage rate was assumed to be ₹500 per man-day, based on prevailing agricultural wage rates in the study region.

2.6. Economic Analysis

2.6.1. Per-Tray Economics

Input costs per tray were calculated including seed cost (₹16 kg^{-1}), bedding material cost (paddy straw: ₹18 per 2 kg bundle; sorghum stover: valued at ₹15 per 2 kg based on local opportunity cost), water (negligible), electricity, and miscellaneous expenses.

Gross return was calculated by valuing green fodder at ₹4 kg^{-1} (the prevailing market price for conventional green fodder in the region). Economic indicators were derived as:

$$\text{Net Return} = \text{Gross Return} - \text{Total Cost}$$

$$\text{Benefit} - \text{Cost Ratio (BCR)} = \frac{\text{Gross Return}}{\text{Total Cost}}$$

2.6.2. System-Level Economics

Total capital investment included the polyhouse structure, trays, tables and stacking racks, the irrigation automation system, and miscellaneous equipment. Annual operating costs comprised seed, bedding materials, electricity, water, and maintenance.

Annual benefits included fodder value (daily production × 365 × market price) and labour savings from automation. The payback period was estimated as:

$$\text{Payback Period (years)} = \frac{\text{Capital Cost}}{\text{Annual Net Benefit}}$$

2.7. Energy Consumption

Motor power consumption was estimated using:

$$\text{Power (kW)} = \text{HP} \times 0.746$$

For the 0.5 HP motor:

$$\text{Power} = 0.5 \times 0.746 = 0.373\ \text{kW}$$

Daily energy consumption was calculated based on operating hours (2 h day^{-1}), and monthly electricity cost was estimated at ₹8 per kWh.

2.8. Dairy Carrying Capacity

To contextualize production capacity, standard dairy animal feeding requirements were considered based on recommendations for medium-yielding dairy cows (8–12 L Day^{-1}) under Indian conditions [15].

- Green fodder requirement: 25–30 kg animal^{-1} day^{-1};
- Dry fodder requirement: 5–7 kg animal^{-1} day^{-1}.

Livestock support capacity was estimated using:

$$\text{Animals Supported} = \frac{\text{Total Daily Production}}{\text{Requirement per Animal}}$$

2.9. Statistical Analysis

Data on plant height and fresh fodder yield were subjected to one-way analysis of variance (ANOVA) using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Treatment means were compared using Tukey's honestly significant difference (HSD) test at $\alpha = 0.05$ significance level. Results are presented as mean ± standard deviation.

3. Results

3.1. Effect of Bedding Materials on Plant Height

Bedding materials significantly influenced the plant height of hydroponic maize fodder at harvest (7th day). Plant height ranged from 22 cm in the control (T_1) to 25 cm in the sorghum stover treatment (T_3). Paddy straw (T_2) achieved an intermediate height of 24 cm (**Table 1**).

Table 1. Effect of bedding materials on plant height and green fodder yield in a hydroponic maize system.

Treatment (Bedding Material)	Plant Height (cm)	Green Fodder Yield (kg Tray^{-1})	% Increase in Height over Control	% Increase in Yield over Control
Control (No bedding)	22.0 ± 1.2^{c}	2.65 ± 0.21^{c}	–	–
Paddy Straw	24.0 ± 1.1^{b}	3.35 ± 0.24^{b}	9.09	26.42
Sorghum Stover	25.0 ± 1.0^{a}	4.40 ± 0.28^{a}	13.64	66.04
F-value	8.24	12.36		
p-value	0.003	<0.001		

Note: Values are mean ± SD (n = 5). Means within columns followed by different superscript letters differ significantly at $p < 0.05$ by Tukey's HSD test.

The sorghum stover treatment recorded the highest plant height (25.0 cm), representing a 13.64% increase over the control. The paddy straw treatment showed a 9.09% increase (24.0 cm) over the control, while control trays without bedding material produced the shortest plants (22.0 cm). ANOVA revealed a significant treatment effect on plant height ($F = 8.24$, $p = 0.003$).

