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Influence of environment on germination and growth of fodder crops: A review

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Abstract

Fodder crops supply energy, protein, mineral nutrients and fibre. It is an important foundation for livestock feeding systems. Their productivity depends on the environment wherein it is established and grown. The influence of environmental conditions begins with seed germination and continues through seedling establishment, vegetative growth, biomass accumulation and forage quality. The germination rate, final germination percentage, seedling vigour and field establishment are determined by temperature, water availability, salinity, soil reaction, light, oxygen supply and soil physical conditions. During later growth stages, temperature, rainfall, soil moisture, solar radiation, atmospheric humidity, vapour pressure deficit and atmospheric carbon dioxide influence photosynthesis, nutrient uptake, leaf expansion, tillering, root development and biomass production. Among these factors, temperature and water availability are particularly important during germination, while drought and salinity become major constraints during subsequent crop growth. For example, perennial ryegrass attained approximately 95% germination at 25°C, whereas germination declined sharply at 35°C, demonstrating the narrow thermal range within which some cool-season forages establish successfully (Javaid *et al.*, 2022). Similarly, annual cool-season grasses generally germinate most successfully around 20°C, whereas perennial grasses tend to perform better near 15°C (Butler *et al.*, 2017). Water deficit restricts seed imbibition and radicle emergence and subsequently reduces leaf expansion, stomatal conductance, photosynthesis and biomass production (Staniak and Kocoń, 2015). Salinity acts through both osmotic limitation and ion toxicity, with substantial genotypic variation in tolerance among alfalfa, sorghum, cowpea and other forage species (Bhattarai *et al.*, 2022). The most important is that environmental stresses seldom occur independently; heat, drought, salinity and nutrient limitations frequently interact and may produce responses that cannot be predicted from individual stresses alone. Considerable genetic variation and genotype × environment interaction have been documented among forage grasses and legumes, providing opportunities for breeding climate-resilient fodder cultivars (Shariatipour *et al.*, 2023). This review examines the influence of major environmental factors on germination, establishment, growth, forage yield and nutritional quality and discusses management, breeding and research approaches for improving fodder production under increasingly variable climatic conditions.

Keywords: Fodder crops, forage crops, seed germination, seedling establishment, temperature, drought, salinity, water availability, climate change, forage yield, forage quality.

1. Introduction

Fodder crops are an essential component of livestock production because they provide the plant-based energy, protein, minerals and fibre required for maintenance, growth, reproduction and production. Unlike many food crops, where grain or marketable yield is often the principal consideration, successful fodder production depends on the establishment of a uniform plant population, rapid vegetative development, high biomass production and acceptable nutritional quality. Consequently, environmental conditions influence not only the amount of forage produced but also its chemical composition, digestibility and eventual feeding value (Capstaff and Miller, 2018) ^[6]. The environmental influence begins before a seedling becomes visible in the field. Germination requires coordinated water uptake, membrane reactivation, enzyme activity, respiration, mobilisation of stored reserves and radicle emergence. Temperature, water availability and salinity can determine whether these processes proceed normally or become

