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Review article

Seed production of tropical range grasses in India: towards quality and sustainability

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Abstract

In tropical and sub-tropical countries, agriculture is predominantly crop-livestock-based mixed farming, influenced by climate change events. However, for various reasons, livestock productivity in these countries is considerably lower as compared to temperate countries. Regional and seasonal deficits in nutritious fodder availability are a significant constraint in sustainable and profitable livestock production. Globally, the primary impediment to enhancing fodder production and sustainable grassland management is the timely unavailability of quality seeds and planting materials, especially improved cultivars. Tropical countries encounter several issues in the range grass seed production, such as poor germination, seed dormancy, non-synchronous flowering, seed shattering, poor ovule-to-seed ratio, low seed yield, etc., due to extreme climates and lack of domestication of tropical forage species. Effective utilization of high-quality seeds or planting materials coupled with proper agronomic management practices can increase forage yield by 30 to 40%. However, comprehensive seed production information on tropical range grasses is still lacking among farmers and other stakeholders. This review not only underscores the constraints, principles, and opportunities for seed production in tropical range grasses but also systematically elaborates on various advanced management practices, such as suitable planting methods, optimal sowing times, water and nutrient management, cutting practices, and harvesting management to enhance quality seed production. This, in turn, will aid in utilizing existing and forest wastelands for sustainable seed production of tropical range grasses, consequently boosting the supply of green fodder and ecosystem services.

Keywords: Climate change, Green fodder, Livestock productivity, Range grasses, Seed production

Introduction

Livestock products play a pivotal role in global food and nutritional security by providing 17% of calories, 13% of energy, and 33% of protein in the world's diet (Rosegrant *et al.*, 2009; Smith *et al.*, 2013). Tropical and subtropical regions harbour 70% of the world's livestock population and production index for milk and meat products despite facing moderate to low water availability (245–219 m^3 $year^{-1}$) (Halli *et al.*, 2018; Halli *et al.*, 2022a). The quality and timely availability of fodder, particularly forage, significantly influence animal productivity, health and by-product yield (Chand *et al.*, 2022; Chand *et al.*, 2025b). Therefore, any initiative aimed at elevating livestock productivity must address the consistent availability of high-quality fodder and its post-harvest management. Without such efforts, the existing gap between forage demand and supply, viz., 11.24% deficit for green fodder and 23.4% for dry fodder in India, will only widen (Roy *et al.*, 2019). Tropical range grasses play a significant role in supplying year-round green forage, preventing soil erosion, increasing carbon sequestration, enhancing soil health, ecosystem services, etc (Namgial *et al.*, 2025). This review aims to discuss the status, challenges, and prospects of tropical grass seed production, mostly cultivated in India, under different agro-climatic conditions. Besides, it offers updated insights into the agronomic principles of seed production, including management practices, grazing management, and rejuvenation practices of tropical range grasses.

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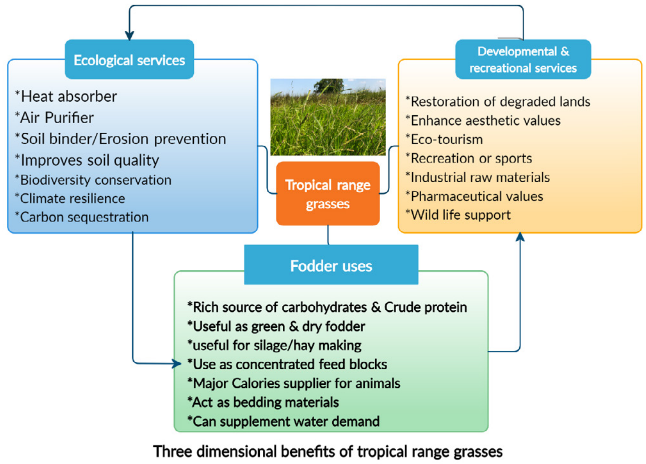

Fig 1. Three-dimensional benefits of range grasses

Tropical grasslands and range grasses: Tropical grasslands encompass approximately 3.4 billion hectares and play a crucial role in sustaining the livestock sector worldwide (Bibi *et al.*, 2016). These grasslands contribute to 26% of the world's farmland and 85% of productive farmland (Boval and Dixon, 2012). Of these grasslands, 45% are in arid and semi-arid grassland ecosystems (Reid *et al.*, 2008; Malaviya *et al.*, 2018). In India, grasslands cover nearly 24% of the land area and exhibit diverse ecological characteristics (Singh and Milchunas, 1983; Halli *et al.*, 2022b). Grasslands are especially vital for livestock, which rely almost entirely on pasture for their feed, which greatly influences the global demand for livestock-based products, including meat and milk (Boval and Dixon, 2012). Grasslands or rangelands are integrated and interdependent human-animal-plant-soil-climatic systems ecology associated closely with social, cultural, legal, economic and other ecological components. Grasses are widely adaptable to diverse agro-ecosystems, a major source of livestock feed, ecosystem reclamation, wildlife protection, and other ecological services (Singh *et al.*, 2022), as described in Fig 1.

However, increasing human population pressures, accelerating anthropogenic activities, *viz.*, construction of roads and railway lines, housing societies, declining forage resources, and global warming, led to climate change are collectively and continuously putting pressure on the cultivable lands and grasslands worldwide. Tropical grasslands display a wide range of yields with different nutritional values under rain-fed and irrigation conditions as they have diverse grasses suited to different agro-climatic conditions (Table 1); however, their optimal management practices for better yield and high quality remain unsolved (Srinivasan *et al.*, 2024). Range grasses require less seed rate per unit area, more spacing and nutrients than annual cultivated fodder crops due to their high productivity and perennial nature (Table 2). In the past, overgrazing practices have resulted in natural grassland degradation and have threatened, to a great extent, the ecological system and food chain (Kumar *et al.*, 2024). Consequently, effective tropical grassland maintenance, rejuvenation, intensification, and production approaches could be highly profitable, particularly when high-quality forages or low-cost crop by-products are available (Roy, 2009).

Status of varietal improvement and seed production: The availability of quality planting materials and seeds of grasses remains a major constraint (Vijay *et al.*, 2018) despite rising demand across various sectors, including grassland and pasture development, community lands, soil conservation, forest management, dairying, etc. (Table 3). Substantial progress has been made with temperate grasses; however, efforts for varietal development and diversification, seed production and dissemination in tropical grasses remain relatively nascent. A few varieties have been developed through conventional breeding approaches in India and also expanded to a great extent to tropical and subtropical climatic conditions in India (Table 4). However, genetic improvement of tropical grasses is tedious. It faces many challenges, such as polyploidy coupled with the apomictic nature of most grasses, self-incompatibility, abscission of spikelets after maturity, small floral parts coupled with non-synchronous flowering/anthesis and spikelet maturity (Roy *et al.*, 2019). Most breeding programs in tropical range grasses are confined to evaluating existing diversity and selecting desirable morphotypes (Sandhu *et al.*, 2015). In India, many concerted efforts were made towards forage genetic improvement and grassland development. Several native core collections have been developed for *Dichanthium* (Roy *et al.*, 2021), *Sehima nervosum* (Roy *et al.*, 2022), *Heteropogon contortus* (Roy *et al.*, 2021), and *Megathyrsus maximus* (Roy *et al.*, 2020a).

