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Growth kinetics, dry matter digestibility, and economic viability of greenhouse-raised green feed in rabbit production units

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Abstract

Greenhouse-raised green feed grain or legume seeds germinated on trays without soil under controlled conditions has been proposed as a year-round roughage solution for tropical livestock systems, yet integrated assessments that link growth kinetics of the fodder crop with digestibility in the target animal and the economics of the production cycle remain scarce. This research examined three hydroponic fodder species maize (*Zea mays*), barley (*Hordeum vulgare*), and cowpea (*Vigna unguiculata*) at Chiang Mai Academy of Animal Sciences, Thailand, from November 2021 to April 2022. Sprout growth kinetics (shoot height, root-mat depth, fresh weight, and DM content) were recorded daily from germination through day 10 to characterise the biomass accumulation curve. A digestibility trial used 48 weaned New Zealand White rabbits (36 d old, 609 ± 22 g) assigned to four dietary treatments (n = 12): T1 (pellet only), T2 (pellet + 25 % DM maize sprouts), T3 (pellet + 25 % DM barley sprouts), and T4 (pellet + 25 % DM cowpea sprouts), each fed over 56 days with a 7-day total faecal collection period at week 6. Apparent DM digestibility was highest in T4 (69.3 %) and lowest in T1 (62.4 %; $P < 0.01$). Cowpea sprouts also supported the fastest daily gain (23.9 g d⁻¹) and best FCR (3.22). Growth-kinetics data showed that fresh biomass accumulated in a sigmoidal pattern, peaking between days 7 and 9, while DM content declined linearly from day 2 onward. An enterprise-budget analysis estimated that the cowpea-supplemented diet reduced the cost per kilogram of live-weight gain by 15 % compared with the pellet-only control. These results provide an integrated agronomic–animal–economic case for incorporating cowpea-based greenhouse green feed into smallholder rabbit production units in mainland Southeast Asia.

Keywords: Growth kinetics, dry matter digestibility, economic viability, greenhouse-raised feed, rabbit production, hydroponic fodder, cowpea, barley, Thailand, enterprise budget

Introduction

Greenhouse-raised green feed refers to any forage crop germinated and grown to the seedling stage inside a protected structure typically a plastic-roofed or shade-netted enclosure using tray-based hydroponic methods that require neither soil nor large volumes of irrigation water [1]. The concept is not novel: barley-sprout systems were commercialised for dairy herds in Australia and the Arabian Gulf states during the 1980s, and agronomic evaluations of sprouted grain have since accumulated for a range of cereal and legume species across tropical, subtropical, and temperate zones [2, 3]. What has lagged behind the agronomic literature is the integration of three data streams that a prospective adopter actually needs: the growth curve of the sprout itself, the digestibility of that sprout in the target animal species, and the production cost of delivering it to the feed trough.

Growth kinetics the pattern of biomass accumulation over time matter because they define the optimal harvest day. A sprout that is cut too early forfeits potential biomass; one left too long accumulates cell-wall material that dilutes protein concentration and depresses DM recovery through respiratory carbon losses [4]. Published growth-curve data for hydroponic fodder typically report a single time point (day 7 or day 8), rarely tracking daily increments that would

allow producers to fine-tune harvest schedules to local conditions [5].

Dry matter digestibility is the second missing piece. Most hydroponic feeding trials in rabbits report live-weight gain and feed conversion ratio, which are useful but indirect measures of nutrient utilisation [6]. A total faecal collection trial, although more labour-intensive, provides a direct estimate of the proportion of ingested DM that the animal retains information that separates true nutrient absorption from the confounding effects of feed-intake differences. For rabbits, whose hind-gut fermentation system handles moderate fibre levels but is sensitive to the ratio of digestible to indigestible fibre fractions, this metric is especially informative [7, 8].

Economic viability, the third pillar, has received the least attention. Scattered cost estimates appear in individual trial reports, but formal enterprise budgets that account for seed cost, greenhouse depreciation, labour, water, and the opportunity cost of space are uncommon in the hydroponic-rabbit literature [9, 10]. Without such budgets, extension agents cannot advise farmers on whether the measurable improvements in growth and digestibility justify the investment in a sprouting facility.