delayed or inhibited. A detailed study of perennial ryegrass showed that temperature, salinity, osmotic stress, pH and sowing depth could alter both germination and early seedling characteristics, with maximum germination occurring around 25°C (Javaid *et al.*, 2022) ^[1]. Temperature is particularly important because the biochemical reactions involved in germination are temperature dependent. The response is not uniform among forage species. Cool-season annual grasses generally perform best at relatively moderate temperatures, whereas perennial grasses often have lower optimum temperatures (Butler *et al.*, 2017) ^[2]. Similar differences have been reported among tall fescue genotypes and alfalfa populations, indicating that genetic variation can influence the temperature range over which successful establishment occurs (Ahmed and Escobar-Gutiérrez, 2022) ^[7]; (Ahmed *et al.*, 2019) ^[8]. Water availability represents another major environmental limitation. Seeds must absorb sufficient water to initiate metabolic activity, while established forage plants depend on adequate soil moisture for cell expansion, stomatal functioning, photosynthesis and nutrient acquisition. Under drought, reductions in leaf area, stomatal conductance, root development and biomass production have been observed in both tropical and temperate forage grasses (Zuffo *et al.*, 2022) ^[9]; (Bista *et al.*, 2018) ^[10]. Salinity is particularly relevant in arid and semi-arid forage-producing regions. Increasing salt concentration reduces the external water potential of the germination medium and can cause ionic imbalance after uptake. Studies in alfalfa, forage sorghum, forage cowpea and bermudagrass have demonstrated differences among genotypes in their ability to maintain growth under saline conditions (Bhattarai *et al.*, 2022; Fan *et al.*, 2023) ^[4] ^[11]. Environmental stresses are also becoming increasingly difficult to separate under field conditions. High temperature commonly occurs during periods of limited water availability, while saline soils are frequently associated with high

evaporative demand. Therefore, evaluating temperature, drought, salinity, radiation and atmospheric CO₂ independently provides only part of the picture. Their combined influence needs greater attention when developing fodder production systems suited to changing climates (Mäkinen *et al.*, 2018) ^[12]; (Grimoldi and Di Bella, 2024) ^[13].

2. Importance of Environmental Conditions for Fodder-Crop Establishment

Establishment is one of the most decisive stages in fodder production. A crop that fails to establish a uniform stand has fewer plants available to intercept solar radiation and produce biomass. Poor emergence also creates open spaces that may favour weeds and ultimately reduce forage yield. The establishment process depends on the interaction between seed quality and the surrounding soil environment. Perennial ryegrass provides a clear example of this interaction. Germination was highest near 25°C, while extreme temperatures, increasing NaCl concentration and severe osmotic stress reduced germination and seedling growth (Javaid *et al.*, 2022) ^[1]. Burial depth also influenced emergence. Under the experimental conditions, approximately 90% emergence was obtained at 1 cm, whereas emergence was absent at the soil surface and at depths of 6–7 cm (Javaid *et al.*, 2022) ^[1]. Temperature and salinity may further modify one another. Research involving forage grasses has shown that the effect of salt stress on germination depends partly on temperature, while studies of desert forage grass have demonstrated joint effects of temperature and salinity on germination and seedling development (Liu *et al.*, 2021) ^[14]; (Malik *et al.*, 2022) ^[15]. These observations show that establishment cannot be explained by seed quality alone. The final field population reflects the interaction between seed characteristics, soil moisture, temperature, salinity, aeration and placement of the seed within the soil profile.

Table 1: Major environmental factors influencing germination and establishment of fodder crops

Environmental factor	Major influence	Sensitive stage	Representative fodder crops
Temperature	Germination percentage, rate and seedling vigour	Germination	Ryegrass, alfalfa, fescue, Brachiaria, oat
Water availability	Imbibition and radicle emergence	Germination	Ryegrass, Brachiaria, oat and legumes
Salinity	Osmotic inhibition and ion toxicity	Germination and seedling growth	Alfalfa, cowpea, sorghum, bermudagrass
Soil pH	Nutrient availability and establishment	Germination/early growth	Ryegrass and other grasses
Light	Photomorphogenesis and photosynthesis	Emergence onward	Grasses and legumes
Oxygen	Respiration and root development	Germination	Seed-propagated fodders
Sowing depth	Emergence percentage and emergence speed	Establishment	Ryegrass and grasses

Source: Compiled and adapted from Butler *et al.* (2017) ^[1]; Javaid *et al.* (2022) ^[2]; Hsu *et al.* (1985) ^[9]; Shen *et al.* (2008) ^[10]; and other sources.

