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Review Article

Productivity of Napier grass (*Pennisetum purpureum*) in Response to Nitrogen Fertiliser Application in Tropical Regions: A Meta-Analysis

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ABSTRACT

The major forage in tropical livestock systems is napier grass (Pennisetum purpureum), and the first input applied to improve its yield is nitrogen. How big a response that is remains to be seen. Field trials are discordant, and many compare multiple nitrogen rates to one untreated control, giving undue weight to the evidence. This meta-analysis synthesises the tropical record that accounts for that dependence. English-language articles were retrieved from Scopus, ScienceDirect and Google Scholar following PRISMA. Effect sizes are reported as Hedges' g and pooled using a random-effects model with cluster-robust variance estimation, with each study (rather than each comparison) serving as the unit of analysis. Twelve studies fulfilled the criteria. Nitrogen increased organic matter, crude protein, plant height, fresh biomass yield and tiller number ($P < 0.05$), crude protein being the most consistent response. There were no changes in dry matter, crude fibre, NDF or ADF. The ether extract, stem diameter, leaf area and leaf number were only studied twice each and could therefore not be reliably assessed. There is no single optimal rate that can be defended because few dose subgroups included 3 independent studies. The practical message is not as broad as the primary literature suggests. Moderate nitrogen supply, before the stand lignifies, increases protein and tillering, but higher rates add little.

Keywords: Chemical composition, forage yield, meta-analysis, napier grass, nitrogen fertilisation

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INTRODUCTION

Forage carries most of a ruminant's diet, commonly 60 to 80% of intake, and it is

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the cheaper half of the ration. In the tropics, that supply has to run year-round, yet the swing between wet and dry seasons keeps interrupting it (Loresco et al., 2019; Monte & Marcos, 2024; Umami et al., 2015). Grasses fill much of the gap, since they yield heavily and tolerate marginal conditions. Forage is also a large share of production cost, so the way a stand is managed sets its value. Quality decides what each animal gains; yield decides what a hectare returns.

Napier grass (*Pennisetum purpureum* Schumach.), also known as elephant grass, is one of the principal forage species of the tropics. Native to sub-Saharan Africa (Muktar et al., 2023), it has since been cultivated across tropical and subtropical regions. The species is a tall, tufted perennial characterised by rapid regrowth and high biomass potential, and it remains productive on soils of low fertility and under limited water (Islam et al., 2023; Rusdy, 2016). Rusdy (2016) reported it to be the highest-yielding of the tropical grasses, which accounts for its use by smallholders and commercial producers alike, as a cut-and-carry forage and as a silage crop to maintain feed supply through the dry season (Kaewpila et al., 2020).

The performance of a livestock system rests on both the yield and the quality of its forage, and soil fertility, managed chiefly through fertilisation, is the principal means of improving them (Umami et al., 2015). Maleko et al. (2019) reported that balanced fertilisation reliably promotes forage growth. Under warm climates, the nutritional composition of the plant, including its energy, protein, and mineral content, is sensitive to management; where these attributes are suboptimal in a grass such as Napier, animal performance declines accordingly (Mutimura et al., 2015).

Getting the agronomy right, especially the fertiliser rate and timing of the cut, is key to a heavy crop. Nitrogen is the first nutrient to run short in the bulk that a stand takes out (Knoll et al., 2013; Rengsirikul et al., 2011). It is highly sensitive to Napier grass. As the rate increases, yield also increases up to a ceiling, since nitrogen builds the chlorophyll and the new leaves that drive photosynthesis (Oliveira et al., 2015; Zewdu et al., 2002). However, evidence is limited, and few studies have identified the actual role of nitrogen in regulating growth and quality of this grass.

Nitrogen has been central to yield and nutritive value, and this has increased interest in forage quality and in production efficiency. It's not just the rate that matters. Plant composition and vegetative growth are also influenced by the source and form of nitrogen. A sustainable system must balance the inputs and the storage and uptake of the plant, as over-accumulation degrades quality (Kering et al., 2012; Monti et al., 2008) and increases cost (Aravindhakshan et al., 2011; Haque et al., 2009). Reported responses in Napier grass are inconsistent and vary with dose, environment and management. This meta-analysis was designed to quantify, in tropical conditions, the global effect of nitrogen on the growth, yield and nutritional quality of the grass.

MATERIAL AND METHODS

Literature Search and Study Selection

The review was conducted in the light of the PRISMA framework (Selcuk, 2019). The objective was to collect published information on the influence of nitrogen fertilisation on the nutrient composition and morphology of Napier grass (Pennisetum purpureum) in tropical environments. Three sources were searched, namely, Scopus (https://www.scopus.com), ScienceDirect (https://www.sciencedirect.com), and Google Scholar (https://scholar.google.com). Keywords: "Nitrogen Fertiliser", "Pennisetum purpureum", "Nutrient Content" and "Morphology".