Consequently, varietal development becomes pivotal in establishing grasslands and pasture land under diverse and challenging climatic conditions in arid and semi-arid tropics. However, merely 25 to 30% of the required quantity of quality seed is available for cultivated fodder crops, and 15 to 20% for range grasses and legumes in India and many developing countries (Vijay *et al.*, 2018). Grasses are shy seeders as they are mostly bred for high green and dry biomass. In addition, the criteria for higher biomass (>5% over the best check) in varietal release is also one of the reasons for low seed yield in improved cultivars (Chand *et al.*, 2020). Concerted efforts toward ensuring the timely availability of quality propagating materials are imperative to meet livestock's fodder and nutritional demand (Chand *et al.*, 2023). Notably, the use of high-quality seeds and varieties can enhance crop yield by up to 15 to 20% with improved crop management practices (Singh *et al.*, 2013; Maity *et al.*, 2016; Chand *et al.*, 2024). However, the development of seed production

Table 1. List of tropical grasses with their fodder yield and nutritive value

Sl. No	Tropical grasses	Botanical name	Yield (t ha^{-1})	Nutritive value
1	Forest blue grass	*Bothriochloa intermedia* (R.Br.) A. Camus	GFY: 12.6–18	CP; 6.0%
2	Indian blue grass	*Bothriochloa pertusa* (L.) A. Camus	GFY: 44 with 73% DM	CP; 7.1–2.4%
3	Congo signal grass	*Brachiaria brizantha* (A.Rich.) Stapf	DM; 4–120	CP; 9.6–8.1%
4	Para grass, Buffalo grass	*Brachiaria mutica* (Forssk.) Stapf	GFY; 19.5-27.55	CP; 7%, Ca; 0.76% & P; 0.49%
5	Buffel/Anjan grass	*Cenchrus ciliaris* L.	DM; 6–12	CP; 11.0%
6	Bird wood grass	*Cenchrus setigerus* Vahl	DFY; 3.9 – 7.9	CP; 7.8%
7	Rhodes grass	*Chloris gayana* Kunth	GFY; 17–20.5	CP; 5% & Ca; 0.5%
8	Dhwalu/Gusia grass	*Chrysopogon fulvus* (Spreng) Choiv	DFY; 4.2–10	CP; 4.6–5.4%
9	Bermuda/Lawn grass	*Cynodon dactylon* (L.) Pers	DM; 4–5 (rainfed) and 30–35 (irrigated)	CP; 7–11.1% & CF; 18.6–28.2%
10	Marvel grass	*Dichanthium annulatum* (Forsk) Stapf	GFY; 8.4–13.5	CP; 5–7%
11	Pangloa/Digit grass	*Digitaria decumbens* Stent	GFY; 7–13	CP; 11.8%, & CF; 30.2%
12	Kamal/Brown beetle grass	*Diplachne fusca* (Linn.) P. Beauv	GFY; 30–40	CP; 8.5%
13	Spear/Lampa grass	*Heteropogon contortus* (L.) P. Beauv.ex Roem & Schult	DFY; 6.4	CP; 10%, Ca; 1.14 % & P; 0.19%
14	Sewan grass	*Lasiurus sindicus* Henr	DFY; 2.5–3.5 (rainfed) & 7–8.5 (irrigated)	CP; 12.8% & CF; 27.0%
15	Blue panic	*Panicum antidotale* Retz.	GFY; 20 (rainfed) & 50–60 (irrigated)	CP; 7.3% & low P; 0.09%
16	Guinea grass	*P. maximum* Jacq	GFY; 50–60 (rainfed) & 80–100 (irrigated)	CP; 5–8%
17	Bahia grass	*Paspalum notatum* Fluegge	GFY; 20–40	CP; 11–12%
18	Dinanath grass	*Pennisetum pedicellatum* Trin	GFY; 35-45	CP; 7.4% & Ca; 0.42%
19	Rat's tail grass	*Sehima nervosum* (Rottl.) Stapf.	GFY; 16-18	CP; 2.3–6.9% & Ca; 0.68%
20	Setaria grass	*Setaria sphacelata* Stapf. ex Hubb	GFY; 22.8–23.8 (rainfed) & 61.2 (irrigated)	CP; 5.3–6.9%
21	Bajra Napier Hybrid	*Pennisetum glaucum* × *P. purpureum*	GFY; 70–250	CP; 8.7–10.2% & CF; 28–30.5%

*DM: Dry matter; Ca: Calcium; CP: Crude protein; CF: Crude fibre; GFY: Green fodder yield; DFY: Dry fodder yield; P: Phosphorus (Source: Trivedi, 2002; Kumar *et al.*, 2012)

procedures and techniques for these crops has witnessed minimal progress over the last three decades. Likewise, agronomic practices related to seed production in tropical range grasses still lack systematic planning due to insufficient knowledge on seed production standards, practices, and quality enhancement methods.

Challenges in Seed Production

The production of quality seed in tropical range grasses encounters numerous challenges that must be addressed on priority to bridge the gap between seed demand and production (Fig. 2). Furthermore, the majority of tropical grass species inherently possess a limited seed yield potential due to the lack of domestication (Boonman, 1971). The primary hurdles in tropical grass seed production are linked to indeterminate growth habit, polyploidy leading to sterility, apomictic reproduction, non-synchronous flowering, uneven spikelet maturity, seed shattering, etc. These grasses exhibit a low ovule-to-seed ratio, leading to the formation of numerous

Table 2. Comparison of seed production packages among cultivated and range grasses

Crop	Suitable season	Seed rate (kg/ ha)	Row spacing (cm)	N:P: K (kg/ha)
Cultivated fodder				
Fodder sorghum	Kharif	15–20	30	90:30:0
Fodder maize	Kharif	25–30	50	90:30:30
Fodder cowpea	Kharif	20–30	50	60:40:30
Fodder guar	Kharif	20–30	40	60:40:30
Fodder oat	Rabi	50–60	25	90:30:0
Berseem	Rabi	20	35	20:80:30
Lucerne	Rabi	15	40	20:80:30
Range grasses and legumes				
Cenchrus setigerus	Kharif/ perennial	3–5	50	60:30:30
Cenchrus ciliaris	Kharif/ perennial	4	50	60:30:30
Brachiaria brizantha	Kharif/ perennial	6–10	50	60:40:30
Pennisetum pedicellatum	Kharif/ annual	5–8	50	60:40:30
Clitoria ternatea	Kharif/ perennial	10–15	40	30:40:40
Panicum maximum	Kharif/ perennial	3–5	50	80:50:50
Stylosanthes hamata	Kharif/ perennial	8–10	40	30:40:40
Bothriochloa intermedia	Kharif/ perennial	4	50	40:30:0
Chloris gayana	Kharif/ perennial	6–8	50	50:30:0
Dichanthium annulatum	Kharif/ perennial	4–6	50	20:20:0
Panicum antidotale	Kharif/ perennial	6–7	50	20:30:0
Paspalum notataum	Kharif/ perennial	10	40	60:30:0
Setaria sphacelata	Kharif/ perennial	2–5	50	60:40:0
Chrysopogon fulvus	Kharif/ perennial	5	40	40:20:0
Heteropogon contortus	Kharif/ perennial	5	50	40:30:0
Sehima nervosum	Kharif/ perennial	8	50	20:20:0

(Source: Chauhan *et al.*, 2017; Chauhan *et al.*, 2021; Roy *et al.*, 2020b)

