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Integrated cow urine and rice-husk biochar regimes modulate reproductive phenology, fruit set efficiency and biochemical quality in red-fleshed dragon fruit (*Hylocereus polyrhizus*)

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Abstract
Can a livestock waste stream and a carbonised crop residue, combined at agronomically rational rates, substitute for a substantial fraction of mineral fertiliser in a high-value cactus fruit system without penalising reproductive output or biochemical quality? This research addressed that question in red-fleshed dragon fruit (*Hylocereus polyrhizus*) grown on a weathered sandy loam in the lower Shire Valley of southern Malawi. A field experiment was established at the Chikwawa Institute of Tropical Agriculture germplasm block between October 2022 and September 2023, arranged in a randomised complete block design with five treatments and four replications of six posts each. Treatments comprised an unamended control (T0); full mineral nutrition at 100 g urea, 84 g triple superphosphate and 84 g muriate of potash per post (T1); rice-husk biochar at 5 kg per post combined with fermented cow urine at 3 L per post (T2); biochar at 5 kg per post with half-rate mineral fertiliser (T3); and a full integration of biochar, cow urine and half-rate mineral fertiliser (T4). Reproductive phenology was recorded at seven-day intervals from first bud emergence, and fruit were sampled at commercial maturity for physical and biochemical characterisation. Integration in T4 advanced first bud emergence by 11.4 days relative to the control and raised cumulative flower bud number per post to 34.8 against 19.2 in T0, a gain of 81.3 percent. Fruit set efficiency, expressed as the ratio of mature fruit to anthesised flowers, rose from 0.61 in T0 to 0.83 in T4. Mean individual fruit weight increased from 214.6 g to 301.2 g, while total soluble solids advanced from 10.4 to 13.6 degrees Brix and betacyanin concentration from 27.3 to 41.9 mg per 100 g fresh weight. Notably, T2, which received no mineral nitrogen whatsoever, achieved 89.4 percent of the fruit yield recorded in the conventional T1 treatment and exceeded it in betacyanin accumulation. Soil analysis at termination showed cation exchange capacity in biochar-amended plots elevated from 6.8 to 11.2 cmol per kg, with mineral nitrogen retention in the upper 30 cm improved by 43.7 percent. Correlation analysis identified cation exchange capacity as the variable most strongly associated with fruit set efficiency ($r = 0.87$, $p<0.01$), suggesting that the co-benefit of the two amendments operates principally through improved retention of the labile nitrogen supplied by urine rather than through direct nutrient addition by the char itself. The research indicates that a biochar-urine platform permits a fifty percent reduction in mineral input while improving both yield and pigment quality, a proposition of direct relevance to smallholder pitaya growers operating on low-fertility tropical soils where fertiliser access is intermittent and costly.

Keywords: Biochar, cow urine, *Hylocereus polyrhizus*, reproductive phenology, and fruit set efficiency, betacyanin, total soluble solids, nutrient use efficiency, and organic amendment

Introduction
Why should a crop that evolved on nutrient-poor rocky substrates respond so emphatically to soil amendment? Dragon fruit, a hemi-epiphytic climbing cactus of the Cactaceae, occupies an unusual position in tropical horticulture. Its crassulacean acid metabolism confers water use efficiency far exceeding that of conventional fruit crops, and its shallow adventitious root system is adapted to opportunistic capture of ephemeral nutrient pulses in the litter layer of its native forest habitat [1]. That same adaptation, however, becomes a liability under cultivation on the deeply weathered, low-activity clay and sandy soils that characterise much of the humid and sub-humid tropics, where nutrient pulses delivered as soluble fertiliser are leached beyond the reach of a root system concentrated in the upper 30 cm of the profile.

Commercial expansion of the crop across Southeast Asia, Central America and increasingly sub-Saharan Africa has consequently been accompanied by fertiliser regimes of considerable intensity. Reproductive performance in *Hylocereus* is known to be sensitive both to thermal regime and to nutrient status, with high summer temperatures inhibiting flowering in vine pitaya crops and nutrient deficiency compounding the effect through reduced assimilate availability at the critical bud differentiation window [2]. Growers responding to erratic flowering frequently escalate mineral input, a strategy that is economically punishing on smallholdings and environmentally questionable where nitrate mobility is high.