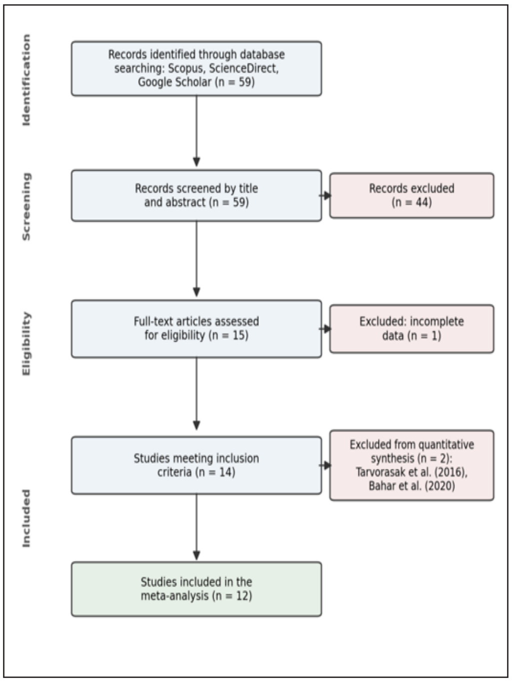

Figure 1. PRISMA flow diagram of the literature search and study selection process

All retrieved articles were screened using a fixed set of inclusion criteria. Inclusion criteria for a study were: (1) peer-reviewed publications in English; (2) experimental work on Pennisetum purpureum of any cultivar or variety; (3) carrying nitrogen fertilisation treatments with matching controls; (4) reporting quantitative data on nutrient composition, morphological traits or both; and (5) reporting details of replication and experimental design. Out of the initial screening, 59 articles were relevant to nitrogen effects on Napier grass in the tropics. A close look at titles and abstracts reduced that to 15. One more was then dropped for incomplete data, leaving 14 that met the criteria; after the two exclusions set out below, 12 studies remained in the quantitative synthesis (Table 1). From these we pulled yield, dry matter, organic matter, crude protein, ether extract, crude fibre, neutral detergent fibre (NDF), acid detergent fibre (ADF), tiller number, stem diameter, plant height, leaf area, and leaf number. Figure 1 lays out the selection process, which followed the PRISMA protocol for systematic reviews and meta-analyses.

This meta-analysis covered the Napier grass complex, defined here as *Pennisetum purpureum* Schumach. (syn. *Cenchrus purpureus*) together with its interspecific hybrids with pearl millet (*P. glaucum*, syn. *P. americanum*). Both pure cultivars (for example, Mott, Taiwan, Red, and BRS Capiacu) and interspecific hybrids (Napier Pakchong 1 and King grass) were included, because the hybrids are derived from *P. purpureum*, are grown and harvested as cut-and-carry forage under comparable management, and are reported in the literature as hybrid Napier grass (Dokbua et al., 2021; Tarvorasak et al., 2016; Muktar et al., 2023). Variety type, pure cultivar or interspecific hybrid, was recorded for every observation and carried into the subgroup analysis as a moderator.

Indexing was deliberately left out of the inclusion rules. Pairing Scopus and ScienceDirect with Google Scholar reaches a wide range of national and regional journals, so a peer-reviewed study in a national outlet still qualified as long as it met the data and design criteria above. If we had only considered the Scopus-indexed pool, most of the tropical Napier and Pakchong work would have been removed as it is more likely to be published in national journals. We did maintain the English language criterion, for the sake of uniformity in data extraction, and accept that this may leave local studies in other languages under-represented.

Table 1
Studies included in the meta-analysis of nitrogen fertilisation in Napier grass

Reference	Country	Variety (Type)	N Source	N rate, kg/ha (basis)	Harvest Age (d)
Veraque & Gorne (2023)	Philippines	Napier (pure)	Urea	0, 30, 60, 120, 240 (per application)	60, 105
Phakamas & Yampracha (2018)	Thailand	Pakchong 1 (hybrid)	Urea	0, 62.5 (soil-test based)	75
Dokbua et al. (2021)	Thailand	Hybrid Napier (hybrid)	Ammonium sulfate	0, 250, 500, 1000 (seasonal total)	70 (6 cuts)
Rukmana et al. (2024)	Indonesia	Red Napier (pure)	Urea	0, 100, 200, 300 (per application)	70
Syam et al. (2021)	Indonesia	Taiwan (pure)	Urea	0, 300 (per application)	60
Widodo et al. (2019)	Indonesia	Mott (pure)	Urea	0, 150, 300 (per application)	42
Fauzi et al. (2019)	Indonesia	Mott (pure)	Urea	0, 300 (per application)	60
Fauzi et al. (2020)	Indonesia	Taiwan, Mott (pure)	Urea + ammonium sulphate	0, 500, 1000 (per application)	60
Alves et al. (2022)	Brazil	BRS Capiaçu (pure)	Protected urea	0, 100, 200 (kg N/ha/year)	60, 90, 120
Hendarto & Setyaningrum (2022)	Indonesia	King grass (hybrid)	Manure & NPK/urea	50, 75, 100 (per application)	60
Zewdu et al. (2002)	Ethiopia	Napier (pure)	Inorganic N (+ manure arm)	0, 46, 92 (per cut)	60
Girgiri et al. (2024)	Nigeria	Napier (pure)	Poultry manure (organic)	0, 42, 56 (N-equivalent)	84

Data Extraction

According to Higgins and Deeks (2008), a meta-analysis systematically applies statistical methods to synthesise and quantify effect sizes derived from multiple studies. The effect size represents the magnitude and direction of a treatment's impact based on quantitative observations of a specific phenomenon. In this study, all variables meeting the inclusion criteria were extracted from the selected articles, including the mean values and measures of variance (standard deviation or standard error) for the outcome variables of interest in both treatment and control groups. Standard error (SE) values were converted to standard deviation (SD) following the method described by Higgins and Deeks (2008), using the formula $SD = SE \times \sqrt{n}$, where n denotes the number of samples in each treatment group. As the studies applied varying nitrogen fertiliser rates, all fertilisation doses were standardised and expressed in kilograms per hectare (kg/ha). The nitrogen application rates were then categorised into four levels: A = 0-100 kg/ha, B = 100-250 kg/ha, C = 250-500 kg/ha, and D > 500 kg/ha. All extracted data from the included studies were compiled and organised in Microsoft Excel 2021 in comma-separated value (CSV) format, which is compatible with subsequent statistical analyses.