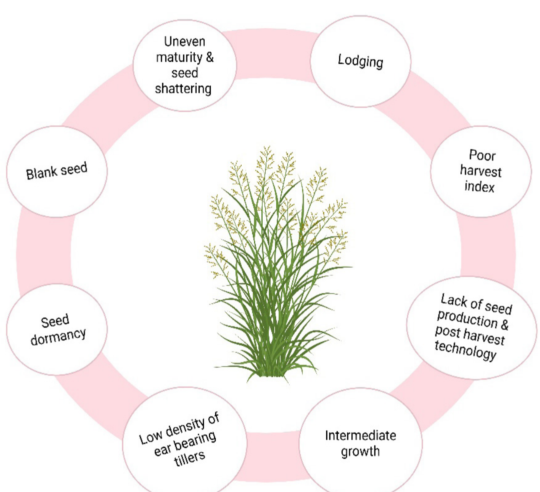

Fig 2. Constraints in tropical range grasses seed production

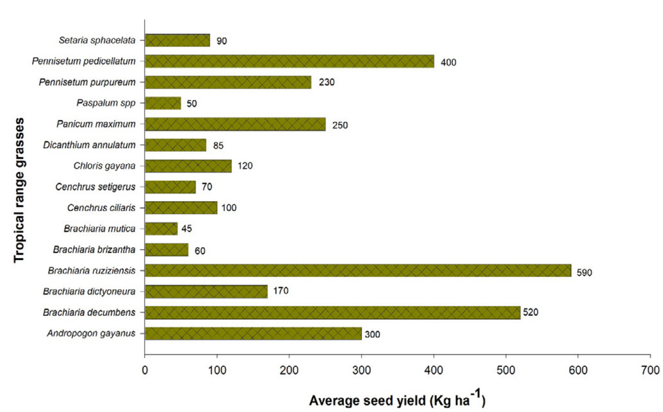

Fig 3. Variation in the seed yield of range grasses (Bhatt *et al.*, 2002)

Table 3. Stakeholders of range grasses for multiple uses based on their suitability

Stakeholders	Preferable grass species
Grassland and pasture development authority	Due to their nutritious and sustained fodder yield, *Cenchrus ciliaris, Brachiaria, Bothriochloa, Chrysopogon fulvus, Panicum maximum, Panicum antidotale, Chloris gayana, Dichanthium annulatum, Iseilema laxum, Setaria sphacelata, Sehima nervosum*, and *Paspalum notatum.*
Soil & water conservation, National highway authorities, and Mining development corporation	These grass species are used mainly due to their hardier and superior root systems: *Cenchrus setigerus, Panicum maximum, Heteropogon contortus, Brachiaria, Cenchrus* spp., *Lasiurus scindicus* and *Festuca* spp.
Forest department	Mainly used as fodder crops for wild animals (*Pennisetum pedicellatum, Panicum maximum, Cenchrus ciliaris* and *Cenchrus setigerus*)
Farmers and dairy authorities	For their own animal feed, either through the plantation on bunds or utilization in silvi and horti-pasture systems in uncultivable land (*Panicum maximum, Brachiaria, Cenchrus,* Bajra Napier hybrid, *Dactylis,* and *Festuca*)

Table 4. Range grass varieties recommended for tropical and sub-tropical regions

S.N.	Range grasses	Varieties
1.	*Panicum maximum*	Punjab Guinea Grass-1 (PGG-1), PGG-14, Bundel Guinea- 1 (BG-1), BG-2, CO-1, CO-2, CO-3, JHGG 08-1, RSDGG-1, TNGG 062, Hamil, Haritha, Harithasree, Makueni, Marathakam, PGG-101, PGG-14, PGG-19, PGG-518, PGG-616, PGG-9, Riversdale, Dharwad Guinea Grass-1 (DGG-1)
2	*Pennisetum glaucum* × *P. purpureum*	APBN-1, BNH-10, CO-1, CO-2, CO-3, CO-4, CO-5, CO-6, Swetika-1, NB 21, NB-37, PBN-233, PBN-83, Phule Jaywant (RBN-13), Sampoorna (DHN-6), Suguna, Supriya, Yeshwant (RBN-9), PBN-342, Phule Gunwant, BNH 11, BNH 14, PBN-346, PBN 351, TSBN 15-15, BNH 26
3	*Brachiaria ruziziensis*	Dharwad *Brachiaira ruziziensis* Selection-1(DBRS-1)
4	*Cenchrus ciliaris*	Bundel Anjan-1, Bundel Anjan-3 (IGFRI-727), Marwar Anjan (CAZRI-75), RCCB-2, CAZRI Anjan 2178, CAZRI Anjan 358, Gujarat Anand Anjan Grass-1, Gujarat Anand Anjan Grass-2, RCCB-2, RCC-10-6, Bundel Anjan 4 (IG 67-365)
5	*Cenchrus setigerus*	Marwar Dhaman (CAZRI -76), TNCS 265 (CO 2), Bundel Dhaman 1 (IGFRI-96-706)
6	*Chrysopogon fulvus*	Bundel Dhawalu grass-1 (IGC-9903), Dongari Gawat 2-4-11, GAU D-1
7	*Pennisetum pedicellatum*	Bundel Dinanath-1, Bundel Dinaanth-2, COD-1 (TNDN-1), Jawahar Pennisetum-12, Pusa Dinanath Grass, Bundel Dinanath 3 (JHD 19-4)
8	*Heteropogon contortus*	Bundel Lampa Ghas-1 (IGHC-03-4)
9	*Dichanthium annulatum*	Gujarat Marvel Grass-1, Marvel-7, Marvel-8, Marvel-93, Marvel-09-4, JHD-2013-2, Phule Govardhan, Phule Marvel-06-40, Him Palam Setaria Grass-2
10	*Sehima nervosum*	Bundel Sen Ghas-1
11	*Setaria sphacelata*	Setaria-92, S-18, Nandi, PSS-1 (Golden Timothi)
12	*Lasiurus scindicus*	RLSB-11-50, CAZRI Sewan 1
13	*Chloris gayana*	Rhodes-10

(Source: Roy *et al.,* 2020b; Chand *et al.,* 2025a)

blank or chaffy seeds and recovery of low quantities of 'pure germinating seeds' (PGS). The presence of physiological dormancy and an extended germination duration (typically lasting 15–28 days) render these grass species more susceptible to weather fluctuations (Vijay *et al.,* 2018). The limited density of ear-bearing tillers (only 30–50%) reduces the number of flowers, resulting in a poor harvest index (only 2–3%) (Malaviya *et al.,* 2013). Furthermore, the degradation and depletion of natural grasslands and rangelands, coupled with the impacts of climate change, are negatively influencing seed production in range grasses (Vijay *et al.*, 2018; Timpong-Jones *et al.*, 2023). Consequently, global variability in grass seed yields is considerable, ranging from approximately 30 to over 1200 kg ha^{-1} (Fig. 3) (Bhatt *et al.*, 2002). Therefore, it becomes imperative to formulate strategies that allow for obtaining moderate yields of both green forage and seed from the same crop by adhering to appropriate management principles (Geetha, 2001). Lack of assured markets and fair prices is also discouraging farmers and other entrepreneurs from entering the forage seed production market (Chand *et al.,* 2023).

Table 5. Field and seed standards of range grasses for seed production

Grass species	Field standards						Seed standards									
	Isolation distance (m)		Permitted off types		Other weed plants		Pure seed		Other crop seeds (No. kg^{-1})		Total weed seed (No. kg^{-1})		Other weed seeds (No. kg^{-1})		Germination (%)	
	*FS	*CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS	FS	CS
Cenchrus ciliaris	20	10	0.1	1.0	-	-	80	80	20	40	20	40	-	-	30	30
Chrysopogon fulvus	20	10	0.1	1.0	-	-	80	80	20	40	20	40	-	-	15	15
Pennisetum pedicellatum	20	10	0.1	1.0	-	-	95	95	20	40	20	40	-	-	50	50
Panicum maximum	20	10	0.1	1.0	-	-	80	80	20	40	20	40	-	-	20	20
Melilotus indica	50	25	0.2	0.1	-	-	98	98	10	20	10	20	-	-	65	65
Dichanthium annulatum	20	10	0.2	1.0	-	-	90	90	10	20	10	20	-	-	40	40
Pennisetum purpureum	10	10	0.01	0.30	0	0	99.9	98.8	-	-	-	-	-	-	-	-
Vigna umbellata	50	20	0.1	0.2	-	-	98	98	0	0	5	10	-	-	70	70
Setaria sphacelata	400	200	0.1	1.0	-	-	95	95	20	40	20	40	-	-	50	50

*FS: Foundation seed; CS: Certified seeds (Source: IMSCS, 2013; Sumner and Miller, 1949)

Principles of range grass seed production: Improved crop varieties and recommended agronomic practices can significantly contribute to improving seed production (Boonman, 1971). These practices help to find out the best management practices for quality seed production in tropical range grasses.