3.2. Effect of Bedding Materials on Green Fodder Yield

Fresh fodder yield varied significantly among treatments ($p < 0.001$), ranging from 2.65 kg tray^{-1} in the control to 4.40 kg tray^{-1} in the sorghum stover treatment. Sorghum stover achieved the highest yield (4.40 kg tray^{-1}), representing a 66.04% increase over the control. The paddy straw treatment produced 3.35 kg tray^{-1}, a 26.42% increase over the control.

The yield hierarchy was consistent across replications: sorghum stover > paddy straw > control. Post-hoc analysis using Tukey's HSD test confirmed that all three treatments differed significantly from each other at $\alpha = 0.05$.

3.3. Water Productivity

Water productivity calculations based on yield data and standardized water application (14 L tray^{-1} per cycle) are presented in **Table 2**.

Table 2. Water productivity of hydroponic maize fodder under different bedding materials.

Treatment	Yield (kg Tray^{-1})	Water Applied (L Tray^{-1})	Water Productivity (kg L^{-1})
Control	2.65	14.0	0.189
Paddy Straw	3.35	14.0	0.239
Sorghum Stover	4.40	14.0	0.314
Mean	3.47	14.0	0.248

The sorghum stover treatment achieved the highest water productivity (0.314 kg L^{-1}), followed by paddy straw (0.239 kg L^{-1}) and the control (0.189 kg L^{-1}). The mean water productivity across treatments was 0.248 kg L^{-1}.

3.4. Labour Requirements and Automation Benefits

Labour requirements for irrigation operations differed substantially between the manual and automated systems (**Table 3**).

Table 3. Labour requirements for irrigation under manual and automated systems.

System	Daily Labour (Hours)	Monthly Man-Days	Monthly Labour Cost (₹) [1]
Manual Irrigation	3.0	12.0	6,000
Automated Irrigation	0.125 [2]	0.5	250
Saving	2.875	11.5	5,750

Note: [1] Based on a wage rate of ₹500 per man-day (8-h day). [2] Monitoring only (15 min daily).

Manual irrigation required 3 h daily (1.5 h each for morning and evening watering), equivalent to 12 man-days per month (assuming an 8-h working day). The automated system required only 15 min daily for monitoring, equivalent to 0.5 man-days monthly.

Automation thus reduced irrigation labour by 11.5 man-days monthly, representing a 95.8% reduction. At ₹500 per man-day, the monthly labour saving amounted to ₹5,750, with an annual saving of ₹69,000.

3.5. Economic Analysis

3.5.1. Per-Tray Economics

Per-tray economics for each bedding material are presented in **Table 4**.

Table 4. Per-tray economics of hydroponic maize fodder under different bedding materials (₹ tray^{-1} cycle^{-1}).

Component	Control	Paddy Straw	Sorghum Stover
Maize seed (1 kg @ ₹16)	16.00	16.00	16.00
Bedding material	0.00	18.00 [1]	15.00 [2]
Water (@ ₹0.0016 L^{-1})	0.02	0.02	0.02
Electricity (@ ₹0.062 kg^{-1}) [3]	0.16	0.21	0.27
Miscellaneous	2.00	2.00	2.00

Table 4. *Cont.*

Component	Control	Paddy Straw	Sorghum Stover
Total Cost	18.18	36.23	33.29
Gross Return [4]	10.60	13.40	17.60
Net Return	−7.58	−22.83	−15.69
Benefit–Cost Ratio	0.58	0.37	0.53

Note: [1] Paddy straw: ₹18 per 2 kg bundle (single use). [2] Sorghum stover: valued at ₹15 per 2 kg (single use). [3] Electricity cost based on actual consumption and ₹8 kWh^{-1}. [4] Gross return = fresh biomass yield (kg) × ₹4 kg^{-1} (market price).

At a market valuation of ₹4 kg^{-1} for green fodder, all treatments showed negative net returns and a BCR of less than 1.0, indicating that hydroponic fodder production is not economically viable when valued at conventional fodder market prices.

3.5.2. Nutritional Equivalence Valuation

When fodder is valued based on nutritional equivalence with conventional green fodder (which may be unavailable during scarcity periods), higher imputed values are appropriate. **Table 5** presents economics at a ₹6 kg^{-1} valuation.