Statistical Analysis

Statistical analyses were performed using the OpenMEE software (Wallace et al., 2017) to calculate the standardised mean differences (SMD) between nitrogen fertiliser treatments and the control group. Nitrogen fertiliser dose was treated as a fixed effect, while variation among studies was treated as a random effect. The comparisons were based on SMD values with 95% confidence intervals (CI). Subgroup analyses were also conducted by nitrogen dose category and harvest age to identify potential sources of heterogeneity.

Many of the included trials reported two or more nitrogen rates against one shared control. Their comparisons are therefore not independent. Pooling them as if they were would shrink the variance and inflate the apparent body of evidence, the precise problem flagged at review. To avoid it, the standardised mean differences were combined under a random-effects model with a cluster-robust variance estimator (Hedges et al., 2010; Tipton, 2015), with the study, not the individual comparison, as the unit of analysis. Each parameter is reported with both counts: k comparisons drawn from m independent studies. An estimate was treated as reliable only where m reached three. Heterogeneity was summarised with the I-squared statistic (Higgins et al., 2003), and subgroups by harvest age and nitrogen dose followed the same three-study rule. Two trials were set aside. Tarvorasak et al. (2016) grew the grass in solution culture, where nitrogen is a concentration rather than a field rate, and Bahar et al. (2020) dosed per clump rather than per hectare. One further trial, Dokbua et al. (2021), reported no measure of dispersion and was dropped from the plant-height and stem-diameter analyses, while the acid detergent fibre values of Alves et al. (2022) were rebased to a whole-plant dry-matter basis.

The effect size was estimated as the difference between the experimental and control group means, divided by the pooled standard deviation of the selected treatment group. Heterogeneity among studies was assessed using DerSimonian and Laird's Q statistic (*Chi-square test*) and the inconsistency index (I^2) as described by (Higgins et al., 2003). When P-values were less than 0.05, the effect of nitrogen fertilisation was considered statistically significant. A significant result ($P < 0.05$) indicated that different nitrogen fertiliser doses had a measurable effect on the nutrient composition and morphological characteristics of Napier grass grown under tropical conditions compared to the control group.

Each standardised mean difference was calculated within a study, comparing the fertilised treatments with the unfertilised control grown on the same soil. Between-study differences in baseline soil nitrogen therefore do not bias the estimated effect of nitrogen fertilisation, although they may influence the magnitude of the response and contribute to the between-study heterogeneity observed for several parameters. Baseline soil nitrogen was not reported consistently across the included studies, so it could not be included as a moderator, and we acknowledge this as a limitation.

RESULTS AND DISCUSSION

Effect of Nitrogen Fertilisation on Yield

The effects of nitrogen fertilisation on yield and chemical composition are summarised in Table 2. Pooled across the data, nitrogen lifted fresh biomass yield (SMD = 1.19; 95% CI = 0.36 to 2.02; p = 0.020; k = 16 comparisons from 4 studies). The direction is positive, and the effect is significant relative to unfertilized controls. However, only the 60-day harvest age subgroup survived the three-study rule and remained significant (SMD = 1.36, 95% CI = 0.19 to 2.53, p = 0.038). Each dose category was based on 2 studies or fewer and therefore could not be estimated. This leaves any claim about yield per dose on weak ground.

That growth is due to what happens with nitrogen in the plant. It is present in both chlorophyll and protein, so it is responsible for photosynthesis, cell division and growth all at once. A good supply of it will speed up both vegetative growth and biomass accumulation. Liman et al. (2018) reported that appropriate rates of inorganic nitrogen enhance nutrient availability and root uptake, and thus fresh yield. Tropical soils are generally moist, which enhances diffusion and nitrogen uptake (Hendarto & Setyaningrum, 2022; Ismail, 2012), and plant height, tiller number and leaf area increase with this.

The harvest age pulls on nitrogen use as hard as the supply does (Fauzi et al., 2020; Girgiri et al., 2024). Nitrogen fuels young tissue, and biomass builds fast at the start. As the stand matures, lignification and structural growth tend to slow further gain. A young plant has more leaf to stem and more moisture, so it returns more fresh forage; an older one lays down structural mass slowly. Nitrogen also provides the biochemistry necessary to define quality (Leghari et al., 2016). None of this is a straight-line scale. Beyond a

Table 2
Effect of nitrogen fertilisation on yield and chemical composition of Napier grass

Variables	Covariates	N	Studies	SMD	CI 95% (Lower)	CI 95% (Upper)	SE	P-value	I^2 (%)
Yield	Overall	16	4	1.19	0.36	2.02	0.26	0.020	32
	Harvest age								
	60 d	14	3	1.36	0.19	2.53	0.27	0.038	31
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	4	2	—	—	—	—	not estimable	—
	100- 250 kg/ha	2	1	—	—	—	—	not estimable	—
	250- 500 kg/ha	2	1	—	—	—	—	not estimable	—
	>500 kg/ha	8	1	—	—	—	—	not estimable	—
Dry Matter	Overall	24	9	0.43	-0.34	1.20	0.33	0.231	47
	Harvest age								
	42 d	2	1	—	—	—	—	not estimable	—
	60 d	17	6	0.52	-0.26	1.30	0.30	0.147	29
	70 d	3	1	—	—	—	—	not estimable	—
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	5	3	-0.33	-1.74	1.07	0.33	0.415	0
	100- 250 kg/ha	6	4	0.06	-4.75	4.87	1.51	0.971	77
	250- 500 kg/ha	5	4	0.30	-1.54	2.14	0.58	0.636	64
	>500 kg/ha	8	1	—	—	—	—	not estimable	—
Organic Matter	Overall	14	4	1.20	0.27	2.13	0.29	0.026	0
	Harvest age								
	42 d	2	1	—	—	—	—	not estimable	—
	60 d	12	3	1.14	-0.24	2.53	0.32	0.071	0
	Range dose								
	100- 250 kg/ha	3	2	—	—	—	—	not estimable	—
	250- 500 kg/ha	3	2	—	—	—	—	not estimable	—
	>500 kg/ha	8	1	—	—	—	—	not estimable	—