Field and seed standards: In developing countries, informal seed sectors are the primary source of seed production for seed quality and supply, with the involvement of only a few government and private organizations. The lack of seed standards in tropical grasses poses a major challenge for implementing seed supply chains and seed certification processes for range grasses in India. At present, field and seed standards are available for only a limited number of range grasses (Table 5). Recently, the ICAR–IGFRI (Jhansi, India) has developed seed standards for four tropical range species (Vijay *et al*., 2024).

Sowing or planting of grasses: Sowing or planting involves selecting suitable grasses or varieties, healthy seeds or planting materials, optimal seed rates, proper seed treatment, and planting methods.

Time of sowing: The time of seed sowing/planting significantly affects crop yield due to growth conditions. Most range grasses are propagated during the rainy season (July to September). Sowing blue buffel grass (*Cenchrus glaucus*) in the first week of June led to higher seed yield (256.37 kg ha^{-1}) (Geetha, 2001). Conversely, *C. setigerus* exhibited higher seed setting and yield when sown in spring (February to April) rather than the rainy season (Anonymous, 2017). Monsoon-related pollen washout and fungal disease infestations might explain lower seed yield and quality during the monsoon or rainy season (July to September).

Seed treatment: Many grass species have protective hair-like structures on seeds, which are associated with different dormancy types, making seed treatment easy and beneficial for germination and establishment. Ascorbic acid treatment (25 ppm) effectively overcomes dormancy and improves fluffed *C. ciliaris* seed germination by 80% (Geetha, 2001). Similarly, seed pelleting with $ZnSO_4$ @ 10 g + DAP @ 60 g or $CuSO_4$ @ 10 g + DAP @ 60 g kg^{-1} promotes longer shoot lengths in *C. ciliaris* and *C. setigerus* (Anonymous, 2017). Seeding efficiency needs to be enhanced to support large-scale grassland restoration worldwide, as grasslands are experiencing significant degradation driven by human activities and climate change. Seed sowing after dehusking enhances germination rates, improves seed handling, and makes sowing easier in Australian grass species (Pedrini *et al*., 2018).

Planting methods or tillage: Planting methods or tillage practices have a significant effect on initial grass establishment and production costs. For instance, zero tillage implements are preferable for sowing in established pasturelands. However, *Brachiaria* cultivars established through transplanting show higher tiller counts (60–117%), inflorescence production (20%), and seeds per unit area (90%) compared to direct seed sowing (Hare *et al.*, 2007). Grass-legume intercropping systems may increase biomass, nutritive value and seed yield compared to monocrops (da Silva *et al.*, 2023). It improves soil properties, viz., microbial biomass carbon, available nitrogen, and dehydrogenase activity compared to sole grass. Net returns of grass-legume intercropping systems can be up to 30 to 40% higher than the monocropping of grass species (Choudhary *et al.*, 2018). *Setaria sphacelata* intercropped with *Desmodium tortuosum* (IL1568), *Megathyrsus maximus* intercropped with *Stylosanthes hamata,* and *Macroptilium atropurpureum* increased seed yield and saved 20 to 30 kg N ha^{-1} with an additional yield of leguminous fodder (ICAR, 2009). In grass species, the seedling-transplanting method has a higher survival percentage, vigorous growth and productivity than direct seeding (Yáñez-Chávez *et al.*, 2023).

Depth of sowing and spacing: Proper seeding depth (not exceeding 1.0 cm) and covering seeds with soil adequately prevent displacement due to water and wind. However, larger-seeded species like smooth bromegrass (*Bromus inermis*) may be planted at a depth of 1.3 to 1.9 cm. Proper spacing (between/within rows) determines the input use efficiency for grasses, as there will be significant competition for available resources, viz., soil moisture, nutrients, light, and CO_2. *C. ciliaris* shows higher fertile tillers, better seed yield and quality at a wide spacing (Kumar *et al.*, 2005). For instance, *C. ciliaris* shows a high seed yield (70 kg ha^{-1}) at a row spacing of 100 cm compared to 25 cm (67.2 kg ha^{-1}) and 75 cm (69.3 kg ha^{-1}) under the sub-humid eastern zone of Tanzania (Kizima, 2015).

Canopy management: Desired crop morphology, achieved by regular canopy management and defoliation, improves the final output significantly, as it changes the microclimates. Grasses like *Megathyrsus maximus*, *Pennisetum polystachion*, *Setaria sphacelata*, and *Brachiaria mutica* tolerate high shading (up to 75%). Others, such as *B. decumbens*, *C. ciliaris*, *C. setigerus*, *Chrysopogon fulvus*, *Dichanthium annulatum*, and *Paspalum notatum*, tolerate moderate shading (40–60%) (Bhatt *et al.*, 2002). *M. maximus* shows increased leaf length and width under > 50% shade, with genotypes from tropical humid regions exhibiting better shade tolerance (Malaviya *et al.*, 2020). Cutting at lower heights removes the growing point and reduces carbohydrate storage in stems (Whiteman, 1980). Regular harvesting in a short period negatively affects the growth and production of grasses, as they require more extended regrowth periods (Crowder and Chheda, 1982). Cutting management practices are crop, location and stage-specific, and there is a negative correlation between the number of cuttings and seed production. For instance, uncut *C. ciliaris* yields pure seed better than *a* single cut (30 and 45 days after sowing/regeneration and 50% flowering stage) under the arid climate of the Thar Desert (Rajora *et al.*, 2016). Besides, agro-morphological traits such as number of fertile tillers/meters, plant height, 1000 seed weight, spike length, seeds/spike, seed weight/spike and dry matter yield were maximum under uncut conditions. Cutting management influences fodder and seed yield and affects fodder nutritive values by removing dead, diseased, and damaged leaves, tillers, and plants (Table 6).