3. Environmental Factors Influencing Seed Germination

3.1 Temperature

Temperature is one of the most influential environmental variables controlling germination. It regulates membrane activity, enzyme function, respiration, reserve mobilisation and radicle emergence. Every forage species has a lower thermal limit, an optimum range and an upper limit beyond which germination becomes progressively impaired. Cool-season forage grasses show considerable variation in their thermal requirements. Annual cool-season grasses generally achieve maximum germination around 20°C, whereas perennial species often perform better at approximately 15°C, although individual species differ considerably (Butler *et al.*, 2017) ^[2]. Perennial ryegrass illustrates this response clearly, with germination

reaching approximately 95% at 25°C but declining rapidly at 35°C (Javaid *et al.*, 2022) ^[1]. Temperature also affects seed quality before sowing. The conditions experienced during seed development can influence seed size, fertility, subsequent germination and seedling dry weight. Thus, temperature affects fodder crops not only at the time of germination but also during the production of the seed itself (Akpan and Bean, 1977) ^[15]. Tall fescue populations exhibit intraspecific variability in germination response to temperature, suggesting that selection could be used to improve establishment under changing thermal conditions (Ahmed and Escobar-Gutiérrez, 2022) ^[7]. Similar genetic variation has been identified in alfalfa (Ahmed *et al.*, 2019) ^[8].

Table 2: Selected temperature responses reported in fodder crops

Crop/group	Important temperature response
Annual cool-season grasses	Maximum germination generally around 20°C
Perennial cool-season grasses	Optimum generally around 15°C
Perennial ryegrass	Approximately 95% germination around 25°C
Perennial ryegrass	Sharp decline in germination at 35°C
Tall fescue	Considerable genotypic variation in temperature response
Alfalfa	Genetic variation in germination response to temperature

Source: Compiled and adapted from Bhattarai *et al.* (2022) ^[5]; Sandhu *et al.* (2017) ^[13]; Guo *et al.* (2020) ^[14]; Shah *et al.* (2020) ^[27]; and other sources.

Temperature therefore needs to be considered when selecting sowing windows. Establishing a cool-season forage during excessive heat can result in slow or uneven emergence, whereas planting a warm-season forage during unsuitable low temperatures can delay establishment.

3.2 Water Availability and Drought

Water is indispensable for seed germination because imbibition initiates the metabolic sequence required for radicle emergence. When water availability is insufficient, seed hydration is delayed and enzyme activation and cell expansion are restricted. Under severe water deficit, germination may cease altogether. Variation among populations indicates that germination responses can also reflect adaptation to local rainfall conditions. Populations of forage grasses originating from contrasting rainfall environments have shown different responses to water availability, suggesting that local climatic history can shape germination behaviour (Zuffo *et al.*, 2022) ^[9]. Research on *Brachiaria* forage grasses has similarly demonstrated that both temperature and osmotic potential influence germination characteristics (Müller *et al.*, 2024) ^[17]. This is important because drought tolerance expressed by a mature plant does not necessarily mean that the same genotype will have superior tolerance during germination. Following establishment, drought affects the plant more extensively. Water limitation reduces leaf expansion and stomatal conductance and consequently restricts photosynthesis and biomass accumulation. Tropical forage grasses differ considerably in their response, with some cultivars maintaining better leaf area, growth and root development than others under stress (Cardoso *et al.*, 2015; Zuffo *et al.*, 2022) ^[18] ^[9]. Repeated water deficiency can also alter biomass partitioning and root morphology. Such changes may help plants improve water acquisition or reduce water loss, but they may also reduce above-ground forage production (Mastalerczuk and Borawska-Jarmulowicz, 2021) ^[19].