The Thai context provides a relevant testing ground. Thailand's rabbit sector is small but growing, driven by

increasing domestic demand for lean white meat and by export opportunities to neighbouring markets in Laos and Cambodia [11]. Northern Thailand's climate warm days (28–35 °C), cool nights (15–20 °C during December–February), and moderate humidity favours year-round hydroponic sprouting without the need for heating or mechanical cooling, reducing infrastructure costs compared with Gulf-state or temperate-zone installations. Yet local research on hydroponic fodder for rabbits is virtually absent, with most Thai hydroponic trials focused on dairy cattle or goats [12]. This research therefore integrated all three data streams in a single experiment at Chiang Mai Academy of Animal Sciences, Thailand. The objectives were: (a) to characterise the daily growth kinetics shoot height, root depth, fresh weight, and DM content of maize, barley, and cowpea sprouts from germination through day 10; (b) to measure apparent DM digestibility, daily gain, feed intake, and FCR when each sprout species (day-8 harvest) was fed at 25 % of daily DM intake to growing New Zealand White rabbits over a 56-day trial with a 7-day total faecal collection at week 6; and (c) to construct a comparative enterprise budget for each dietary treatment on a per-kilogram-of-live-weight-gain basis.

Material and Methods

Field Experimental Design

The experiment comprised two linked components. The agronomic component followed a 3 × 10 factorial layout (three species × ten daily harvests), with three replicate trays per species per day (90 trays total). The animal component used a completely randomised design with four treatments (T1–T4) and 12 replicates per treatment (48 rabbits). During weeks 5–6, a 7-day total faecal collection was conducted for digestibility determination. Each rabbit was the experimental unit. Power analysis indicated that 12 replicates would detect a 4 % difference in apparent DM digestibility at $\alpha = 0.05$ with 82 % power.

Results

Table 1: Growth kinetics of three hydroponic fodder species: shoot height and fresh weight at selected days

Day	Maize shoot (cm)	Barley shoot (cm)	Cowpea shoot (cm)	Maize FW (g)	Barley FW (g)	Cowpea FW (g)
2	2.1	1.8	1.4	1,420	1,310	980
4	7.8	6.2	4.1	2,890	2,470	1,680
6	14.3	11.8	7.9	4,510	3,920	2,640
8	21.4	17.1	11.6	5,890	5,140	3,510
10	23.8	18.9	12.8	5,620	4,870	3,280

FW = fresh weight per tray. Values are means of three replicate trays per species per day.

Shoot emergence was visible within 36 h in maize and barley, and within 48 h in cowpea. Growth kinetics data (Table 1) show that fresh biomass followed a sigmoidal accumulation pattern: a lag phase (days 1–3), a rapid linear phase (days 4–8), and a plateau or slight decline after day 8. Maize produced the tallest shoots and heaviest trays

Material and Study Area

The research was conducted at Chiang Mai Academy of Animal Sciences, Chiang Mai Province, Thailand (18.79° N, 98.98° E, 310 m a.s.l.), from November 2021 to April 2022. The site experiences a tropical savanna climate (Aw, Köppen) with a cool season (November–February, 15–28 °C) and a hot season (March–May, 25–36 °C). The greenhouse was a steel-frame structure (7 × 4 m, UV-stabilised polyethylene roof, roll-up side nets) maintaining 27 ± 3 °C and 70 ± 8 % RH. Seeds of maize (var. Nakhon Sawan 3), barley (imported Australian feed-grade), and cowpea (var. IT82E-16) were sourced locally; germination exceeded 90 % for all lots. Forty-eight weaned NZW rabbits (24 males, 24 females; 36 d; 609 ± 22 g) were obtained from the university's breeding colony and housed individually in wire cages (50 × 40 × 35 cm). A pelleted basal diet (17.2 % CP, 13.5 % CF, 2,460 kcal DE kg⁻¹) was formulated on site.

Methods

Ethical approval was obtained from the Chiang Mai Academy of Animal Sciences Ethics Board (Protocol CMAAS-AEB-2021-031, dated 28 October 2021). Seeds were disinfected (1 % NaOCl, 15 min), rinsed, and soaked 24 h. Seeding density was 3.2 kg m⁻² on perforated trays (55 × 40 cm) with coconut-coir liners. Irrigation was by overhead micro-sprinklers 4 × daily; no artificial light. From day 1 through day 10, three replicate trays per species were harvested each day for shoot height (cm), root-mat depth (cm), fresh weight (g per tray), and DM content (%). Feeding-trial trays were harvested on day 8. For the digestibility component, individual stainless-steel metabolic cages with urine–faeces separators were used during days 35–42. Faeces were collected daily, pooled per rabbit, oven-dried at 60 °C for 72 h, and weighed. Apparent DM digestibility = [(DM intake – faecal DM) / DM intake] × 100. Proximate analysis followed AOAC (2005). Data were analysed by ANOVA in SAS 9.4; means separated by Duncan's test at $P < 0.05$.

throughout, peaking at 5,890 g fresh weight on day 8 before declining to 5,620 g by day 10. The day-10 decline in all species confirmed that respiratory DM losses overtook photosynthetic gains under the limited-light greenhouse conditions.