Table 6. Cutting management and nutrient application in range grasses for seed production

Grasses	Cutting management	Authors
Pennisetum purpureum	At 15 to 30 cm height after 30 to 35 days of planting	Wijitphan *et al.*, 2009
Cenchrus ciliaris	Late cut (February and March) reduced the yield	Garcia *et al.*, 1990
	Cutting and clipping operations did not favour seed production	Reid *et al.*, 2008
Andropogan gayanus	Cut during August and October had a negative effect	Gobius *et al.*, 1998
Pennisetum polystachion, Andropogan gayanus	Delayed or repeated clipping decreased the seed yield	Mishra and Chatterjee 1968
Nutrient application		
Cenchrus ciliaris	Improved the seed yield and available soil N and P with 60 N:26.0 P kg ha^{-1}	Kumar *et al.*, 2005
Agropyron inerme/ *Pseudoroegneria spicata)*	Fertilization of N greatly increased the pure seed	Miltimore et al., 1961
Cenchrus ciliaris	Split application of N along with irrigation improved the seed yield	Humphreys and Riveros 1986
Leymus chinensis	Higher N supply (150 kg ha^{-1}) increased the percentage of pure germinating seeds	Huang *et al.*, 2019

Water management: Arid and semi-arid tropical regions face challenges like low soil moisture and high temperatures, affecting grass reproduction and productivity. Irrigation positively affects grass seed production, enhancing seed yield stability and levels by increasing seed test weight up to 22% (Chynoweth *et al.*, 2012). Many perennial grasses need adequate moisture in the root zone (up to 90 cm) for higher seed yields. Soil with a moisture deficit reduces photosynthesis, leaf expansion, pollination, seed set, and yield in grasses. Supplemental irrigation of 30 to 45 cm increases seed yield two to three-fold in grass species (Crowle, 1966). Adequate water supply in early spring promotes seed-bearing tiller development. However, water application during flowering might affect pollination, especially with sprinkler irrigation (Holzworth *et al.*, 1990; Shock *et al.*, 2015), and seed yield increases in *Lomatium dissectum* (140 mm) and *Eriogonum umbellatum* (173–200 mm) after improved irrigation. Besides, *Sorghum sudanense* yields the highest at 80% field capacity (FC), *Chloris gayana* at 30% FC, *Chloris oxburghiana* at 50 and 30% FC, whereas *Eragrostis superba* and *C. ciliaris* display no differences across soil moisture levels under tropical conditions (Koech *et al.*, 2016). Further research on how deficit irrigation maintains yield and quality with water savings is necessary to address water scarcity in grasses.

Nutrient management: Fertilizer application improves the seed production of grasses, in addition to the native soil fertility. Generally, phosphorus (P) and potassium (K) application at the time of sowing is better for the economic response, enhanced growth rate, and seedling vigor (Halli *et al.*, 2025). Grasses are heavy users of nitrogen (N) compared to P and K; N is the most essential nutrient in grasses like perennial ryegrass (*Lolium perenne* L.) to achieve sufficient uptake for higher seed yields (Wang *et al.*, 2019). Under zero-tilled situations, applying N to stubble fields at 20 to 40 kg ha^{-1} before sowing is common for many tropical range grasses due to N immobilization during the initial growth stages. In addition, N application after defoliation promotes better growth. However, surplus N application can reduce seed production significantly as increased vegetative growth leads to lodging. Grasses require adequate N during floral initiation to promote the development of the maximum number of fertile tillers and viable florets (Hennig and Elliott, 1970). Seed production increases significantly at the low dosage of fertilizer application in *C. pauciflorus* and shows a negative effect at the intermediate and high dosage of fertilizer (Zhang *et al.*, 2015). A few salient findings on this aspect are presented in Table 6. Therefore, improved nutrition enhances seed filling, the percentage of pure seeds, and germination of seeds.

Foliar spray: Foliar sprays with various growth promoters have been used to increase seed production in grass species. Foliar application of plant growth hormones along with K and diammonium phosphate (DAP) at the flower initiation stage increases panicle length, seed setting, seed retention, and seed yield in several range grass species. Foliar spray of 0.5% thiourea, 4% KNO_3, and 100 ppm GA3, applied at panicle initiation stage, has increased seed yield by 39, 50, and 31%, respectively, over the control in *C. ciliaris* under rain-fed conditions (Nagar *et al.*, 2016). Also, 0.5% thiourea, 4% KNO3, and 100 ppm GA_3 increased seed yield by 46, 60 and 39%, respectively, over the control in *C. setigerus*. Foliar spray increases the proportion of spikelets with true seeds, germination, and seedling length. Foliar application of IAA (100 ppm) during the pre-anthesis stage in guinea grass increases seed setting (Vijay *et al.*, 2018). This has led to increased seed setting, as confirmed by X-ray radiography, and increased seed germination from 20 to 45%. The application of kinetin (100 ppm) during the panicle initiation stage has enhanced the seed setting in *Chrysopogon fulvus* and *Sehima nervosum*, whereas tryptophan has increased the seed filling and 1000 seed weight in *Brachiaria* species (Gupta *et al.*, 2022). In guinea grass, auxin treatment has been found to improve the rate of germination as well as the percent germination. The maximum germination (45%) was recorded with a 100-ppm dose of IAA compared to the control (26%) (ICAR, 2009).

Seed treatment: Grass seeds are light in weight and chaffy in nature, making sowing operation difficult, mainly at a proper depth and spacing. Seed treatment with 100 ppm GA_3, hydration for 18 hours + dry dressing of thiram and osmo-conditioning in PEG solution (-10 bars), increased seed germination, field emergence and seed yield in *C. ciliaris, Clitoria ternatea*, Siratro, and Stylo (ICAR, 2009). Soaking of *C. ciliaris* seeds in fresh water for 8 to 10 hours before sowing is effective for improved germination. Pre-treatment of seeds with 0.2% potassium nitrate (KNO_3) has improved seed germination in *C. ciliaris, C. setigerus* and *Panicum maximum* (ICAR, 2009). In *Brachiaria brizantha, Paspalum notatum,* and *Sehima nervosum,* maximum germination was recorded with GA_3 300 ppm seed pre-treatment (ICAR, 2009). Germination percentage and seedling vigour improved by seed invigoration treatments of GA_3 (100 ppm) or KNO_3 (0.2%) and/or soaking in water for 24 hours (ICAR, 2009). Dipping of cut panicles of guinea grass in 100 and 200 ppm solutions of IAA and kinetin improves the maturation process, respectively. The seed retains viability for a longer duration and shattering losses are minimized (ICAR, 2009).

Seed pelleting: Seed pelleting enhances the seed efficiency, increases the uniformity, reduces the seed rate per hectare, and improves the germination. However, there is a non-significant effect of pelleting materials (farm soil, clay, farmyard manure, sawdust, coco peat, and their combinations) on seedling emergence, but a significant effect on seedling dry weight and seedling wilting in *C. ciliaris* and *C. setigerus* (Meena and Nagar, 2019). Seed pelleting with Soil + Clay + FYM (2:1:1) ratio was tolerant, and clay alone was prone to wilting in both species. The small size of grass seeds results in fragile seedlings. The pelleting of individual seeds is complicated and sometimes adverse, as the seed may not break open the pellet and germinate until the pellet is completely dissolved. Under such conditions, the multi-seed pellets supplemented with nutrients have high efficiency. Maity *et al*. (2017) showed that 8-10 true seeds of Dinanath grass, with length < 2 mm and width < 1 mm when pelleted with soil and nutrient mix containing N, P, K, and micronutrients, could lead to 60% seedling establishment and more than 90% seed germination.