3.3 Salinity and Osmotic Stress

Salinity affects seed germination through two closely connected mechanisms. First, dissolved salts lower the external water potential and make water uptake more difficult. Second, ions entering plant tissues can disturb cellular ion balance and interfere with metabolic processes. Alfalfa provides a strong example of genotypic variation in salt tolerance. Increasing salinity reduced germination and early root development, but the magnitude of the response differed among landraces and cultivars (Bhattarai *et al.*, 2022) ^[4]. Salt-tolerance variation has also been detected across a much wider set of alfalfa germplasm, demonstrating the potential value of genetic selection (Fan *et al.*, 2023) ^[11]. Forage cowpea exhibits a similar trend. Increasing salinity progressively reduces germination percentage, germination index, seedling vigour, root and shoot development and seedling dry matter (Kandil *et al.*, 2017) ^[20]. Forage sorghum is another important crop because its salt response

extends from germination through maturity. Genetic studies have identified candidate genes associated with salt tolerance, providing opportunities for developing cultivars capable of maintaining productivity under saline conditions (Fan *et al.*, 2023) ^[11]. At the whole-plant level, salinity affects photosynthesis, nutrient balance, ion homeostasis and biomass accumulation. In bermudagrass, salt stress produces marked physiological and growth responses, while appropriate nitrogen management can partly reduce the damage caused by salinity (Shao *et al.*, 2022) ^[21].

3.4 Soil pH

Soil reaction affects nutrient availability, microbial activity and root development and therefore can influence early establishment. However, the magnitude of the response varies considerably among species. Perennial ryegrass showed relatively stable germination across a broad pH range of approximately 5–10, while temperature, salinity and osmotic stress exerted much stronger effects (Javadi *et al.*, 2022) ^[1]. This finding demonstrates that not all environmental variables have equal importance and that management priorities should be based on the sensitivity of the particular forage crop.

3.5 Light and Solar Radiation

Light becomes increasingly important after emergence because it drives photosynthesis and regulates photomorphogenic development. Solar radiation supplies the energy required for carbon fixation and therefore directly influences biomass accumulation. Forage maize modelling has demonstrated the importance of daily air temperature and solar radiation in determining canopy photosynthesis and growth (Takahashi, 2002) ^[22]. Under adequate soil moisture, greater radiation can support greater carbon assimilation. Under severe drought, however, high radiation can simultaneously increase evaporative demand and aggravate water stress. Thus, the importance of radiation cannot be separated from temperature and water availability.

3.6 Oxygen and Soil Aeration

Oxygen is essential for respiration during germination. Poorly aerated soil restricts oxygen diffusion and can slow respiration, root development and seedling establishment. Excess rainfall or irrigation may create waterlogged conditions in which oxygen availability becomes particularly limiting. Although drought has received greater attention in fodder research, waterlogging deserves greater consideration because irregular rainfall may expose a crop to excessive water at one stage and drought at another. Understanding these contrasting conditions within the same production cycle will become increasingly important under variable climates.

3.7 Sowing Depth and Soil Physical Conditions

Sowing depth influences the distance that a seedling must travel

before emergence and simultaneously modifies the temperature and moisture environment surrounding the seed. Very shallow placement may expose seeds to rapid drying, while excessive depth can exhaust seed reserves before the shoot reaches the surface. In perennial ryegrass, approximately 90% emergence was recorded at a 1-cm burial depth, whereas emergence was not observed at the soil surface or at depths of 6–7 cm under the experimental conditions (Javaid *et al.*, 2022) ^[1]. Appropriate sowing depth should therefore be selected according to seed size, soil texture, expected moisture availability and temperature at planting.

4. Environmental Factors Influencing Seedling Growth and Forage Productivity

4.1 Temperature

Temperature continues to influence the crop after germination by controlling photosynthesis, respiration, leaf expansion, tillering and developmental rate. Cool-season forages generally favour moderate temperatures, whereas warm-season C4 forages are better adapted to warmer environments. Prolonged heat can reduce growth and productivity in cool-season grasses. Tall fescue, for example, undergoes substantial physiological and molecular changes under high-temperature stress (Hu *et al.*, 2014) ^[23]. In contrast, tropical grasses such as *Megathyrsus maximus* possess greater adaptation to warm conditions, although warming can still interact with elevated CO₂ and alter forage nutritional quality (Habermann *et al.*, 2022) ^[24]. High temperature is therefore not simply a question of whether a crop survives. Even when biomass is maintained, rapid development under heat may alter leaf-to-stem ratios and forage quality.