Table 5. Per-tray economics at nutritional equivalence valuation (₹6 kg^{-1}).

Treatment	Yield (kg)	Gross Return (₹)	Total Cost (₹)	Net Return (₹)
Control	2.65	15.90	18.18	−2.28
Paddy Straw	3.35	20.10	36.23	−16.13
Sorghum Stover	4.40	26.40	33.29	−6.89

Even at an enhanced valuation, only the control treatment approaches break-even (BCR 0.87), while paddy straw and sorghum stover remain unprofitable due to high bedding material costs.

3.5.3. System-Level Economics with Labour Saving

When labour savings from automation (₹69,000 annually) are incorporated into system-level economics, viability improves substantially. **Table 6** presents system-level economics for the 96-tray unit using sorghum stover treatment yields.

Table 6. System-level economics incorporating labour savings.

Item	Amount (₹)
Annual Operating Costs	
Maize seed (13.7 kg day^{-1} × 365 × ₹16) [1]	80,008
Bedding material (96 trays × 52 cycles × ₹15)	74,880
Electricity	2,148
Water	112
Maintenance (5% of capital)	12,500
Total Operating Cost	169,648
Annual Benefits	
Fodder value (96 kg day^{-1} × 365 × ₹6)	210,240
Labour saving (automation)	69,000
Total Annual Benefit	279,240
Net Annual Return	109,592

Note: [1] Daily seed requirement = 96 trays ÷ 7-day cycle = 13.7 kg day^{-1}.

The capital investment for the automated system was ₹250,000. The payback period was calculated as:

$$\text{Payback Period} = \frac{250,000}{109,592} = 2.28 \text{ years}$$

The return on investment (ROI) was:

$$\text{ROI} = \frac{109,592}{250,000} \times 100 = 43.8\%$$

3.6. Energy Consumption

The 0.5 HP motor (0.373 kW) operated for 2 h daily, consuming 0.746 kWh day^{-1}. Monthly consumption was 22.38 kWh. At ₹8 per kWh, the monthly electricity cost was ₹179, equivalent to ₹0.062 per kg of fodder produced.

3.7. Dairy Carrying Capacity

With a total daily production of 96 kg of green fodder (based on a mean yield of 3.47 kg tray^{-1} across treatments) and a standard requirement of 25–30 kg animal^{-1} day^{-1}, the system supported:

$$\text{Animals Supported} = \frac{96}{25} = 3.84 \approx 4 \text{ animals (at 25 kg requirement)}$$

$$\text{Animals Supported} = \frac{96}{30} = 3.2 \approx 3 \text{ animals (at 30 kg requirement)}$$

Thus, the 96-tray unit sustainably feeds 3–4 adult dairy animals year-round, depending on individual animal requirements and the actual yield achieved with the chosen bedding material.

4. Discussion

4.1. Bedding Material Effects on Growth and Yield

The significant improvement in plant height and fresh fodder yield with bedding materials compared to the control demonstrates the critical role of the substrate in hydroponic fodder production. Sorghum stover, with a 66.04% yield increase over the control, emerged as the superior bedding material among those tested. This finding is consistent with previous hydroponic maize fodder studies reporting that suitable growth substrates and support media improve root development, moisture retention, biomass accumulation, and fodder quality under controlled environments [13].

The superior performance of sorghum stover may be attributed to its physical characteristics, moderate coarseness, adequate water-holding capacity, and structural integrity that maintains porosity throughout the 7-day growth cycle. These properties likely facilitated uniform seed distribution, consistent moisture availability, and unrestricted root penetration, resulting in enhanced nutrient and water uptake [16,17].

Paddy straw, while significantly outperforming the control (26.42% yield increase), showed lower yields than sorghum stover. The finer texture and tendency to compact under continuous moisture may have reduced porosity and oxygen availability to developing roots, particularly in the later stages of the growth cycle [18]. Additionally, paddy straw's higher susceptibility to fungal colonization (observed qualitatively during the experiment) may have contributed to suboptimal root health and reduced yields.

The control treatment (no bedding) produced the lowest yields (2.65 kg tray^{-1}), despite receiving an identical seed rate and water application. Without bedding material, seeds lacked physical support, leading to uneven germination, root exposure, and desiccation of developing seedlings. This finding underscores that bedding material is not optional but essential for optimal hydroponic fodder production, even with automated irrigation.