Advances in vegetative propagation of grasses: Similar to enhancing seed quality, vegetative propagation in grasses has also progressed gradually due to wider adaptability and greater efficiency. (Scordia *et al*., 2015) studied the new propagation and planting methods in *Arundo donax*, *Miscanthus* hybrid, and *Panicum virgatum* under field and open-air pot conditions. Hydro-seeding was a promising technique to control weeds and to ensure excellent seed emergence in *P. virgatum*. The direct stem planting method was successful for *Miscanthus*, whereas rhizome propagation was for *A. donax* (Vijay *et al*., 2018). A simple paper towel method of germination improved the sprouting of stem cuttings up to 80–85% due to higher water-holding capacity in the Bajra Napier hybrid (*Pennisetum glaucum* × *Pennisetum purpureum*; BNH). Further, they standardized the high-density nursery technique by planting stem cuttings at a close spacing of 5 cm to induce rooting within 15 days. Growth hormones such as auxin, gibberellin, and cytokinin are commonly used worldwide to induce rooting in many plant species. Fejer (1960) reported that gibberellic acid (GA_3) produces an initial elongation of stem cuttings, resulting in taller plants in perennial ryegrass (*Lolium perenne* L.). The main effect of indole-acetic acid (IAA) is rooting in the case of perennial ryegrass. The combined application of IAA and amino salt (9:1) stimulated rooting more than the sole effect of IAA. *In-vitro* rooting of BNH stem cuttings with axillary buds under high moisture conditions and light started rooting within a week and became ready for transplanting. Within stem cuttings, setts consisting of two to three nodes reported higher rooting (91%) and shooting (93%) compared to one-node setts (Vijay *et al*., 2018). Stems with 2 to 10 nodes in BNH were found to be better; however, single-node cuttings can also be used for propagation. Cuttings taken from the lower portion of the parent stem were superior to younger material from the top portion in Napier grass (*Pennisetum purpureum*). Further, horizontal planting of stem cuttings is followed, but under irrigated conditions, vertical planting may also be followed (Knoll and Anderson, 2012). However, scientific findings on vegetative propagation in range grasses are limited compared to commercial crops like sugarcane, vegetables, and flowers. Therefore, potential scope exists in this line to address the uncertainties of range grasses' germination and establishment.

Biotic Stress Management

Weed management: The land selected for grass seed production should be free from weed seeds, enhancing the competitiveness of grasses against weeds during the initial stages. The best and most effective time to remove contaminating weeds from the field is before flowering. Mimicry weeds can be controlled by periodic manual removal and roguing. Easy weed control can be achieved before sowing with the use of broad-spectrum herbicides and secondary tillage operations, whereas weed control options become limited once the crop is sown. The usage of herbicides is restricted in range grasses due to the risk to grazing animals. For example, post-emergent application of Derby (florasulam + flumetsulam) @ 30 mL feddan^{-1} (1 Feddan = 0.42 hectare) and metosulamat @ 40 mL feddan^{-1} against broad-leaved weeds such as *Anagallis arvensis*, *Cichorium pumilum*, *Medicago intertexta*, *Melilotus indica*, *Rumex dentatus*, and *Sonchus oleraceus* found to be effective in grasses (El-Kholy *et al*., 2013). Studies also suggest that reinforcing the principle of rotating herbicides of different modes of action with non-chemical weed control measures minimizes the risk of herbicide resistance evolution (Broster *et al*., 2018). Growing grasses for seed with narrow rows without inter-row cultivation faces significant competition with weeds, resulting in a reduction in seed yield and quality. Important weeds from the aspect of seed production were *Myosotis* sp. and *Chenopodium* sp. (Cagaš *et al*., 2006). Therefore, long-term monitoring of weed occurrence and proportions in individual grass species is of great importance. It may reveal shortcomings in the cultivation technology, show the spread of new or reappeared weed species, and positively influence technological research, including the development of herbicide preparations specifically for grass seed cultivation.

Insect and disease management: Although grasses are comparatively more tolerant to pests and diseases than field crops due to their coexistence with each other, inheritance and typical morphology. Wild grass species act as an alternate host reservoir for the virus spread to nearby food or fodder crops. For example, 21 virus species have been reported to infect 36 grass species and 59 wild grass species under Australian conditions (Jones, 2013). Among them, barley yellow dwarf virus (BYDV), cereal yellow dwarf virus (CYDV), wheat streak mosaic virus

(WSMV), and ryegrass mosaic virus (RyMV) were the most common, reaching high infection incidences. Insect pests significantly affect the green herbage, as perennial grasses provide consistent shelter to them. Root-feeding insect (*Heteronychus arator*), known as African black beetle (ABB), has significant pasture biomass losses in Australia (Karpyn *et al.*, 2017). Endophytic fungi from the genus *Epichloë* have a symbiotic relationship with *Lolium perenne*. Endophytic fungi release bioactive secondary metabolites, viz., ergovaline, lolitrems, peramines, lolines, and ergopeptines, which deter insect pests from feeding activities. Besides, insects and diseases can independently affect plant growth and fitness, and their interactive effect cannot be overlooked. Dickson and Mitchell (2010) reported no interactive effect of herbivore insects and pathogens on four graminoid species (*Poa pratensis, Schizachyrium scoparium, Andropogon gerardii,* and *Carex siccata*). However, insect (Cecidomyiid midge, *Contarinia wattsi*) management was more profitable than fungus for seed production in grasses. Likewise, grasses infected with clavicipitaceous fungi increase the insect resistance (Clement *et al.,* 2018). Perennial ryegrass, tall fescue, and chewings fescue infected with Acremonium provide resistance to insects such as billbugs, webworms, and chinch bugs. There are more instances of ergot infestation in *Cenchrus species* during the monsoon, whereas thrips and red spiders exist in many grasses. During the monsoon (June to September), prevailing weather conditions (average max. temperature, 35.56°C; max. RH, 86%; min. RH, 64.42%, and evaporation rate, 7.12 mm day^{-1}) create a congenial environment for insect and disease activity.

Collection of Seeds

Importance of seed collection: Determining the proper harvesting time, stage, and method of collection is a significant task and the most crucial decision for achieving high quantity with assured seed quality. Temperature and photoperiod requirements for optimal germination depend on species and harvest time. Winter-matured seeds have reduced biomass and germination compared to the summer-matured ones. For example, germination of *C. ciliaris, P. divisum,* and *P. turgidum* is seasonally dependent (Bhatt *et al.,* 2020). Further, summer-matured seeds of these three grass species had higher germination percentage irrespective of germination temperature and photoperiod. Research findings on the optimum harvest stage and physiological maturity for good seed yield and quality in different grasses are detailed in Table 7. Grasses are susceptible to shattering as they attain maturity. Grass seed yield and its quality parameters are influenced by harvesting season and growth stages. In arid conditions, seeds can be harvested in all three seasons, but higher seed yields with good quality seed can be obtained during autumn and spring. However, high biomass can be achieved in the monsoon season. Meena and Nagar (2019) studied the effect of seasons, viz., monsoon, autumn, and spring, on seed yield and quality traits in *C. ciliaris* in arid zones of India. They reported the highest seed yield without any infestation in the spring-harvested seeds. Poor spikelet germination and ergot infestation were observed in monsoon season-harvested seed.

Measures to achieve uniform maturity and seed yield: Generally, grasses require about 30 days from flowering to seed maturity. However, hot and dry weather reduces the ripening period, whereas cool and wet climatic conditions delay maturity. In many grasses, uneven maturity is a major problem in determining the harvesting stage of the crop, as the seeds at the top of the panicle begin to shatter while anthesis only commences in the bottom portion. It was also observed that after a single destructive harvest, collecting seeds from harvested heads at intervals yielded higher-quality filled seeds (Anonymous, 2015). The physiological maturity stage of the seed has the highest seed quality and helps reduce shattering losses during harvest. The *P. pedicellatum* seeds harvested at physiological maturity enhanced the seed recovery and increased seed yield by 10 to 15% (Gupta *et al.,* 2022). Immersing *P. maximum* harvested panicles in IAA (100 ppm) solution maintains their vitality, minimizes shattering losses and ensures a greater number of matured seeds (Malaviya *et al.,* 2013). Moreover, GA_3 or KNO_3 applications can also enhance seed germination by removing seed dormancy (Lay *et al.,* 2015). Similarly, in Guinea grass, the external application of phytohormone (IAA @ 100 ppm) during anthesis increases synchrony in seed maturity and seed germination (Malaviya *et al.,* 2013).