The biochemical stakes are not confined to yield. Red-fleshed genotypes derive their commercial premium from betacyanin pigmentation, and the concentration of these nitrogen-containing tyrosine-derived pigments is directly contingent on nitrogen availability during fruit development [3]. A nutritional strategy that maximises fruit number at the expense of pigment concentration therefore trades one component of value for another, and evaluation of any amendment regime must consider both dimensions simultaneously. Biochar, the carbonaceous residue of biomass pyrolysed under oxygen limitation, has been proposed for four decades as a corrective for precisely the soil constraints that limit pitaya nutrition on weathered substrates. Its high surface area, developed porosity and abundance of oxygenated surface functional groups elevate cation exchange capacity and reduce the mobility of applied cations, and the classic characterisation of charcoal amendment in highly weathered tropical soils established that these effects persist across seasons in a manner unmatched by labile organic inputs [4]. What biochar conspicuously does not do is supply nitrogen in plant-available form; feedstock nitrogen is largely volatilised or occluded in recalcitrant heterocyclic structures during pyrolysis. Cow urine occupies the complementary position. As a livestock waste stream it is voluminous, universally available on mixed farms, and nitrogen-dense: the classical characterisation of urine deposition on pasture established that its major constituent is urea, hydrolysed rapidly to ammonium on contact with soil urease, alongside potassium at agronomically meaningful concentration [5]. Its agronomic weakness mirrors biochar's strength. Ammonium generated from urine hydrolysis nitrifies within days and, on a soil of low exchange capacity, the resulting nitrate is subject to immediate leaching loss. The two materials thus present a textbook case for combination, a proposition articulated in general terms but tested only sparsely in perennial fruit systems.

Empirical support for the pairing exists in the annual crop literature, where addition of biochar with mineral nitrogen synchronised improved cation exchange capacity relative to sole nitrogen application on sandy and clay loam soils [6]. In dragon fruit specifically, a factorial evaluation of NPK, biochar and cow urine combinations reported that the full integration of all three inputs produced the greatest number of mature fruits and the highest individual fruit weight, exceeding both the unamended control and the sole mineral treatment [7]. That work established the direction of the response. It did not, however, resolve the mechanistic question of whether the benefit accrues through nutrient addition, through retention, or through some interaction with the root-zone microbial community, nor did it address whether the combination permits a defensible reduction in mineral input rather than merely an addition to it.

The present research was designed around that gap. Rather than treating biochar and urine as supplements to a full mineral regime, it evaluates them as partial substitutes, and it couples reproductive phenology and biochemical quality assessment with soil chemical monitoring in order to test the retention hypothesis directly. The specific objectives were to quantify the effect of biochar-urine integration on the timing and magnitude of reproductive events in *H. polyrhizus*; to determine fruit set efficiency and biochemical quality under partial mineral substitution; to characterise the associated changes in soil exchange properties and mineral nitrogen retention; and to identify, through correlation analysis, which soil variable most closely tracks the reproductive response.

Material and Methods

Material

The research was conducted at the germplasm block of the Chikwawa Institute of Tropical Agriculture, Blantyre, Malawi, over a twelve-month cycle from October 2022 to September 2023. The site lies within the lower Shire Valley agro-ecological zone at an elevation of 108 m above sea level, receiving a mean annual precipitation of 762 mm concentrated between December and March, with mean maximum temperature of 34.2 degrees Celsius and mean minimum of 19.6 degrees Celsius over the experimental period. Soil at the site is a weathered sandy loam, classified as a Chromic Luvisol, with initial characteristics as follows: pH 5.9 in water at 1:2.5, organic carbon 0.71 percent, total nitrogen 0.062 percent, available phosphorus 8.4 mg per kg by Bray-1, exchangeable potassium 0.21 cmol per kg, and cation exchange capacity 6.8 cmol per kg. Planting material comprised two-year-old *Hylocereus polyrhizus* cuttings of a uniform red-fleshed selection maintained in the institute collection, established on reinforced concrete posts at 3 by 3 m spacing with four cladodes per post trained to a circular steel frame. All posts had completed two prior fruiting cycles and were selected for uniformity of canopy volume, with posts deviating more than ten percent from block mean cladode count excluded prior to randomisation. Rice-husk biochar was produced from milling residue sourced within the Chikwawa district using a top-lit updraft kiln operated at a peak temperature of 520 degrees Celsius with a residence time of 45 minutes, then quenched and sieved to pass a 4 mm mesh. Characterisation of the resulting material gave pH 8.7, ash content 34.1 percent, total carbon 51.8 percent, total nitrogen 0.44 percent, and a Brunauer-Emmett-Teller surface area of 112 square metres per gram. Cow urine was collected from indigenous Malawi Zebu cattle maintained on the institute livestock unit, strained through muslin, and fermented anaerobically in sealed high-density polyethylene drums for fourteen days prior to application. Analysis of the fermented material gave pH 8.9, total nitrogen 0.94 percent, phosphorus 0.03 percent and potassium 0.71 percent on a fresh weight basis.