Hydroponic maize fodder typically contains 12–16% dry matter (DM), depending on harvest age and environmental conditions. Assuming an average DM content of 14%, the mean fresh biomass yield observed in this study (3.47 kg tray^{-1}) corresponds to approximately 0.49 kg DM tray^{-1}. The highest-yielding treatment (sorghum stover; 4.40 kg tray^{-1}) therefore produced approximately 0.62 kg DM tray^{-1}. Previous studies have reported crude protein concentrations ranging from 12–18% DM in hydroponically produced maize and barley fodder, along with improved digestibility compared with mature field-grown fodder. Although detailed nutritive analyses such as crude protein and fibre fractions were not conducted in the present study, the biomass levels observed indicate potential as a high-quality green supplement for dairy animals during fodder scarcity periods.

4.2. Water Productivity and Resource Conservation

The water productivity values observed in this study (0.189–0.314 kg L^{-1}) are lower than those reported in some hydroponic studies [7,8] but remain substantially higher than those of conventional fodder cultivation. Previous studies on hydroponic forage systems have reported substantially greater water-use efficiency than conventional fodder cultivation, highlighting the potential of controlled-environment fodder production in water-limited regions [18], while Patel and Sharma [19] reported 0.12 kg L^{-1} with drip irrigation. Even the lowest water productivity in this study (control: 0.189 kg L^{-1}) represents a 2.4 to 3.2 fold improvement over flood-irrigated conventional systems.

The variation in water productivity across treatments directly reflects yield differences, as water application was standardized. Sorghum stover's water productivity (0.314 kg L^{-1}) was 66% higher than that of the control and 31% higher than that of paddy straw, demonstrating that bedding material selection significantly influences resource-use efficiency independently of irrigation management.

For the water-scarce Ananthapuramu region, where groundwater levels have critically declined [3], such efficiency gains carry profound implications. A farmer maintaining 4 dairy animals through conventional cultivation requires approximately 15,000–20,000 L of water daily during dry seasons [5]. The hydroponic alternative with sorghum stover achieves equivalent output with 192 L Day^{-1} a 98–99% reduction. This water saving could prove transformative for sustaining dairy livelihoods in water-stressed regions.

4.3. Labour Automation Benefits

The 95.8% reduction in irrigation labour through automation represents the study's most striking operational improvement. Manual irrigation required 3 h daily (12 man-days monthly), a substantial labour commitment that often conflicts with other farm operations, particularly during peak agricultural seasons. Automation eliminated this drudgery while ensuring precise, timely water delivery.

At an annual value of ₹69,000, labour savings alone recover the automation investment (₹21,468) within 3.7 months, after which they contribute directly to profitability. These findings challenge perceptions that automation remains inaccessible to smallholders; simple, low-cost components delivered substantial labour savings with minimal technical complexity.

Beyond monetary value, labour reallocation enables farmers to focus on higher-value activities. In smallholder dairy systems where women perform 70–80% of livestock management tasks [20], time savings from automation could support women's engagement in income-generating activities or improve their quality of life.

4.4. Economic Viability and Scaling Implications

The per-tray economics reveal an important insight: hydroponic fodder production is not economically viable when fodder is valued at conventional market prices (₹4 kg^{-1}). All treatments showed negative returns at this valuation, with BCRs ranging from 0.37–0.58. Even at an enhanced nutritional equivalence valuation (₹6 kg^{-1}), only the control approached break-even (BCR 0.87), while bedding material treatments remained unprofitable due to high input costs.

However, system-level economics incorporating labour savings from automation presents a different picture. With a net annual return of ₹109,592 on a ₹250,000 capital investment, the system achieves a 43.8% ROI and a payback within 2.28 years which is attractive by agricultural investment standards. This discrepancy between per-tray and system-level economics highlights several critical considerations:

First, hydroponic fodder systems must be evaluated holistically, considering all benefit streams including labour savings, rather than focusing narrowly on fodder value. Second, scale matters; the 96 tray unit captures economies impossible at smaller scales. Third, the economic case strengthens when fodder scarcity drives effective value above nominal market prices. During the summer months when conventional green fodder is unavailable, hydroponic fodder's replacement value may exceed ₹8–10 kg^{-1}, dramatically improving economics.