Table 7. The optimum time for the harvest of range grasses for quality seed production

Grasses	Physiological maturity	Authors
C. ciliaris	21-28 days from the commencement of flowering	Gonzalez and Mendoza, 1992
C. ciliaris, C. setigerus	12-16 days after anthesis	Yadav and Rajora, 1999
Andropogon gayanus	21-28 days after peak flowering	Gonzalez and Mendoza, 1996
P. pedicellatum	Varied from 3rd to 6th week after 50% flowering	Narayanasamy, 1994
P. maximum	15-20 days after panicle emergence	Machado *et al.,* 1984

Reduction of seed volume and mechanical harvesting: The lightweight spikelets of grass species, along with appendages, occupy higher volumes than the seeds of food crops. The higher volumes are problematic in storage and transport, occupying large spaces and increasing costs. The true seeds, i.e., caryopsis of the grass species, are much smaller and denser than the spikelets and offer a possible solution to reduce the volume. Mechanical defluffing in dinanath grass (*P. pedicellatum*) via a cotton batting machine has reduced seed weight or bulkiness by 94% and volume by 98%, facilitating easier handling and storage (Vijay *et al.,* 2018). Naked seeds facilitate easy sowing through the preparation of seed pellets with a better germination percentage (Maity *et al.,* 2017). This technique could be adapted to separate naked seeds of other similar range grass species, such as *Cenchrus*, *Chrysopogon*, etc. Additionally, a tractor-mounted machine prototype has been developed with an upward directional movement of the bruising cylinder to collect matured dinanath grass seeds. More than 85% of grass seeds were collected in two passes of operation with opposite directions and reducing seed dimensions, increasing bulk density, high seed recovery without affecting seed quality, and reducing processing cost compared to the traditional defluffing method (Anonymous, 2018; Singh *et al.,* 2021).

Burning and fall management: Managing grasslands or pasture lands periodically is one of the important practices. Controlled burning of perennial range grasses is a highly useful and age-old economic practice for suppressing undesirable woody plants, weeds, and dead tillers in grasslands (Reed-Dustin *et al.,* 2016). In many cases, burning straw residues is also an effective tool for stimulating seed yields of several grass species by enhancing seed germination, relative root elongation, seedling length, and mass (Hulbert, 1988). Fire events in grasslands potentially increase flowering percentage and seed yield. For example, (Pilon *et al.,* 2018) reported early flowering in Cerrado grasslands, dominated by nine grass species including *Paspalum carinatum* and *P. pectinatum*, of south-eastern Brazil, only after fire. It increases the duration and intensity of light reaching the ground, high nutrient availability due to ash deposition, more hormonal triggering by the loss of aerial parts, and induces chemical signals due to burning. Likewise, Baruzzi *et al.* (2022) found the lowest reproduction in wiregrass (*Aristida beyrichiana*) burned during the early dry season, the highest reproduction and poor seed germination when burned during mid-dry season, and the highest seed germination when burned during the early wet season. Fontenele *et al.* (2020) reported the stimulative effect of fire on the flowering of nine early-flowering Neotropical savanna grasses. However, seed production succeeding fire was of poor quality, low seed fertility (<7%) and poor seed germination (<50%). Controlled and periodic burning is therefore essential to ensure uniform flowering and seed yield in perennial grasses. However, extensive studies on tropical and subtropical grasses need to be conducted for large-scale benefits.

Climate Change and Seed Production

Abiotic stresses: Abiotic stresses resulting from climate change, mainly temperature, carbon dioxide, and water availability, significantly affect the performance of grasses, including seed production. However, our understanding of their effects on tropical grasses and forage species, which contribute significantly to the worldwide milk, meat, and wool industries, remains limited.

Effect of temperature: The Intergovernmental Panel on Climate Change (IPCC) recently reported that the world is on track to reach the 1.5°C threshold within the next two decades, and even small increments in temperature will intensify risks to people, livestock, species, and ecosystems (IPCC 2022). Negative impacts of elevated night-time temperatures on tiller and seed production have been observed in perennial ryegrass (Aamlid *et al.,* 2000). Plant reproductive organs are generally more sensitive to high temperatures compared to vegetative propagation parts. Elevated temperatures during pre- and post-flowering phases can reduce the window of time for pollen receptivity and pollen tube growth (Reddy and Kakani, 2007). Additionally, higher temperatures might lead to changes in crop calendars in tropical regions, potentially shortening the effective growing season, particularly in areas with high cropping intensity (Abrol and Ingram, 1996). High temperatures have been shown to disrupt flowering and seed production by affecting plants' reproductive metabolism (Kudo *et al.,* 2004). Pre- and post-anthesis air temperatures are reported to account for 70% of the variability in perennial ryegrass seed numbers (Hampton and Hebblethwaite, 1983). Sherry *et al.* (2007) found that warming advanced flowering and fruiting phenology in nine species that flower before peak summer and delayed it in three species that flower after peak summer. Based on the precipitation experiment, they also observed that warming rather than soil drying was the major phenological cue for change in flowering and fruiting phenology. The changes in reproductive phenology have a lot of implications on seed setting due to changes in competition and availability of pollinators, natural resources, incidence of pests and diseases. Thus, there is a need to do extensive studies on tropical grass species, as information is lacking.

Effect of water availability: Climate change events are predicted to reduce global water availability for irrigation due to increased air temperature and altered spatial and temporal precipitation distribution (Konapala *et al.*, 2020). Furthermore, it is estimated that around half of the world's population (~8 billion people) will experience severe water scarcity at least during some part of the year. This, in turn, will affect most of the sustainable development goals of the world (Caretta *et al.*, 2022). Water shortage affects various seed quality parameters of grasses, including reproduction, pollen viability, pollination, seed set and size, dormancy, and ultimately yield (Chynoweth *et al.*, 2012). This reduction might be associated with reduced photosynthesis, translocation, and leaf expansion due to soil moisture deficit. Therefore, growing tolerant grass varieties in conjunction with irrigation practices, such as deficit irrigation and *in-situ* moisture conservation, would improve water use efficiency to combat decreasing water availability. Grasses like *Sorghum sudanense*, *Chloris gayana*, *Chloris oxburghiana*, *Eragrostis superba*, and *Cenchrus ciliaris* are known to perform well with 20–30% reduced irrigation under lean periods (Koech *et al.*, 2016).

Effect of CO_2: Predictions indicate that atmospheric CO_2 levels are projected to rise from approximately 379 ppm to over 550 ppm and potentially exceeding 800 ppm by 2100, which will further heighten the challenges to successive seed production (Hampton *et al.*, 2016). Grass species have also exhibited increased seed production under elevated CO_2 levels by enhancing the availability of plant-accessible nitrogen. Commencement of early anthesis and seed development can lead to rapid inbreeding and reduced crop performance in grasses, as there are more chances for breakdown of self-incompatibility mechanisms (Simmonds, 1979). Elevated CO_2 concentrations have been linked to decreased time to ear emergence in one cultivar and extended time to ear emergence by up to 10 days in four other cultivars of perennial *Lolium perenne* (Edwards *et al.*, 2001; Maw *et al.*, 2014). Reports also indicate the higher seed production in rangeland *Bromus spp*. under elevated CO_2 exposure (Huxman *et al.*, 1999; Smith *et al.*, 2000; Thurig *et al.*, 2003). Elevated CO_2 (eCO_2) enhances the seed yields of C_3 arable crops by 11 to 30% while leaving the yields of C_4 crops unchanged (Hatfield and Prueger, 2011). Reich *et al.* (2018) reported that long-term exposure to eCO2 (more than 12 years) reversed the pattern with increased biomass in C_4 plants, challenging the C_3-C_4 eCO2 paradigm. Thus, there is a need to conduct long-term studies on the effect of CO_2 in various tropical grasses along with the combined effect of temperature and eCO2, rather than individual effects.