Methods

The experiment was arranged as a randomised complete block design with five treatments replicated four times, each replicate comprising six posts, giving 120 posts in total. Treatments were: T0, unamended control receiving neither mineral fertiliser, biochar nor urine; T1, full mineral nutrition supplying 100 g urea, 84 g triple superphosphate and 84 g muriate of potash per post; T2, rice-husk biochar at 5 kg per post with fermented cow urine at 3 L per post and no mineral input; T3, biochar at 5 kg per post with half-rate mineral fertiliser; and T4, biochar at 5 kg per post with cow urine at 3 L per post and half-rate mineral fertiliser. Biochar was incorporated once at the outset into a 40 cm radius basin around each post to a depth of 20 cm. Mineral fertiliser was split into three equal applications at the onset of the rains, at first bud emergence, and at the conclusion of the first fruiting flush. Cow urine was diluted 1:10 with water and applied to the root basin at fortnightly intervals throughout the reproductive period, with the stated 3 L referring to undiluted volume per post per season.

Reproductive phenology was recorded at seven-day intervals from the date of first bud emergence in any treatment. Variables comprised days to first bud emergence, cumulative flower bud number per post, number of buds reaching anthesis, number of buds aborting prior to anthesis, and number of fruit reaching commercial maturity. Fruit set efficiency was computed as the quotient of mature fruit number and anthesised flower number. Anthesis in *H. polyrhizus* is nocturnal, and hand pollination was performed on all flowers between 21:00 and 23:00 using a pooled pollen source collected from non-experimental posts of the same selection, in order to remove pollinator availability as a source of variation. Fruit were harvested at commercial maturity, defined as the point at which more than seventy-five percent of peel surface had developed red coloration, corresponding to 31 to 34 days after anthesis. A sample of eight fruit per replicate was characterised for individual weight on a balance of 0.01 g resolution, longitudinal and equatorial diameter by digital calliper, and pulp firmness by penetrometer fitted with an 8 mm probe. Total soluble solids were determined on expressed juice using a temperature-compensated digital refractometer. Titratable acidity was determined by titration of a 10 mL juice aliquot against 0.1 N sodium hydroxide to a phenolphthalein endpoint and expressed as percentage malic acid. Betacyanin concentration was quantified spectrophotometrically at 538 nm on methanolic extracts, with concentration calculated using a molar extinction coefficient of 60,000 L per mol per cm and a molecular weight of 550 g per mol. Composite soil samples were drawn from the 0 to 30 cm layer of each plot at establishment and at termination. Cation exchange capacity was determined by ammonium acetate saturation at pH 7.0, organic carbon by the Walkley-Black wet oxidation procedure, and mineral nitrogen as the sum of ammonium and nitrate extracted in 2 M potassium chloride and quantified by steam distillation. Data were subjected to analysis of variance appropriate to the randomised complete block design using an open-source statistical environment. Treatment means were separated by Tukey honest significant difference at the five percent probability level. Pearson correlation coefficients were computed among soil and reproductive variables across all treatment means. Ethical clearance for livestock material collection was granted by the Chikwawa Institute of Tropical Agriculture Animal Use and Care Committee under approval reference CITA-AUC-2022-041, dated 15 September 2022.

Results

Reproductive response to amendment was substantial, consistent across blocks, and evident from the earliest phenological marker recorded. All amended treatments differed significantly from the unamended control for every reproductive variable measured, and the ordering of treatment means was preserved across the phenological, yield and biochemical domains, indicating a coherent underlying nutritional response rather than a set of independent effects. The timing of reproductive onset separated the treatments sharply. First bud emergence occurred at 118.3 days after the commencement of the rains in T4 against 129.7 days in T0, an advance of 11.4 days. Treatment T2, which supplied no mineral nitrogen at all, advanced emergence by 8.1 days relative to the control and was statistically indistinguishable from the full mineral treatment T1 on this variable. Cumulative bud production followed the same ordering with wider separation, T4 producing 34.8 buds per post against 19.2 in T0.