Table 2 *(continued)*

Variables	Covariates	N	Studies	SMD	CI 95% (Lower)	CI 95% (Upper)	SE	P-value	I² (%)
Crude Fibre	Overall	10	4	-0.31	-2.85	2.23	0.80	0.724	59
	Harvest age								
	42 d	2	1	—	—	—	—	not estimable	—
	60 d	6	2	—	—	—	—	not estimable	—
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	4	2	—	—	—	—	not estimable	—
	100- 250 kg/ha	3	2	—	—	—	—	not estimable	—
	250- 500 kg/ha	3	2	—	—	—	—	not estimable	—
Ether Extract	Overall	6	2	-1.67	-9.85	6.51	0.64	0.235	48
	Harvest age								
	60 d	4	1	—	—	—	—	not estimable	—
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	4	2	—	—	—	—	not estimable	—
	100- 250 kg/ha	2	1	—	—	—	—	not estimable	—
Crude Protein	Overall	23	8	1.32	0.74	1.91	0.25	0.001	12
	Harvest age								
	42 d	2	1	—	—	—	—	not estimable	—
	60 d	19	6	1.39	0.79	1.99	0.23	0.002	0
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	6	3	1.06	-1.89	4.01	0.69	0.261	42
	100- 250 kg/ha	5	3	2.28	-2.75	7.31	1.17	0.191	52
	250- 500 kg/ha	4	3	1.82	1.26	2.39	0.13	0.005	0
	>500 kg/ha	8	1	—	—	—	—	not estimable	—

Table 2 *(continued)*

Variables	Covariates	N	Studies	SMD	CI 95% (Lower)	CI 95% (Upper)	SE	P-value	I^2 (%)
NDF	Overall	13	4	0.08	-0.68	0.84	0.24	0.756	17
	Harvest age								
	60 d	11	3	0.01	-1.02	1.04	0.24	0.966	27
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	4	2	—	—	—	—	not estimable	—
	100- 250 kg/ha	1	1	—	—	—	—	not estimable	—
	>500 kg/ha	8	1	—	—	—	—	not estimable	—
ADF	Overall	6	3	-0.10	-0.69	0.50	0.14	0.554	0
	Harvest age								
	60 d	4	2	—	—	—	—	not estimable	—
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	4	2	—	—	—	—	not estimable	—
	100- 250 kg/ha	2	1	—	—	—	—	not estimable	—

Note. N = number of comparisons; Studies = number of independent studies (clusters). SMD = standardised mean difference (Hedges' g) from a random-effects model with cluster-robust variance estimation; SE = standard error; I^2 = heterogeneity. Subgroups based on fewer than three independent studies are reported as not estimable. Shaded P-values are significant at $P < 0.05$

certain point, uptake efficiency declines as the root zone becomes saturated and excess is lost by leaching and volatilisation. Yield is a balance against soil condition and cost to find a workable dose.

Effect of Nitrogen Fertilisation on Chemical Composition

Nitrogen had no effect on dry matter (SMD = 0.43; 95% CI = -0.34 to 1.20; p = 0.231; k = 24 from 9 studies); the 60-day subgroup was no different (SMD = 0.52; p = 0.147) and the three dose bands that could be estimated, 0 to 100, 100 to 250 and 250 to 500 kg N/ha, told the same flat story. Organic matter was an exception. It climbed under nitrogen (SMD = 1.20; 95% CI = 0.27 to 2.13; p = 0.026; k = 14 from 4 studies), although its one estimable subgroup, the 60-day cut, was marginal and non-significant (SMD = 1.14; 95% CI = -0.24 to 2.53; p = 0.071).

Napier grass can store large quantities of dry matter, ranging from approximately 85.4 t/ha with no fertiliser to as high as 130 t/ha with heavy nitrogen (Islam et al., 2023; Tulu et al., 2021). The range is wide because it is influenced by variety, season, site, soil fertility and management. Dry matter is a quality indicator as it contains most of the nutrients (Rengsirikul et al., 2011; Widodo et al., 2019). But the pooled result shows no steady rise in dry matter with nitrogen. Dose and harvest age are more important than the nutrient itself. The clearest response is seen at about 70 days, when the plant is actively growing and is using nitrogen efficiently for new tissue. With the later cuts, the effect is less because of increased lignification and fibre content.

The wide range in dry matter reported by Zetina-Córdoba et al. (2013) among studies is most likely due to the different nitrogen rates applied. The mechanism is well understood: nitrogen availability fuels photosynthesis and nutrient uptake and switches on the growth hormones auxin, cytokinin and gibberellin that divide and enlarge cells and thus build dry matter (Fauzi et al., 2020). At a given rate, the extra nitrogen contributes little, for as the rate increases the efficiency of uptake falls.

Other fractions provided less reliable answers to nitrogen than did organic matter. Most of the treatments showed an increase because the nutrient is used in the synthesis of organic constituents, mainly protein, structural polysaccharides and lignin (Hendarto & Setyaningrum, 2022; Leghari et al., 2016). One exception, however. In the 250-500 kg N/ha range, the response lost statistical significance, indicating that the organic fraction saturates and stops rising when nitrogen is abundant.