Biotic stresses: Among biotic stresses, "silvertip" is a disease condition where the stalk above the last node turns silvery white and dies without producing seed. It affects most grass species; however, fine-stemmed grasses such as *Festuca* and *Poa spp.* are highly susceptible (Berkenkamp and Meeres, 1975). This condition is attributed to over 30 species of arthropods, including thrips, mites, and chloropid flies. Incidents are primarily influenced by variations in climatic conditions, contributing to silver top occurrence (Soroka and Gossen, 2005). Other biotic stresses in grass seed production, such as ergot, rust, and powdery mildew, are also associated with the occurrence of high temperatures combined with fluctuations in other climatic factors (Cagaš *et al.*, 2006). However, effective strategies for managing biotic stress in grasses include practices like very low mowing, clippings removal after harvest, post-harvest burning, and scalping. These approaches promote a greater number of fertile panicles and ensure good seed yield.

Opportunities

The significant variability for seed yield and quality among tropical grasses underscores the potential for further enhancement. Expanding the area under fodder cultivation faces challenges, as farmers often prioritize commercial and food crops. Therefore, the avenue for progress lies in horizontal and vertical intensification, aiming to increase yield per unit area and time. Achieving this intensification involves using non-cultivable areas for pastures/grasslands and introducing high-yielding forages in cultivable lands (Bhatt *et al.*, 2002). The demand for range grass seeds or planting materials has been steadily rising among various stakeholders. Furthermore, the growing global temperature and water scarcity issues create a market for climate-resilient tropical grass seeds, offering export opportunities for tropical countries like India, given their diverse climates and available rich genetic diversity. In this context, the role of seed production in tropical range grasses/pastures holds paramount importance. Further, the scope exists to develop new varieties with desired traits and monitor plant response to biotic and abiotic stresses using advanced breeding tools and phenotyping facilities.

Understanding grass genetics via advanced sequencing technology: Tropical grasses possess genetic diversity due to polyploidy and apomictic characteristics. Grasping grass genetics is crucial for enhancing crop productivity and sustainability. Next-generation sequencing (NGS) has enabled in-depth exploration of gene sequences and regulatory regions controlling vital agronomic traits such as seed dormancy, uneven maturity, seed shattering, chaffy seed formation, indeterminate growth habit, apomixis, and poor harvest index. NGS has already been used for genome sequencing and developing single-nucleotide polymorphisms (SNPs)-based markers in grass species like *Brachypodium distachyon* and *Medicago* (Cheung *et al.*, 2006; Vogel *et al.*, 2010). The other forage species with an appreciable reference genome is perennial ryegrass (*Lolium perenne*).

However, its assembly quality has limited its application in functional genomics (Byrne *et al.,* 2017). Orchard grass is another species where a chromosome-scale reference genome is available (Huang *et al.,* 2020). NGS is invaluable for precise mapping and transferring beneficial genes to cultivated grasses for more productivity suited to changing climates.

Precision genome editing tools for accelerated breeding: Genome editing tools are powerful for precise plant breeding (Kausch *et al.,* 2019). Although no genome-edited grasses are reported, targeted mutations have been achieved in related grasses like *P. virgatum* (Liu *et al.,* 2018) and *Setaria viridis* (Basso *et al.,* 2021) using CRISPR/Cas technology. Trait-focused genetic procedures, including mapping and expression profiling, have identified new candidate genes influencing advantageous agronomic traits. Genome editing tools can be utilized for meticulous genome engineering, enhancing grass traits (Liu *et al.,* 2018) and accelerating product development.

High-throughput phenotyping for disease monitoring: Early disease detection is crucial for taking timely control measures to safeguard seed yield. Traditional diagnosis is labor-intensive and subjective. High-throughput phenotyping (HTP) is a modern approach to identifying plant responses to stresses at early growth stages (Tanger *et al.,* 2017). HTP techniques screen architectural traits, detect genotypes, assess physiological characteristics, and monitor disease outbreaks. Methods like RGB imaging, 3D scanning, thermal sensing, and fluorescence imaging accurately identify, quantify, and monitor plant diseases precisely in a robust manner (Shakoor *et al.,* 2017).

Scope of drones in forage seeding: The world's available grazing resources are diminishing rapidly due to the shift of land towards intensive agriculture. To ensure the profitability of the dairy sector and environmental health, reseeding grasslands or pasturelands with perennial grasses is crucial. These tropical grasslands are the main source of livelihoods for many pastoralist and nomadic communities, and are directly involved in their preservation, protection, and improvement for enhanced production primarily through reseeding. Ensuring a sufficient supply of high-quality seeds is imperative. The Indian subcontinent boasts 51.6 million hectares of community land, offering the potential to yield around 22.20 million tons of dry matter. It provides a promising avenue to develop and deploy high-yielding grass varieties to enhance fodder production to meet the demand of both domestic animals and wildlife (Chandra *et al.,* 2022). However, accessing these sparsely distributed common lands or wastelands is challenging due to their large area, the presence of vegetation, and wild animals. Under such circumstances, unmanned aerial vehicles (UAVs), commonly known as 'drones,' can be proven to be highly advantageous. A pilot study was conducted in India (Hessarghatta, Karnataka) using a quad-copter agricultural drone equipped with seed-sowing devices, which demonstrated successful seeding of grazing guinea, *Stylosanthes hamata*, and *C. ciliaris* over 20 hectares in just two days, with robust seed germination (Chandra *et al.,* 2022). The advancement of seed pelleting technology has further improved the efficiency by addressing relevant issues, viz., seed size and awns, and enhanced germination percentage. The germination process requires minimal attention after seed pellet dispersion, earning the name "fire and forget" planting. Pelleting also enhances moisture and nutrient retention in seeds and encourages microbial inoculation through the coating. For instance, Vijay *et al.* (2018) reported that mechanical defluffing of seeds in *P. pedicellatum* significantly reduces seed volume, making the obtained naked seeds suitable for pelleting and effective sowing. These advancements facilitate large-scale grass seed coverage using UAVs, fostering the development of common grazing lands, pasturelands, and forestlands.

Conclusion

Tropical range grass seed production is a promising yet underexplored domain with substantial potential and opportunities. It demands a combination of scientific principles and practical skills, similar to seed production in food crops, due to unique challenges. The productive tiller plays a pivotal role in determining grass seed yield. Thus, management strategies should prioritize stimulating early tillering, promoting uniform maturity, minimizing shattering, and ensuring survival for improved seed yield. This approach supports the establishment of new grasslands for sustainable fodder production and enhanced resilience against climate change. Farmers can harvest green herbage in initial cuts, followed by seed and dry matter production. Defoliation at the beginning of the season increases tillering and seed-filling percentage in most grass species. Improved vegetative propagation methods can contribute to the availability of quality planting materials. Application of UAVs and seed pelleting techniques, especially for range grasses, is vital as they efficiently cover a large area within a limited time and resources, particularly in unreachable territories. Ultimately, increased seed production can be achieved with quality seeds, optimal resource utilization, and sound agronomic practices. Future research programs should focus on understanding grass genetics, followed by accelerated breeding and the use of high-throughput phenotyping to develop new varieties. However, the post-harvest seed processing standardization and innovative storage methods are also critical to maintain seed longevity and germination in range grasses. This comprehensive information would help researchers understand the seed production potential and constraints of various rangeland grasses, while also highlighting opportunities for further improvement. It would also serve as a valuable guide for policymakers in formulating national fodder strategies and the National Seed Mission aimed at enhancing the country's fodder production and quality. At the same time, the fodder seed production industry requires policy support comparable to that provided for food crops.

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