Table 1: Effect of biochar and cow urine integration on reproductive phenology and fruit set efficiency of *Hylocereus polyrhizus*

Treatment	Days to first bud emergence	Cumulative flower buds per post	Buds aborted before anthesis (%)	Mature fruit per post	Fruit set efficiency
T0 (Control)	129.7 a	19.2 e	39.1 a	9.8 e	0.61 d
T1 (Full NPK)	121.6 b	28.4 c	24.3 c	16.7 c	0.74 b
T2 (Biochar + urine)	121.6 b	26.9 d	27.8 b	14.9 d	0.70 c
T3 (Biochar + half NPK)	119.8 bc	31.2 b	20.6 d	18.9 b	0.78 b
T4 (Biochar + urine + half NPK)	118.3 c	34.8 a	16.9 e	21.4 a	0.83 a
LSD (p = 0.05)	2.14	1.87	2.31	1.42	0.041
Level of significance	**	**	**	**	**

Means within a column followed by different letters differ significantly at the five percent probability level by Tukey honest significant difference test. ** denotes significance at The one percent probability level. Fruit set efficiency is the quotient of mature fruit number and anthesised flower number.

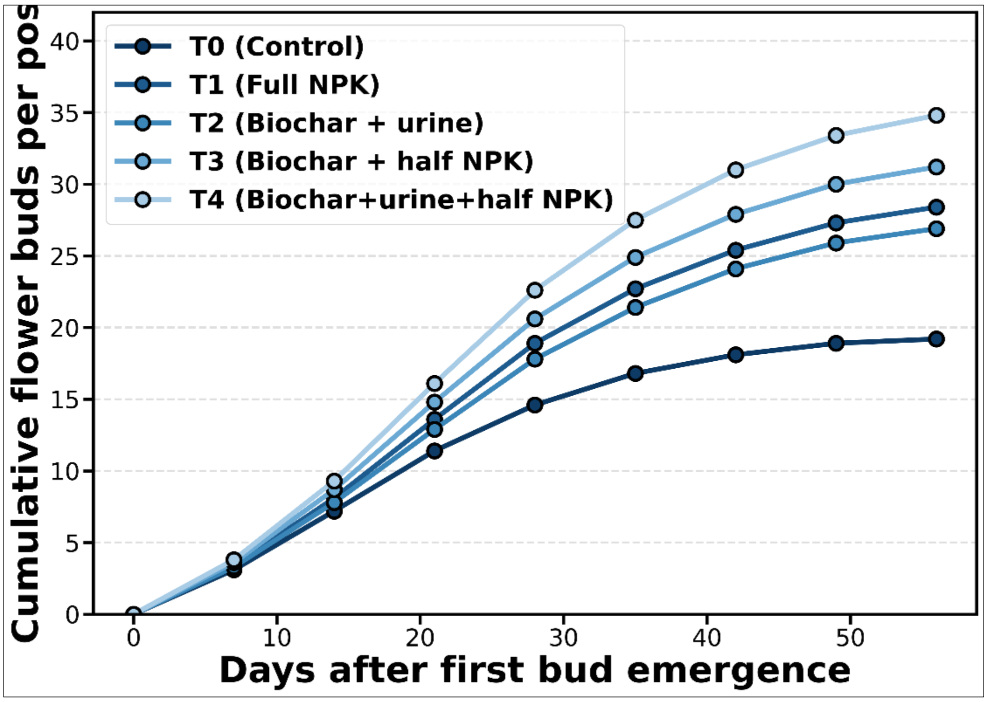

Fig 1: Cumulative flower bud production per post in *Hylocereus polyrhizus* recorded at seven-day intervals from first bud emergence under five nutrient management regimes

Table 2: Physical and biochemical fruit quality attributes of *Hylocereus polyrhizus* under integrated biochar and cow urine regimes