This increase in organic matter is linked to the additional fresh and dry biomass produced by faster growth. This fraction is fed by the same nitrogen-fed photosynthesis and hormone activity that splits and swells cells. Cell-wall share fits into that, as a larger structural fraction generally means more dry matter and more organic matter goes along with it. So nitrogen does raise organic matter, but only as much as the rate and the growth stage allow.

Crude fibre was unaffected by nitrogen (SMD = -0.31; 95% CI = -2.85 to 2.23; p = 0.724; k = 10 from 4 studies), and no subgroup of harvest-age or dose met the three-study bar. Ether extract also showed (SMD = -1.67; 95% CI = -9.85 to 6.51; p = 0.235), but this is read with caution because of two studies. Crude protein was the one clear exception, increasing significantly (SMD = 1.32; 95% CI = 0.74 to 1.91; p = 0.001; k = 23 from 8 studies), and the increase persisted both at the 60 day cut (SMD = 1.39; p = 0.002) and in the 250 to 500 kg N/ha band (SMD = 1.82; 95% CI = 1.26 to 2.39; p = 0.005), with the lower doses remaining flat.

Nitrogen affects the chemical fractions unevenly. As a rule, it reduces the crude-fibre content, but seldom to any appreciable extent. This is because nitrogen prefers young, metabolically active tissue. So the structural pieces, cellulose, hemicellulose and lignin, make up a smaller portion of the whole than they would in an unfertilized plant. As Muhtarudin et al. (2020) put it directly, a better supply of soil nutrients sharpens the plant's control over its cell walls and holds the fibre down.

The small, non-significant increase at 250-500 kg/ha suggests a threshold. Further, as the plant matures, its cell walls thicken, and it develops structural fibre. This is in agreement with Kumari et al. (2022), who reported that inorganic fertilisation improves tissue quality, while nutrient deficiency limits wall formation. Crude fibre cuts both ways. Too much reduces digestibility, increases rumen retention time and pulls productivity down; too little is no better, because ruminants need fibre for normal rumen pH and microbial balance (Goldan et al. 2023; Tuturoong et al., 2020). Fahey et al. (2019) and Hendarto and Setyaningrum (2022) said that lower fibre forage is generally preferred and results in better performance as long as there is sufficient fibre. Age of harvest is important, too, as older stands have more structural tissue.

Nitrogen did not affect ether extract (SMD = -1.67; p = 0.235). The figure is based on only two independent studies, so caution is advised. The lower values are consistent with nitrogen forcing the plant to produce new tissue rather than lipid. This is the normal behaviour of a well-fed plant where dividing and expanding cells are the priority. Plant moisture is also at odds with the ether extract: crude fat increases slowly as the plant matures and dries. Young plants are at the other end, full of dividing cells. Where it has been measured head-on, ether extract in tropical grasses follows regrowth age and season to a much greater degree than it follows fertilisation (Acosta-Balcazar et al., 2024).

Similarly, Maleko et al. (2019) reported that high doses of fertilisers can alter ether extract, and Goldan et al. (2023) connected nutrient supply to growth, biomass, and general quality. Here, a fall in ether extract may be due to breakdown of triglycerides into fatty acids and alcohols. Volatile fatty acids evaporate and pull the fraction down. The ether-extract fraction contains glycerol esters, fatty acids, and fat-soluble vitamins, all of which are likely to vaporise. The fatty acids, on the other hand, protect the surface tissue of the plant, but also serve as an energy store.

Crude protein elicited the strongest and most steady response of all. Nitrogen is the building block of amino acids and protein, so adding more of it directly increases protein synthesis. The literature agrees that a better nitrogen supply improves grass yield, nutritive value and animal performance (Delevatti et al., 2019). Widodo et al. (2019) found that grass given nitrogen alone produced more protein than grass under rotational or traditional cropping, a finding echoed in their results. Here, the response was sustained over nearly all harvest ages and most doses, identifying nitrogen as the principal limitation on protein formation in this grass. When the inorganic fertiliser is well composed, a good supply keeps the meristems active, pushes out new leaves and lifts metabolic rate and protein banks up in the biomass while dry matter and yield rise alongside it (Hendarto & Suwarno, 2018).

Tropical grasses are usually about 10% crude protein, and more nitrogen will usually push the numbers up. And that's pretty much what we saw. Nitrogen has been shown to increase both growth and the accumulation of biomass rich in protein. But the gain is capped by maturity: protein decreases as the plant lignifies and its metabolism slows down. Bayble et al. (2007), Tshering and Penjor (2016) and Wangchuk et al. (2015) recorded sharp protein losses at longer cutting intervals. The evidence taken together suggests that nitrogen accelerates protein-rich tissue in advance of structural tissue, which is why crude protein is so reliably higher in fertilised Napier grass.

Neither fibre fraction moved nitrogen. There was no difference in NDF (SMD = 0.08; 95% CI = -0.68-0.84; p = 0.756; k = 13 from 4 studies), and the subgroup of 60 days was also stable. Whole-plant dry-matter basis ADF was also maintained (SMD = -0.10; 95% CI = -0.69 to 0.50; p = 0.554; k = 6 from 3 studies). This ADF figure corrects an earlier extraction that had entered the annual ADF yield in kg/ha, rather than concentration, which inflated the effect. Plant age, proportion of stem and lignification distinguish both fractions much more than nitrogen (Jimoh et al., 2019; Ojo et al., 2013), and the pooled estimates show the same.