4.2 Water Availability

Water availability is one of the strongest determinants of forage biomass. Deficit irrigation restricts cell expansion, stomatal conductance and photosynthetic carbon assimilation. In forage maize, drought has been associated with reductions in fresh and dry forage yield and energy productivity (Daneshvar Rad *et al.*, 2021) ^[25]. Importantly, forage yield and forage quality may not respond at the same level of water stress. Field research in maize hybrids showed that the thresholds for changes in forage yield and digestibility can differ (Main *et al.*, 2023) ^[26]. Tropical forage grasses also differ in drought tolerance. Some cultivars of *Panicum maximum* have maintained relatively good performance under moderate or severe water stress, indicating the value of selecting appropriate genotypes rather than applying a uniform drought-management strategy to all cultivars (Zuffo *et al.*, 2022) ^[9].

4.3 Rainfall Distribution

Total annual rainfall alone is not a reliable indicator of forage productivity. The timing and distribution of rainfall throughout the growing season are often more important. Rainfall during active vegetative growth supports soil moisture, nutrient transport, whereas a short dry period during establishment can cause disproportionate damage. In rainfed systems, growing-season precipitation is positively associated with forage yield and crude protein concentration (Li *et al.*, 2022) ^[27]. Consequently, climate variability needs to be assessed in terms of rainfall distribution rather than simply annual totals. A region receiving adequate annual rainfall may still experience substantial yield losses if rainfall is poorly distributed.

4.4 Solar Radiation

Solar radiation provides the energy required for photosynthetic

carbon assimilation. Its effect on forage production depends on leaf area, temperature and water availability. Under sufficient moisture, greater radiation generally favours biomass accumulation. Under severe drought, however, high radiation can increase evaporative demand and intensify plant water stress. This interaction is particularly relevant for forage maize and other high-biomass crops. The combined influence of radiation and temperature is therefore more informative than either variable considered independently (Takahashi, 2002) ^[22].

4.5 Atmospheric CO₂

Increasing atmospheric CO₂ can stimulate photosynthesis and improve water-use efficiency, particularly in C3 forage crops. However, the magnitude of this response depends strongly on nutrient and water availability. Elevated CO₂ has increased photosynthetic activity and biomass production in some forage grasses under favourable nutrient conditions, but nutrient limitations can reduce the response (Capstaff and Miller, 2018) ^[6]. Warming can further modify this response. In *Megathyrsus maximus*, warming offset some of the beneficial effects of elevated CO₂ on water relations and amplified the reduction in forage nutritional value associated with elevated CO₂ (Habermann *et al.*, 2022) ^[24]. This indicates that the future response of forage crops cannot be predicted simply from the expected increase in atmospheric CO₂.

5. Physiological and Biochemical Responses to Environmental Stress

Environmental stresses trigger a coordinated set of morphological, physiological and biochemical responses. The response is generally aimed at conserving resources and maintaining cellular function, although these adjustments frequently occur at the expense of biomass production. Under drought, stomatal closure reduces transpiration and limits carbon dioxide entry into the leaf. Leaf expansion is also restricted, resulting in reduced canopy development and photosynthetic capacity. Root growth and biomass allocation may change as the plant attempts to improve water acquisition (Bista *et al.*, 2018) ^[10]. Forage grasses subjected to mild drought show changes in photosynthetic performance, plant water status and biochemical compounds associated with stress adaptation (Fariaszewska *et al.*, 2020) ^[28]. Tropical C4 grasses may also employ contrasting water-use strategies. Such differences suggest that the same management approach may not be equally effective across species or cultivars (Cardoso *et al.*, 2015) ^[18]. Drought also affects nutrient uptake. Water stress can reduce nutrient concentration and alter the activity of proteins responsible for nutrient acquisition, with drought-sensitive and drought-tolerant grasses showing different responses (Bista *et al.*, 2018) ^[10]. Salinity imposes an additional burden because plants must maintain cellular ion balance while coping with osmotic and oxidative stress. Regulation of Na⁺ and K⁺ balance, compatible-solute accumulation, antioxidant responses and modification of photosynthetic activity are among the mechanisms associated with salt tolerance (Fan *et al.*, 2023) ^[11].