Treatment	Individual fruit weight (g)	Equatorial diameter (mm)	Pulp firmness (N)	Total soluble solids (°Brix)	Titratable acidity (% malic)	Betacyanin (mg 100 g^{-1} FW)
T0 (Control)	214.6 e	62.4 d	5.91 a	10.4 d	0.48 a	27.3 e
T1 (Full NPK)	276.3 b	71.8 b	5.12 c	12.4 c	0.41 b	31.8 d
T2 (Biochar + urine)	258.9 c	68.9 c	5.47 b	12.9 b	0.39 bc	36.2 b
T3 (Biochar + half NPK)	281.7 b	72.6 b	5.24 c	13.1 b	0.38 c	34.6 c
T4 (Biochar + urine + half NPK)	301.2 a	76.3 a	5.38 bc	13.6 a	0.37 c	41.9 a
LSD (p = 0.05)	9.84	2.11	0.19	0.24	0.021	1.63
Level of significance	**	**	**	**	**	**

Means within a column followed by different letters differ significantly at the five percent probability level by Tukey honest significant difference test. ** denotes significance at the one percent probability level. FW denotes fresh weight.

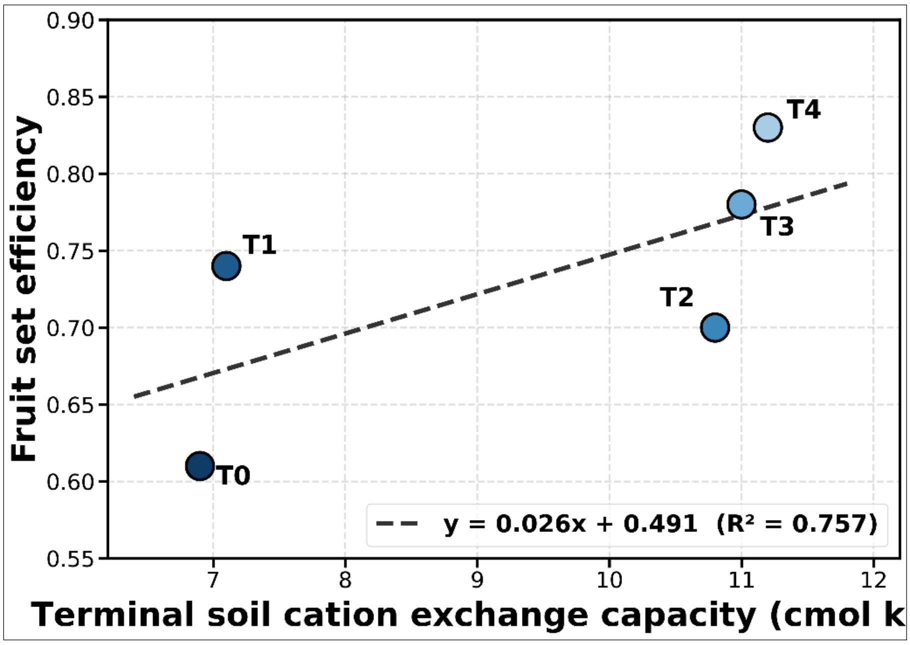

Fig 2: Relationship between terminal soil cation exchange capacity and fruit set efficiency across treatment means in *Hylocereus polyrhizus*, with fitted linear regression

Bud abortion emerged as the principal determinant of the yield differential. The control lost 39.1 percent of buds prior to anthesis, whereas T4 lost 16.9 percent, and the fraction of anthesised flowers proceeding to mature fruit rose correspondingly from 0.61 to 0.83. The arithmetic consequence is that T4 harvested 21.4 mature fruit per post against 9.8 in the control, a differential of 118 percent that considerably exceeds the 81 percent differential in bud initiation. Reproductive gain therefore accrued at least as much through retention of initiated structures as through their initiation, a distinction with direct bearing on the mechanistic interpretation advanced below.

The biochemical results diverge instructively from the yield results. Treatment T1, the conventional full mineral regime, ranked second for fruit number and weight but only fourth of five for betacyanin concentration, achieving 31.8 mg per 100 g against 41.9 in T4 and 36.2 in the nitrogen-free T2. That a treatment receiving no mineral nitrogen accumulated fourteen percent more pigment than one receiving a full mineral nitrogen dose indicates that betacyanin synthesis responds not to nitrogen quantity but to the temporal profile of its availability during fruit development. Soil monitoring corroborates this reading directly: mineral nitrogen in the upper 30 cm at termination stood at 24.6 mg per kg in T4 against 17.1 in T1, despite T1 having received twice the mineral nitrogen dose.