Among all the traits, NDF and ADF tracked nitrogen the least. It hardly registered across treatments, which suggests that structural fibre responds more to plant age than to nitrogen supply. At 60 and 84 days, the stands had matured and lignified, and there was little opportunity for nitrogen to rework the cell wall. There were no categories with three studies, leaving patterns at 100 to 250 kg/ha uninterpreted, and overall nitrogen did not shift either fraction (NDF SMD = 0.08, p = 0.756; ADF SMD = -0.10, p = 0.554). The physiology is simple: both NDF and ADF increase with age as stem fraction and lignin accumulate (Jimoh et al., 2019). High levels of both cut digestibility and intake (Lardner et al., 2015; Nasution et al., 2025). Ojo et al. (2013) also found older plants to be richer in both and poorer as feed.

Effect of Nitrogen Fertilisation on Morphological Traits

The effects of nitrogen fertilisation on the morphological traits are summarised in Table 3. Nitrogen increased plant height with a significant effect (SMD = 0.99; 95% CI = 0.09 to 1.90; p = 0.035; k = 21 from 8 studies). It remained at the 60-day cut (SMD = 0.88; 95% CI = 0.21- 1.54; p = 0.021). All three respective dose bands (0-100, 100-250, 250-500 kg N/ha) pointed upwards; none were significant. In contrast, stem diameter did not respond (SMD = 0.40; p = 0.780). It is reported here for description only based on two studies and a very wide interval.

Nitrogen is part of chlorophyll, amino acids and protein, the materials a plant uses to divide and lengthen its cells, so height increases. Give it enough, and division at the shoot apex runs faster, so the plant stands taller than its unfertilized neighbours. Stronger photosynthesis and steady auxin levels further stretch the internodes (Vennila & Sankaran, 2017), and the stretching is further when the other nutrients and nitrogen arrive together (de Oliveira et al., 2020).

Rukmana et al. (2024) related the height to persistent division in the apical meristem, where the nitrogen supply and plant age together elongate the internodes and increase the volume. Budiman et al. (2012) reported that the height and stem ratio of the crop increased from 8 to 12 weeks (Fauzi et al., 2020). Height is highly correlated with nitrogen availability, which is a major constraint of vegetative growth. The gains at most harvest ages show that plants still in the vegetative phase are spending nitrogen efficiently on photosynthesis and new tissue. The flat response at 84 days tells the opposite story, of heavier lignification and a slower metabolism blunting nitrogen's pull on elongation. Altogether, nitrogen promotes stem growth, vegetative development and carbon assimilation, and this is accompanied by greater height (Dokbua et al., 2021).

Height is more sensitive to nitrogen than stem diameter. In early growth, the nitrogen goes into elongation rather than thickening, so the diameter hardly changes. The increase in radius is related to the development of structures, increases with the age of the plant and the multiplication and swelling of its cells (Zailan et al., 2018) and contributes to the increase of height, volume and size in total. A thicker stem carries more, supports more biomass and better transports water and nutrients (Nasution et al., 2025). And because stems have more lignocellulose and fewer nutrients than leaves (Dokbua et al., 2021), what happens to the stem sets the fibre profile of the whole plant.

Most previous work found that the stem diameter was unaffected by nitrogen rate (Stida et al., 2018), although de Oliveira et al. (2015) observed some movement at the higher end. Above 500 kg/ha, diameter may slightly increase as the plant strengthens its structure to support the additional biomass, but this extra structural material comes at the expense of digestibility and quality (Acosta-Balcazar et al., 2024). Nitrogen is first to division and elongation, so height and leaf expansion precede stem thickening and the diameter is much the same as the rate increases.

Table 3
Effect of nitrogen fertilisation on morphological characteristics of Napier grass

Variables	Covariates	N	Studies	SMD	CI 95% (Lower)	CI 95% (Upper)	SE	P-value	I^2 (%)
Plant height	Overall	21	8	0.99	0.09	1.90	0.38	0.035	51
	Harvest age								
	60 d	15	5	0.88	0.21	1.54	0.24	0.021	23
	70 d	3	1	—	—	—	—	not estimable	—
	75 d	1	1	—	—	—	—	not estimable	—
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	4	3	0.66	-5.06	6.38	1.33	0.669	74
	100- 250 kg/ha	5	3	2.63	-6.49	11.74	2.12	0.341	79
	250- 500 kg/ha	4	3	1.63	-1.02	4.28	0.62	0.118	61
	>500 kg/ha	8	1	—	—	—	—	not estimable	—
Stem diameter	Overall	12	2	0.40	-13.67	14.46	1.11	0.780	50
	Harvest age								
	105 d	4	1	—	—	—	—	not estimable	—
	60 d	8	2	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	6	2	—	—	—	—	not estimable	—
	100- 250 kg/ha	6	2	—	—	—	—	not estimable	—
Number of tillers	Overall	27	7	0.83	0.07	1.59	0.31	0.036	31
	Harvest age								
	60 d	17	4	1.10	-0.71	2.91	0.57	0.147	43
	70 d	3	1	—	—	—	—	not estimable	—
	75 d	1	1	—	—	—	—	not estimable	—
	84 d	2	1	—	—	—	—	not estimable	—
	105 d	4	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	9	4	0.69	-0.98	2.35	0.52	0.279	42
	100- 250 kg/ha	8	3	1.38	-2.27	5.04	0.85	0.246	56
	250- 500 kg/ha	2	2	—	—	—	—	not estimable	—
	>500 kg/ha	8	1	—	—	—	—	not estimable	—