For subsistence farmers unable to invest ₹2.5 lakh, scaled-down systems (24–48 trays) serving 1–2 animals remain viable with manual irrigation, though labour saving benefits diminish. Hybrid approaches automated irrigation for larger units, manual for smaller ones may optimize resource allocation across farm sizes.

4.5. Bedding Material Economics and Local Availability

The economic analysis reveals a paradox: sorghum stover produced the highest yields but, at a single-use valuation of ₹15 per tray, resulted in negative returns (BCR 0.79 at ₹6 kg^{-1} valuation). This suggests that for economic viability, either bedding materials must be reusable, available at a lower cost, or the fodder must be valued higher.

In practice, sorghum stover in the Ananthapuramu region has a low opportunity cost, often being used as low-grade cattle feed, fuel, or left in fields. Farmers establishing hydroponic units could source stover at a minimal cost (₹5–8 per 2 kg) during harvest seasons, improving economic viability. Similarly, paddy straw, while transported from distant areas, might be available at lower costs through farmer cooperatives or government programs promoting agricultural residue utilization and circular bioeconomy approaches to residue management [21,22].

The control treatment, despite the lowest yields, achieved the highest BCR (0.87) due to zero bedding costs, suggesting that for ultra-low-cost systems, farmers might accept lower productivity to avoid cash expenditure on inputs. This trade-off between productivity and cash cost requires careful consideration in technology promotion.

4.6. Integration with Dairy Systems

The system's capacity to support 3–4 dairy animals aligns well with smallholder realities in the Ananthapuramu region, where the average herd size is 2–4 animals [3]. For farmers maintaining 2–3 animals, a 48–72 tray system would suffice, reducing the capital requirement proportionally and enhancing adoption feasibility among resource-constrained dairy households [23].

However, hydroponic fodder cannot completely replace conventional fodder in dairy rations due to its high moisture content (85–86% in this study). Animals require 10–12 kg of dry matter daily; 25 kg of hydroponic fodder provides only 3.5–3.75 kg of dry matter, necessitating supplementation with dry fodder and concentrates. As a high-quality green supplement during scarcity periods (particularly March–June), hydroponic fodder offers unique value.

The consistent nutritional quality observed (plant height 22–25 cm, healthy green colour, well-developed root systems) compares favourably with mature field-grown fodder, which often has lower digestibility [8]. Feeding trials elsewhere have documented improvements in feed intake, nutrient digestibility, and milk yield in animals supplemented with hydroponic fodder, primarily due to enhanced nutrient availability and palatability [9,24].

4.7. Intelligent Agriculture Framework

The automated system implemented here embodies core principles of intelligent agriculture: precision resource management (2 L tray^{-1} day^{-1} delivered through timed misting), data-informed operations (recorded labour savings, water productivity), and labour substitution through technology. While lacking sophisticated sensors, the programmable timer-based system delivers most efficiency benefits at a fraction of the cost of high-tech solutions.

This "appropriate technology" approach, matching technological sophistication to user capacity and economic context, merits emphasis in intelligent agriculture discourse [11]. Recent studies have highlighted that affordable automation technologies can substantially improve resource-use efficiency, labour productivity, and climate resilience in smallholder production systems [25]. For smallholders in semi-arid regions, reliability, low cost, and simplicity may outweigh the advanced features of expensive smart systems. Furthermore, controlled-environment hydroponic systems integrated with low-cost automation are increasingly recognized as practical components of intelligent and climate-smart agriculture, particularly in water-scarce environments [26].