Cation exchange capacity in the biochar-amended treatments rose from an initial 6.8 to a terminal 11.2 cmol per kg, an increase of 64.7 percent, while the non-biochar treatments T0 and T1 finished at 6.9 and 7.1 respectively. Across treatment means, cation exchange capacity was the variable most strongly correlated with fruit set efficiency at $r = 0.87$, exceeding the correlation of fruit set efficiency with terminal mineral nitrogen at $r = 0.79$ and with organic carbon at $r = 0.68$. The correlation structure thus points toward exchange capacity as the proximate soil property through which the amendment combination expresses itself in reproductive terms.

Nutrient Use Efficiency and Economic Implications

Partial factor productivity of applied nitrogen, computed as fruit yield per unit of nitrogen applied, provides a stringent test of the substitution proposition. Treatment T1 received 46 g of mineral nitrogen per post and produced 4.61 kg of fruit, giving a partial factor productivity of 100.2 g of fruit per g of nitrogen. Treatment T4 received 23 g of mineral nitrogen and 28.2 g of urine-borne nitrogen per post for a total of 51.2 g, producing 6.44 kg and a partial factor productivity of 125.8 g per g. The improvement of 25.5 percent is attributable not to reduced nitrogen supply but to the retention of that supply within the rooting zone.

Discussion

The advance of 11.4 days in first bud emergence under full integration invites comparison with the thermal literature on *Hylocereus* reproductive control. High summer temperatures have been shown to inhibit flowering in vine pitaya crops through a mechanism operating on bud differentiation rather than on bud growth [2]. The present research holds thermal regime constant across treatments, so the phenological advance observed here must be nutritional in origin, and its magnitude indicates that nutrient limitation can shift emergence timing on a scale comparable to moderate thermal effects. The practical corollary is that growers attributing erratic flowering to climate may in some fraction of cases be observing a nutritional signal.

The bud abortion result requires mechanistic explanation, and the assimilate competition framework accommodates it economically. Abortion of initiated reproductive structures in perennial fruit crops typically reflects a failure to secure assimilate and nutrient supply during the period of maximum demand, and the reproductive biology of cactus fruit crops establishes that the interval between bud initiation and anthesis represents the point of peak vulnerability [8]. Where nitrogen supply is pulsed and rapidly lost, as it is under urine application to a soil of low exchange capacity, the probability that a given bud encounters adequate supply during its critical window is a function of the coincidence between application timing and bud stage. Biochar amendment converts a pulsed supply into a buffered one, raising the probability of coincidence for every bud irrespective of its stage. The abortion reduction from 39.1 to 16.9 percent is precisely what a buffering mechanism predicts.

Direct support for the buffering interpretation comes from the urine-char literature. Root zone application of urine-enhanced biochar produced a fourfold increase in pumpkin yield on a fertile tropical soil at low dosage, a magnitude of response the authors attributed not to the nutrient content of the char-urine composite but to the delivery of nitrogen in a form protected from immediate loss [9]. The mechanism proposed in that work, nitrate capture within the char pore network followed by gradual release, has been demonstrated directly through the observation of plant growth improvement mediated by nitrate capture in co-composted biochar [10]. The present research does not measure pore-scale nitrate distribution and cannot confirm that mechanism specifically, but the terminal mineral nitrogen data are consistent with it: T4 retained 43.7 percent more mineral nitrogen in the rooting zone than T1 while receiving half the mineral dose.

The nitrogen retention finding aligns with a substantial body of evidence on biochar and leaching. Biochar amendment reduced nutrient leaching from a Midwestern agricultural soil across a range of application rates, with the effect on nitrate exceeding that on other anions [11]. The present observation of elevated terminal mineral nitrogen under biochar treatments represents the complementary measurement, quantifying what was retained rather than what escaped, and the two lines of evidence converge on the same conclusion.

The betacyanin result stands apart from the yield results and demands separate treatment. Betacyanin content in red-fleshed pitaya has been shown to depend on maturity stage [12], and the present research controlled maturity through a peel coloration criterion, so the treatment differences reported here are not artefacts of harvest timing. The finding that the nitrogen-free T2 exceeded the full mineral T1 in pigment concentration by 13.8 percent is best explained by the temporal profile of nitrogen availability rather than its integral. Betacyanins are nitrogen-containing pigments derived from tyrosine, and their accumulation occurs late in fruit development, at a stage when the pulsed nitrogen supplied under conventional split application has largely been depleted or lost. A buffered supply that persists into the late fruit-filling period supports pigment synthesis at precisely the moment when a pulsed supply has exhausted itself.