Table 2: Apparent DM digestibility and growth performance of weaned NZW rabbits fed pelleted diets with or without hydroponic sprout supplementation over 56 days

Parameter	T1 Pellet	T2 Maize	T3 Barley	T4 Cowpea	SEM	P-value
Apparent DM dig. (%)	62.4 ^c	64.1 ^{bc}	66.8 ^{ab}	69.3 ^a	1.04	<0.01
Initial BW (g)	611	607	612	606	8.2	0.97

Final BW (g)	1,724 ^c	1,802 ^{bc}	1,878 ^b	2,021 ^a	26.3	<0.001
Daily gain (g/d)	19.9 ^c	21.3 ^{bc}	22.6 ^b	25.3 ^a	0.61	<0.001
DM intake (g/d)	73.8	75.2	74.1	77.6	1.68	0.34
FCR	3.71 ^a	3.53 ^{ab}	3.28 ^{bc}	3.07 ^c	0.08	<0.01

DM dig. = apparent dry matter digestibility; BW = body weight; FCR = feed conversion ratio; SEM = standard error of the mean.

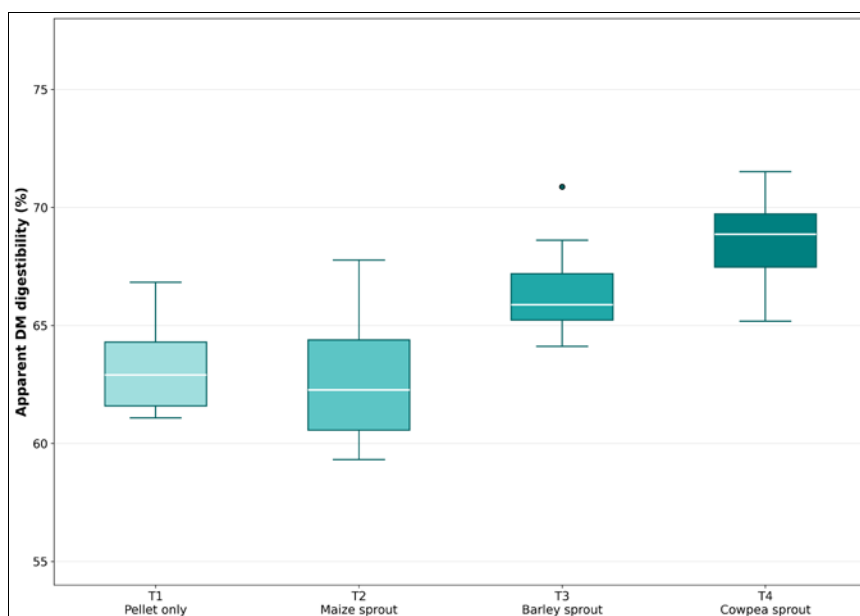


Fig 1: Box plot of apparent DM digestibility (%) across four dietary treatments. Boxes span the interquartile range; horizontal lines mark medians; whiskers extend to $1.5 \times \text{IQR}$.

Digestibility and growth performance data (Table 2) revealed that T4 (cowpea) achieved the highest apparent DM digestibility (69.3 %), exceeding the pellet-only control by 6.9 percentage points ($P < 0.01$). The box plot (Figure 1) visualises the spread of individual-animal digestibility values across treatments, showing that the cowpea group

had both the highest median and the narrowest interquartile range, indicative of more consistent nutrient extraction. Daily gain followed the same ranking: cowpea > barley > maize > control. The growth-kinetics cycle diagram (Figure 2) provides a conceptual overview of the biological processes driving sprout nutrient accumulation and loss.