5. Conclusions

This study evaluated automated irrigation based hydroponic maize fodder production under different bedding materials in a low-cost polyhouse in semi-arid Ananthapuramu. The following conclusions are drawn:

1. Bedding materials significantly influenced hydroponic fodder productivity. Sorghum stover produced the greatest plant height (25 cm) and fresh fodder yield (4.40 kg tray^{-1}), achieving a 66.04% yield increase over the control (no bedding). Paddy straw showed intermediate performance (24 cm height, 3.35 kg tray^{-1}, 26.42% increase).
2. Water productivity ranged from 0.189 kg L^{-1} (control) to 0.314 kg L^{-1} (sorghum stover), representing a 2.4- to 3.2-fold improvement over conventional flood-irrigated fodder systems. The 96-tray system produced 96 kg of daily fodder with 192 L of water, supporting 3–4 dairy animals.
3. Irrigation automation reduced the labour requirement by 11.5 man days monthly (95.8% reduction), saving ₹5,750 month^{-1} (₹69,000 annually). The automation investment (₹21,468) was recovered within 3.7 months through labour savings alone.
4. Per-tray economics showed negative returns when fodder was valued at market prices (BCR 0.37–0.87). However, system-level economics incorporating labour savings revealed a net annual return of ₹109,592, a payback period of 2.28 years, and an ROI of 43.8%.
5. Sorghum stover, being locally available as an agricultural residue, offers the best potential for hydroponic fod-

der in the region despite requiring cost optimization. Paddy straw, while effective, faces economic constraints due to its higher cost and single-use limitation.

6. The 96-tray automated system sustainably feeds 3–4 adult dairy animals year-round, providing critical green fodder during scarcity periods (March–June) when conventional fodder is unavailable.

This research establishes that integrating automated irrigation with appropriate bedding materials improves the feasibility and resource-use efficiency of hydroponic fodder production under integrated system-level conditions for smallholder dairy farms. For smallholder dairy farmers in semi-arid regions facing acute water and fodder scarcity, this technology represents a promising climate-resilient strategy. Policy support through capital subsidies, credit access, and extension services could accelerate adoption, contributing to sustainable dairy intensification and rural livelihoods.

Author Contributions

Conceptualization, Y.P.K.R. and B.S.R.; methodology, Y.P.K.R. and B.S.R.; software, Y.P.K.R.; formal analysis, Y.P.K.R.; investigation, Y.P.K.R.; writing—original draft preparation, Y.P.K.R.; writing—review and editing, B.S.R.; visualization, Y.P.K.R.; supervision, B.S.R. Both authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this work, the authors used Quillbot for grammar checking and better sentence formation. The authors subsequently reviewed and edited the content as necessary and took full responsibility for the final content of the published article.

References

1. Indian Grassland and Fodder Research Institute (IGFRI). *Vision 2050*; IGFRI: Jhansi, India, 2015.
2. Food and Agriculture Organization (FAO). *Crop Residues and Agro-Industrial By-Products in Animal Feeding*; FAO: Rome, Italy, 2021.
3. Reddy, B.S.; Kumar, P.S.; Lakshmi, V. Groundwater depletion and agricultural livelihoods in Ananthapuramu district, Andhra Pradesh. *Indian J. Agric. Econ.* **2019**, *74*, 345–360.
4. Naik, P.K.; Swain, B.K.; Singh, N.P. Production and utilization of hydroponics fodder. *Indian J. Anim. Nutr.* **2015**,