6. Environmental Effects on Forage Yield and Nutritional Quality

Environmental conditions affect both the quantity and quality of forage. A high biomass yield does not necessarily indicate superior feeding value if the crop contains excessive structural fibre, reduced protein or poor digestibility. A global comparison of forage plants grown under contrasting environmental conditions demonstrated considerable variation in fibre, lignin,

minerals, protein and digestibility (Lee, 2018) ^[29]. Temperature can accelerate plant development and alter the balance between leaves and stems. Rapid structural development under high temperature may increase fibre deposition and reduce digestibility. Climate change therefore poses a dual challenge. A crop may maintain acceptable biomass production while simultaneously experiencing changes in nutritional composition. Future climate scenarios for forage grasses indicate that changes in growth can influence subsequent fermentation characteristics and ruminant efficiency (Hart *et al.*, 2022) ^[30]. Drought can similarly reduce total biomass while altering concentrations of crude protein, fibre and other quality-related components. Consequently, environmental evaluation of fodder crops should include both yield and nutritional parameters.

7. Genotypic Variation and Genotype × Environment Interaction

Forage crops do not respond uniformly to environmental stress. Considerable genetic variation exists among species, cultivars and even individual populations. This variation is particularly valuable because it provides the raw material for breeding forage crops capable of maintaining production under stressful environments. In Kentucky bluegrass, evaluation of 100 ecotypes under contrasting water regimes demonstrated significant variation in photosynthetic characteristics and forage production. Drought reduced fresh forage yield by approximately 45% on average, but some ecotypes maintained comparatively stable production (Shariatipour *et al.*, 2023) ^[5]. Similar variation occurs in perennial ryegrass, alfalfa and tropical forage grasses. Differences in root development, water-use efficiency, photosynthetic stability and recovery after stress can contribute to variation in forage yield (Zuffo *et al.*, 2022) ^[9]. Salinity tolerance also differs substantially among alfalfa varieties. Genetic diversity studies demonstrate that some varieties maintain better growth and physiological function under saline conditions than others (Fan *et al.*, 2023) ^[11]. The importance of genotype × environment interaction becomes especially clear when cultivars are evaluated across multiple locations or seasons. A genotype performing well in one environment may not necessarily maintain the same advantage elsewhere. Recent multi-environment evaluations of forage crops confirm the importance of environmental interaction in determining yield stability (Makaju *et al.*, 2026; Atumo *et al.*, 2026) ^[31] ^[32]. For breeding programmes, therefore, selection under a single environment is insufficient. Genotypes should be evaluated under contrasting temperature, moisture and soil conditions before being recommended for wider cultivation.

8. Influence of Climate Change on Fodder Crops

Climate change is expected to affect fodder production through rising temperature, altered rainfall patterns, more frequent drought, extreme rainfall events and increasing atmospheric CO₂. These changes will influence both crop establishment and subsequent productivity. In northern Europe, existing forage cultivars show limitations in their capacity to adapt to projected climatic conditions, particularly where temperature and rainfall patterns change simultaneously (Mäkinen *et al.*, 2018) ^[12]. Temperate grassland systems may experience changes in the length and intensity of the growing season, with consequences for forage production (Emadodin *et al.*, 2021) ^[33]. In tropical forage systems, the combination of heat and water stress may reduce biomass production and nutritional quality. The interaction between warming and elevated CO₂ is particularly important. In *Megathyrsus maximus*, elevated CO₂ and warming

did not produce simple additive effects; instead, warming altered water relations and intensified some negative effects on forage quality (Habermann *et al.*, 2022) ^[24]. Forage crops such as sorghum and pearl millet are of particular interest for water-limited environments because of their adaptation to high temperature and relatively low water availability. However, even these crops require suitable management to maintain yield under increasingly irregular rainfall. Climate resilience should therefore not be interpreted as the ability of a crop to tolerate one stress in isolation. A truly resilient forage crop must be able to establish successfully, maintain growth during stress, recover after stress and retain acceptable nutritional quality.