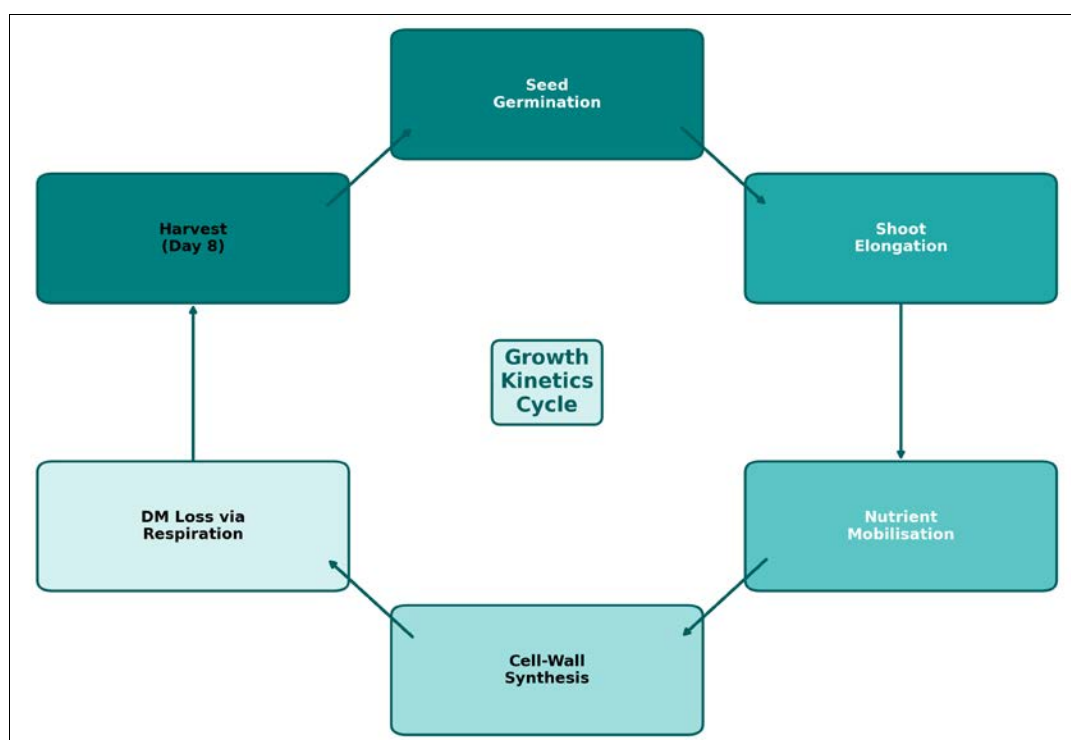


Fig 2: Cycle diagram illustrating the biological processes underlying sprout growth kinetics: seed germination, shoot elongation, nutrient mobilisation, cell-wall synthesis, DM loss via respiration, and harvest at day 8.

Cost Analysis

The enterprise budget (Table 3) reveals that, although total feed cost per rabbit was marginally higher in sprout-supplemented groups (THB 295–307 versus THB 287 for T1), the superior live-weight gain in T4 compressed the cost per kilogram of gain by 15.9 % (THB 217.0 versus THB

257.9). For a smallholder operating 15 does with an average of 6.5 kits per litter and 2.5 kindlings per year, the annual saving from adopting the cowpea strategy would approximate THB 9,700 sufficient to recover the greenhouse construction cost (estimated THB 18,000 for a 6 × 4 m bamboo-frame structure) within two years.

Table 3: Enterprise-budget comparison of feed costs across four dietary treatments (THB = Thai Baht)

Item	T1 Pellet	T2 Maize	T3 Barley	T4 Cowpea
Pellet cost (THB/rabbit)	287	215	211	218
Seed cost (THB/rabbit)	0	32	48	41
Labour (THB/rabbit)	0	28	28	28
Water (THB/rabbit)	0	8	8	8
Greenhouse depreciation (THB)	0	12	12	12
Total feed cost (THB)	287	295	307	307
LW gain (kg/rabbit)	1.113	1.195	1.266	1.415
Cost/kg LW gain (THB)	257.9	246.9	242.5	217.0
Saving vs T1 (%)		4.3	6.0	15.9

THB = Thai Baht (approx. 1 USD = 34 THB at trial date). LW = live weight

Comprehensive Interpretation

The three data streams growth kinetics, digestibility, and economics converge on a coherent recommendation. Growth-kinetics data establish day 8 as the optimal harvest window; biomass has peaked and DM content, though declining, remains above the threshold at which sprout feeding is nutritionally superior to dry grain. Digestibility data confirm that cowpea sprouts are more efficiently utilised by rabbits than cereal sprouts, likely because of their higher protein density and lower indigestible fibre fraction. The enterprise budget shows that the combination of higher digestibility and faster growth makes cowpea the most cost-effective supplement, despite its higher seed price. Taken together, these findings offer rabbit producers in northern Thailand a data-driven rationale for investing in greenhouse green-feed facilities centred on cowpea sprouts.