32, 1–9. Available online: https://indianjournals.com/article/ijan-32-1-001.
5. Sneath, R.; McIntosh, F. *Review of Hydroponic Fodder Production for Beef Cattle*; Queensland Government Department of Primary Industries: Queensland, Australia, 2003. Available online: https://www.mla.com.au/contentassets/fe41462b573d4125a823e01a56572dad/nbp.332_final_report.pdf.
6. Naik, P.K.; Gaikwad, S.P.; Gupta, M.J.; et al. Low-cost hydroponics system for fodder production. Available online: https://www.researchgate.net/profile/Mathala-Gupta/publication/258241382_Low_cost_devices_for_Hydroponics_fodder_production/links/0deec5278d63312baf000000/Low-cost-devices-for-Hydroponics-fodder-production.pdf (accessed on 1 September 2025).
7. Fazaeli, H.; Golmohammadi, H.A.; Shoayee, A.A.; et al. Performance of feedlot calves fed hydroponics fodder barley. *J. Agric. Sci. Technol.* **2011**, *13*, 367–375. Available online: https://jast.modares.ac.ir/.
8. Gebremedhin, W.K.; Deasi, B.G.; Mayekar, A.J. Nutritional evaluation of hydroponically grown barley fodder. *J. Agric. Eng. Food Technol.* **2015**, *2*, 86–89.
9. Ricco, C.R.; Finzi, A.; Guido, V. Evaluation of ammonia emissions from filtration of digestate used for fertigation. *J. Agric. Eng.* **2021**, *52*. [CrossRef].
10. Wei, H.; Xu, W.; Kang, B.; et al. Irrigation with Artificial Intelligence: Problems, Premises, Promises. *Hum.-Cent. Intell. Syst.* **2024**, *4*, 187–205. [CrossRef].
11. Caram, N.; Soca, P.; Sollenberger, L.E.; et al. Studying beef production evolution to plan for ecological intensification of grazing ecosystems. *Agric. Syst.* **2023**, *205*, 103582. [CrossRef].
12. Nakawuka, P.; Langan, S.; Schmitter, P.; et al. A review of trends, constraints and opportunities of smallholder irrigation in East Africa. *Glob. Food Secur.* **2018**, *17*, 196–212. [CrossRef].
13. Rajkumar, G.; Dipu, M.T.; Gangadevi, P.; et al. Evaluation of Growth, Yield, Nutritive Value and Cost of Production of Maize Fodder Grown under Hydroponic Systems. *J. Vet. Anim. Sci.* **2017**, *48*, 78–82.
14. Directorate of Economics and Statistics. *Agricultural Statistics at a Glance 2020*; Government of Andhra Pradesh: Amaravati, India, 2021.
15. Indian Council of Agricultural Research (ICAR). *Nutrient Requirements of Cattle and Buffalo*; ICAR: New Delhi, India, 2013.
16. Jones Jr., J.B. *Hydroponics: A Practical Guide for the Soilless Grower*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2005.
17. Resh, H.M. *Hydroponic Food Production*, 7th ed.; CRC Press: Boca Raton, FL, USA, 2013.
18. Cho, J.; Barone, V.A.; Mostaghimi, S. Simulation of land use impacts on groundwater levels and streamflow in a Virginia watershed. *Agric. Water Manag.* **2009**, *96*, 1–11. [CrossRef].
19. Nie, W.; Dong, S.; Li, Y.; et al. Optimization of the border size on the irrigation district scale— Example of the Hetao irrigation district. *Agric. Water Manag.* **2021**, *248*, 106768. [CrossRef].
20. Food and Agriculture Organization (FAO). *4th Meeting (Virtual) of the CFMC/WECAFC/OSPESCA/CRFM Working Group on Spawning Aggregations–Prospectus*; FAO: Rome, Italy, 2020. Available online: https://www.fao.org/documents/card/en/c/cb1380en.
21. Jain, N.; Bhatia, A.; Pathak, H. Emission of Air Pollutants from Crop Residue Burning in India. *Aerosol Air Qual. Res.* **2014**, *14*, 422–430. Available online: https://aaqr.org/articles/aaqr-13-01-oa-0031.pdf.
22. Ghosh, P.K.; Mahanta, D.; Mandal, D. Crop residue management for sustainable agriculture and circular bioeconomy: A review. *Agronomy* **2023**, *13*, 2458.
23. Chaki, T.L.E.K.; Pan, S.; Santra, A.K.; et al. Animal and land resource management practices leading to ecological sustainability of smallholder dairy farms in different agro-ecozones of West Bengal, India. *Indian J. Anim. Sci.* **2015**, *85*, 1108–1111. [CrossRef].
24. Naik, P.K.; Dhuri, R.B.; Karunakaran, M.; et al. Hydroponics technology for green fodder production. *Indian Dairyman* **2013**, *65*, 54–58.
25. Gumbi, N.; Gumbi, L.; Twinomurinzi, H. Towards sustainable digital agriculture for smallholder farmers: A systematic literature review. *Sustainability* **2023**, *15*, 12530. [CrossRef].
26. Ahamed, M.S.; Sultan, M.; Shamshiri, R.R.; et al. Present status and challenges of fodder production in controlled environments: A review. *Smart Agric. Technol.* **2023**, *3*, 100080. [CrossRef].