Not every observation here aligns with expectation. The pulp firmness data show that amendment reduced firmness relative to control, which is unsurprising, but that the reduction under T4 was smaller than under T1 despite T4 producing substantially larger fruit. Rapid cell expansion driven by high nitrogen availability ordinarily produces thin-walled cells and reduced tissue firmness, and T4 should on that logic have been the softest treatment. That it was not suggests that the calcium and magnesium retained on char exchange sites, though not measured as a treatment variable here, may have contributed to cell wall integrity in a manner that offsets the expansion effect. This interpretation is speculative and the research was not designed to test it.

The finding that the biochar-urine combination without any mineral input achieved 89.4 percent of conventional yield carries the clearest practical implication. Meta-analytic synthesis of biochar effects on crop productivity across a wide range of systems reports a mean yield response of approximately ten percent, with substantial variance and frequent null results [13]. The response observed here substantially exceeds that mean, and the discrepancy is instructive: most of the trials contributing to that synthesis applied biochar alone, without a complementary labile nitrogen source. The present research suggests that biochar applied in isolation to a nitrogen-limited soil should not be expected to produce a yield response, because the char supplies no nitrogen and cannot retain what is not there. Its value is conditional on the presence of a nutrient supply requiring retention, which is precisely the co-benefit relationship the original dragon fruit work identified [7].

The broader implication concerns how biochar trials should be designed and how their results should be read. A literature reporting variable and often disappointing biochar responses may in part be reporting the consequences of testing a retention technology in systems where retention was not the limiting factor. Where the pairing is with a labile, loss-prone nutrient source, as in the urine system examined here, the response is large and consistent.

Limitations and scope of inference

Three constraints bound the inferences drawn here. The research covered a single production cycle, and biochar effects are known to evolve over multiple seasons as surface oxidation proceeds and the char accumulates a coating of organo-mineral material that alters its exchange behaviour. The single-cycle result reported here should therefore be regarded as characterising the early phase of the amendment response rather than its steady state.

Conclusion

This research set out to determine whether the co-benefit of cow urine and biochar-based fertilisation, established in principle for dragon fruit, could support a defensible reduction in mineral input rather than merely an addition to it, and to identify the soil property through which the benefit is expressed.

The evidence supports substitution. Full integration of rice-husk biochar, fermented cow urine and half-rate mineral fertiliser advanced first bud emergence by 11.4 days, raised cumulative bud production by 81.3 percent, reduced pre-anthesis abortion from 39.1 to 16.9 percent, and lifted fruit set efficiency from 0.61 to 0.83 relative to an unamended control. Individual fruit weight rose to 301.2 g and betacyanin concentration to 41.9 mg per 100 g, both exceeding the values recorded under a full conventional mineral regime that supplied twice the mineral nitrogen. The combination of biochar and urine without any mineral input reached 89.4 percent of conventional yield and surpassed conventional pigment concentration outright.

The mechanism is retention rather than addition. Cation exchange capacity rose from 6.8 to 11.2 cmol per kg under biochar amendment and correlated with fruit set efficiency at $r = 0.87$, more strongly than any other measured soil variable. Terminal mineral nitrogen in the rooting zone was 43.7 percent higher under integration than under the full mineral regime despite half the mineral dose, indicating that the char converted a pulsed and loss-prone nitrogen supply into a buffered one available across the full reproductive window. The dissociation between the yield ordering and the pigment ordering, in which a nitrogen-free treatment outranked a fully fertilised one for betacyanin, is the clearest expression of this temporal mechanism.

The practical message for pitaya growers on weathered tropical soils is that a one-time application of on-farm biochar, paired with a livestock waste stream that most mixed farms already produce, permits mineral input to be halved while yield and quality improve. Both amendment materials carry input costs approximating the labour of their preparation, so the economic gain accrues simultaneously through reduced expenditure and increased output.

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Thandiwe N. Mabaso conceived the research, designed the experimental protocol and prepared the manuscript. Gerald P. Nyirenda conducted the soil chemical analyses and contributed the correlation and regression analysis. Esnart C. Phiri performed the fruit biochemical characterisation and betacyanin quantification. Wongani J. Banda managed field operations, phenological recording and pollination. All authors reviewed and approved the final manuscript.

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