9. Management Strategies for Improving Germination and Growth

9.1 Selection of Suitable Temperature and Sowing Time

Sowing time should be selected according to the temperature requirements of the forage species. Cool-season forages should generally be established during periods of moderate temperature, whereas warm-season forages require warmer soil and air conditions. Temperature-based germination information can therefore be converted into practical sowing windows. This approach can reduce delayed emergence and improve stand establishment (Butler *et al.*, 2017; Javaid *et al.*, 2022) ^[2] ^[1].

9.2 Water Management

Irrigation should be scheduled according to crop demand, soil moisture and prevailing atmospheric conditions. Where water is limited, controlled deficit irrigation may be used, provided that severe stress is avoided during sensitive developmental stages. Research in sorghum and other forage crops demonstrates that appropriate irrigation management can improve the balance among forage yield, quality and water-use efficiency (Nahed *et al.*, 2026) ^[34].

9.3 Soil-Moisture Conservation

Soil-moisture conservation practices can help buffer short-term fluctuations in water availability. Mulching can modify soil temperature and reduce moisture loss, thereby creating a more favourable environment for seedling establishment and crop growth. Such practices are particularly useful where irrigation water is limited and rainfall is irregular.

9.4 Seed Priming

Seed priming is a promising approach for improving germination uniformity and early seedling vigour. Hydropriming, Osmo priming and nutrient priming can partially prepare the seed for rapid metabolic activation after sowing. However, future research should place greater emphasis on testing priming treatments under realistic combinations of temperature, drought and salinity rather than evaluating them only under ideal laboratory conditions.

9.5 Salinity Management

Where soils are saline, the selection of salt-tolerant forage species and cultivars is fundamental. Some forage grasses and halophytic species can produce useful biomass under saline conditions and may also contribute to the productive use of salt-affected land (Ashilenje *et al.*, 2022) ^[35]. Management of irrigation water quality, soil drainage and nutrient balance should complement genetic tolerance.

9.6 Balanced Nutrient Management

Nutrient management can influence the ability of forage crops to

cope with environmental stress. In bermudagrass, appropriate adjustment of nitrogen application reduced some of the physiological damage caused by salinity (Shao *et al.*, 2022) ^[21]. Similarly, phosphorus availability can modify the response of forage grasses to elevated CO₂ (Capstaff and Miller, 2018) ^[6]. Thus, fertilizer management should be integrated with irrigation, soil and climate management rather than treated as a separate component of crop production.

9.7 Breeding and Selection for Stress Tolerance

Breeding programmes should give greater attention to rapid germination, vigorous seedling establishment, strong root systems, water-use efficiency, maintenance of photosynthesis under stress, rapid recovery after drought and stable forage yield. Genetic studies in alfalfa, sorghum, perennial ryegrass, Kentucky bluegrass and tropical forage grasses demonstrate that useful variation for these characteristics already exists within forage germplasm (Fan *et al.*, 2023; Shariatipour *et al.*, 2023) ^[11] ^[5].