Table 3 *(continued)*

Variables	Covariates	N	Studies	SMD	CI 95% (Lower)	CI 95% (Upper)	SE	P-value	I^2 (%)
Leaf area	Overall	9	2	0.97	-1.13	3.07	0.17	0.107	0
	Harvest age								
	60 d	9	2	—	—	—	—	not estimable	—
	Range dose								
	250- 500 kg/ha	1	1	—	—	—	—	not estimable	—
	>500 kg/ha	8	1	—	—	—	—	not estimable	—
Number of leaves	Overall	3	2	0.66	-18.25	19.57	1.49	0.735	67
	Harvest age								
	60 d	1	1	—	—	—	—	not estimable	—
	84 d	2	1	—	—	—	—	not estimable	—
	Range dose								
	0- 100 kg/ha	2	1	—	—	—	—	not estimable	—
	250- 500 kg/ha	1	1	—	—	—	—	not estimable	—

Note. N = number of comparisons; Studies = number of independent studies (clusters). SMD = standardised mean difference (Hedges' g) from a random-effects model with cluster-robust variance estimation; SE = standard error; I^2 = heterogeneity. Subgroups based on fewer than three independent studies are reported as not estimable. Shaded P-values are significant at $P < 0.05$

Nitrogen significantly increased tiller number (SMD = 0.83; 95% CI = 0.07 to 1.59; p = 0.036; k = 27 from 7 studies); the two estimable dose bands, 0 to 100 and 100 to 250 kg N/ha, were in the positive direction but not significant. There was no significant increase in leaf area (SMD = 0.97; 95% CI = -1.13 to 3.07; p = 0.107) in two studies and no effect at all on leaf number (SMD = 0.66; p = 0.735) in two studies.

The leaf number is the inconsistent one. It is more directed by genotype and stage of development than nitrogen, so more leaves are not always reliably produced by adding nitrogen. At the very beginning, nitrogen is used for division and elongation, not for new leaves. Under nitrogen, Napier grass may produce more leaves, but the response varies between varieties. Nitrogen does promote leaf number and leaf area, and thus vegetative growth (Oliveira et al., 2015), a more complete canopy feeding back into biomass. Nasution et al. (2025) also said that cultivars differ in efficiency of nutrient conversion to morphological traits such as leaf number, which is one reason why leaf response is very inconsistent.

Leaf area increased again based on only two studies but not significantly (SMD = 0.97; p = 0.107). Mechanistically, chlorophyll and protein synthesis link nitrogen to leaf expansion, but two studies failed to confirm a real effect. Bigger leaves capture more light and therefore photosynthesise more, and a richer supply of nitrogen increases the rate of photosynthesis and vegetative growth, which appears as taller plants and a fuller canopy. The leaf: stem ratio also increases, indicating that leaves are more responsive to nitrogen later in development. Ojo et al. (2014) linked higher yield with increased leaf area through better light interception, and Ernawati et al. (2023) linked it with increased productivity.

Tiller number showed a clear and consistent response to nitrogen. It promotes cell division and basal meristem activity and increases apical dominance, enabling more axillary buds to develop as tillers. The strong showing at low to moderate rates says that only a modest supply is needed to set tillering off. The effect fades with age as meristem activity drops and lignification takes over. The fertilisation scheme is a clear determinant of tillering in Napier grass (Gorne & Aradilla, 2020), and nitrogen improves yield, quality and tiller production (Hazary, 2015). Nitrogen increases the synthesis of proteins and chlorophyll and enhances photosynthesis to promote both vegetative growth and height and tillering and branching, thus producing more tillers (Syam et al., 2021).

Sources of Variation Among Studies

These responses are attributed to nitrogen, but the performance of Napier grass depends on other factors simultaneously: cultivar, soil fertility, rainfall and irrigation, and cutting schedule. None of these is evenly distributed across the included trials. The clearest case: nitrogen source. Almost all studies used an inorganic form, with urea being the most used; organic nitrogen appears only in Girgiri et al. (2024) who used poultry manure, and in a single treatment of Hendarto and Setyaningrum (2022). The pooled estimates thus represent inorganic nitrogen and should not be extrapolated to manure-based systems without additional data. Soil fertility and background soil nitrogen were reported too inconsistently to model. Variation in rainfall, irrigation and harvest age add variation that no analysis here could hold constant. “Harvest age is the biggest thing because it pulls against nitrogen on the quality traits. As the plant matures, fibre goes up, and crude protein goes down. Rate and cutting interval have to be read in conjunction, not one at a time.

Variety was used as a moderator in the analysis, pure Pennisetum purpureum cultivars vs interspecific hybrids. The comparison was only possible for tiller number and plant height. For all other traits, hybrids were represented by at most one study. Where it could be run, the hybrids gave larger point estimates, but the confidence intervals were wide and overlapped those of the pure cultivars. The contrast was based on only two hybrid studies. Therefore, the present data do not allow us to say if hybrids react stronger on nitrogen than pure cultivars. We do not infer anything about the gap, but flag it.