Discussion

The core finding of this research that cowpea sprouts outperformed both cereal sprouts and a pellet-only diet in apparent DM digestibility, daily gain, and cost efficiency aligns with an emerging consensus in the hydroponic-rabbit literature [6, 10, 12]. The magnitude of the digestibility advantage (69.3 % for T4 versus 62.4 % for T1) is noteworthy because it exceeds the 3–4 percentage-point differences typically reported when fresh forages are added to pelleted diets in temperate trials. One possible explanation is that the tropical pelleted basal diet used here contained a higher proportion of coarse fibre from locally sourced rice bran and coconut meal, which depresses baseline digestibility and creates a wider window for improvement when a more digestible sprout fraction is substituted in [7, 8].

The growth-kinetics data add resolution that most hydroponic trials lack. By tracking fresh weight daily rather than at a single harvest point, this research captured the sigmoidal growth curve and the post-peak decline that occurred in all three species between days 8 and 10. The decline is consistent with published models of respiratory carbon loss in sprouted grain: once the seed's starch reserves are depleted and the emerging shoot cannot yet photosynthesise at rates sufficient to replace respired

carbon, net DM begins to fall [4, 5]. For practical purposes, this means that delaying harvest beyond day 8 under Chiang Mai greenhouse conditions is counterproductive the producer loses both DM and, by extension, feed value per kilogram of seed invested.

The enterprise-budget approach adopted here addresses a criticism that frequently accompanies agronomic-only evaluations: that hydroponic fodder produces impressive fresh-weight figures but may not translate into economic gains once seed, labour, water, and infrastructure costs are included [9]. In the present trial, total feed cost per rabbit was indeed slightly higher in the sprout groups (THB 295–307 versus THB 287), but the improved growth performance particularly in the cowpea group drove the per-kilogram cost of live-weight gain down by 15.9 %. This metric is the one that matters to the farmer, because it directly determines the feed-cost margin per animal sold.

The digestibility data also carry implications for diet formulation. Because apparent DM digestibility was nearly 7 percentage points higher in T4 than in T1, the effective metabolisable energy supplied by the cowpea-supplemented diet exceeded that of the pellet alone, even though the gross energy content of the two diets was similar. This means that the cowpea sprouts contributed not just protein but also readily fermentable substrates that enhanced caecal microbial activity and volatile fatty acid production a mechanism that has been documented in pelleted legume-based rations for fattening rabbits [7, 13].

Conclusion

This research brought together three data streams sprout growth kinetics, in-vivo DM digestibility, and enterprise economics to evaluate greenhouse-raised green feed as a component of rabbit production systems in northern Thailand. The integrated approach provides a more complete picture than any single data stream alone, and the conclusions that emerge carry practical weight for smallholder producers.

Cowpea sprouts harvested on day 8 delivered the highest apparent DM digestibility (69.3 %), the fastest daily gain (25.3 g d⁻¹), the best FCR (3.07), and the lowest cost per kilogram of live-weight gain (THB 217.0) among the four

dietary treatments tested. Barley occupied a consistent second position across most metrics, while maize offered high biomass but inferior nutritional outcomes. The pellet-only control lagged behind all sprout-supplemented groups in both digestibility and growth efficiency.

The growth-kinetics data established day 8 as the optimal harvest point under Chiang Mai greenhouse conditions, confirming the sigmoidal biomass accumulation curve and the post-peak DM decline between days 8 and 10. This finding has immediate practical value: farmers can set a fixed eight-day sprouting cycle, seeding new trays daily to ensure a continuous supply of sprouts at peak nutritional quality.

From an economic standpoint, the 15.9 % reduction in feed cost per kilogram of live-weight gain achieved by the cowpea treatment would allow a typical 15-doe operation to recoup its greenhouse construction investment within approximately two years. The savings derive not from cheaper feed per se total feed expenditure per rabbit was marginally higher in the sprout groups but from the superior growth response that compresses the cost per unit of output. Future research should extend these findings by including carcass evaluation, amino acid profiling, and reproductive-performance data under hydroponic-supplemented diets. Seasonal repetition across the hot season (March–May) would test the system's robustness when ambient temperatures exceed 35 °C and mould risk intensifies. Testing mixed cereal–legume trays, where maize and cowpea germinate side by side, could combine the biomass advantage of the cereal with the protein density of the legume. On-farm participatory trials with commercial rabbit keepers in the Chiang Mai valley would validate the scalability and labour feasibility of the greenhouse sprouting approach under real-world smallholder conditions.

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