10. Interactions among Environmental Factors

A major limitation of conventional environmental studies is that individual stresses are often examined separately. In the field, however, plants rarely experience only one stress. The interaction between temperature and salinity is particularly important during germination. Increasing salinity can reduce germination, but the severity of the response depends on temperature (Liu *et al.*, 2021) ^[14]. Similar interactions occur between temperature and water availability in Brachiaria and other forage grasses (Müller *et al.*, 2024) ^[17]. The interaction between CO₂ and temperature provides another example. Elevated CO₂ may stimulate growth, but warming can reduce or modify this response and may simultaneously reduce nutritional value (Habermann *et al.*, 2022) ^[24]. Likewise, drought and nutrient deficiency can occur together. Reduced soil moisture limits nutrient diffusion and root activity, meaning that the crop may experience both water and nutrient stress simultaneously. This reinforces the need for multi-stress experiments that reproduce field conditions more realistically.

11. Research Gaps and Future Perspectives

Despite considerable progress in understanding environmental effects on fodder crops, several important research gaps remain. First, much of the available literature still examines temperature, drought or salinity separately. Field-grown fodder crops, however, frequently experience combinations of these stresses. Future experiments should therefore include multiple-stress treatments. Second, germination tolerance and mature-plant tolerance are often studied independently. A genotype that germinates successfully under drought or salinity may not necessarily maintain high biomass production after establishment. Research linking early establishment characteristics with final forage productivity would therefore be valuable. Third, genotype × environment interaction requires greater attention. Multi-location and multi-season experiments should be used to identify cultivars with stable performance rather than simply selecting the highest-yielding genotype in a single environment. Fourth, climate-change experiments should evaluate both forage quantity and quality. Maintaining biomass alone is not sufficient if high temperature or drought simultaneously reduces crude protein concentration or digestibility. Fifth, greater attention should be given to fodder crops relevant to Indian agro-climatic conditions. Sorghum, maize, pearl millet, cowpea, berseem, oats, lucerne, Napier

grass, Guinea grass and Brachiaria/Urochloa should be evaluated under region-specific combinations of temperature, soil moisture, rainfall and salinity. Finally, future studies should combine field experiments with remote sensing, crop modelling, physiological phenotyping, molecular breeding and environmental monitoring. Such integration would help identify not only which fodder crops tolerate environmental stress, but also why they tolerate it and how that tolerance can be incorporated into practical production systems.

12. Conclusion

Environmental conditions influence fodder crops from the earliest stage of seed germination to final harvest. Temperature, water availability and salinity are especially important during germination, while temperature, soil moisture, rainfall, solar radiation, atmospheric CO₂ and soil conditions continue to regulate growth and productivity after establishment. The evidence reviewed demonstrates that environmental stress can affect germination percentage, emergence rate, root and shoot development, photosynthesis, nutrient acquisition, biomass partitioning and forage nutritional quality. Perennial ryegrass, for example, showed approximately 95% germination at 25°C but a marked decline at 35°C, illustrating the importance of matching sowing conditions with crop-specific thermal requirements (Javaid *et al.*, 2022) ^[1]. Similarly, drought and salinity can reduce forage production through changes in water relations, photosynthesis, nutrient uptake and ionic balance (Bista *et al.*, 2018; Bhattarai *et al.*, 2022) ^[10] ^[4]. At the same time, the considerable variation among forage species and genotypes demonstrates that environmental stress does not inevitably result in severe production losses. Some genotypes maintain comparatively stable growth, water-use efficiency or forage quality under stressful conditions. This variation provides an important foundation for breeding climate-resilient fodder crops. No single management practice can, however, provide complete protection against environmental variability. Reliable fodder production under changing climatic conditions will require an integrated approach involving suitable genotype selection, appropriate sowing time and depth, efficient irrigation, soil-moisture conservation, salinity management, balanced nutrition and improved seed quality. Future research should particularly focus on combinations of environmental stresses and should evaluate both forage quantity and nutritional quality. Greater use of multi-environment trials, physiological screening, remote sensing, crop modelling and molecular breeding could accelerate the development of forage crops capable of maintaining productivity under increasingly variable climatic conditions. Such an integrated approach will be essential for ensuring a stable supply of nutritious fodder and supporting sustainable livestock production.

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