Heterogeneity and Publication Bias

Funnel plots are presented in Figures 2 and 3 and show obvious asymmetry. Such asymmetry can be read as a sign of publication bias, in the sense of the smaller or null results not being published. Bias isn’t the only source, though. Experimental conditions, nitrogen levels, cultivar, and environment alone will skew a funnel plot. These tests have little power with only a handful of studies per parameter and must be read with care. The

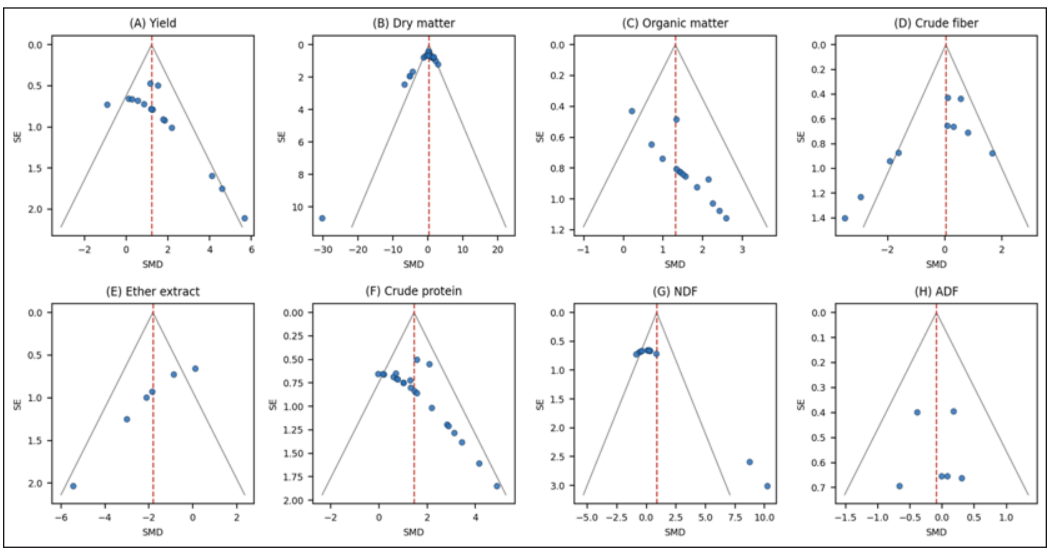

Figure 2. Funnel plot analysis on (A) Yield, (B) Dry Matter, (C) Organic Matter, (D) Crude Fibre, (E) Ether Extract, (F) Crude Protein, (G) Neutral Detergent Fibre, and (H) Acid Detergent Fibre to Detect Publication Bias

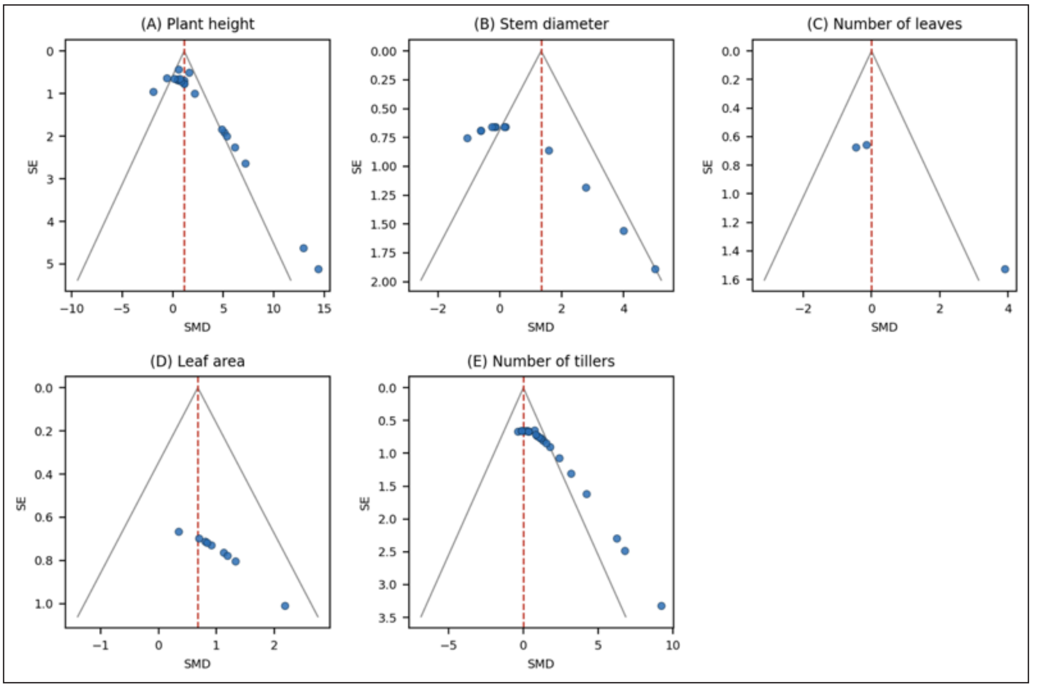

Figure 3. Funnel plot analysis on (A) Plant height, (B) Stem diameter, (C) Number of leaves, (D) Leaf area, and (E) Number of tillers to detect publication bias

broader point is in line with the rest of the analysis: the tropical Napier nitrogen literature is still small and patchy, and its findings are best judged with the number of independent studies underpinning each estimate firmly in mind.

CONCLUSION

However, once the shared-control dependence is dealt with, a clearer picture emerges: nitrogen does more for the nutritive value and vegetative density of Napier grass than for its yield. Crude protein, organic matter and tiller number moved most, each supported by several studies. Fresh yield and plant height behaved similarly. Crude fibre, NDF and ADF remained unchanged, as did dry matter. Four traits, ether extract, stem diameter, leaf area and leaf number, were reduced to two studies each and cannot be concluded. We do not offer any optimal rate. It was never tested head-to-head, and almost every dose subgroup was too thin to estimate. The defensible reading is simpler: moderate nitrogen, applied before the crop lignifies, raises protein and tillering, and pushing the rate higher buys little more. These statements are true for inorganic nitrogen in the cultivars studied here. They do not extend to manure-based systems or to varieties that are untested. The limitation is the evidence base. What the field needs next is straightforward: more independent tropical field trials that report dispersion for both treatment and control and state the nitrogen rate basis and source outright.

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