

when water supply is inadequate. The effect of drought on growth is closely tied to root performance, since deeper and more extensive root systems improve access to subsoil moisture and support better recovery under episodic stress. Across legumes, deep rooting, greater root length, and higher rooting density are repeatedly identified as promising traits for drought avoidance, whereas drought in common bean reduced rooting depth by 14%, root biomass by 29%, and total root length by 35%, with parallel declines in pod set and pod weight. For sword bean, this suggests that irrigation practices and soil-water management that maintain root activity during both vegetative and early reproductive stages will be essential for sustaining aboveground growth and reproductive success.

Water stress effects also depend on stress timing, intensity, and recovery opportunities rather than on soil moisture status alone. Reviews of legume drought responses note that yield loss varies by species and variety according to phenology, soil texture, and agro-climatic conditions, while intermittent drought can differ biologically from terminal drought because recovery capacity becomes part of the response (Khatun et al., 2021). This distinction is important for sword bean because a long growth cycle increases the chance that the crop will encounter both short-term water deficits and later-season moisture decline, making stage-specific water management more relevant than a single uniform irrigation strategy. Some legume responses to limited water are adaptive rather than purely damaging. Drought escape through faster development, early flowering, and earlier seed set is recognized as a major legume strategy, and plants with indeterminate growth can partly compensate after short drought by producing new organs during recovery. In practical terms, sword bean management under water-limited environments may benefit from synchronizing planting date and moisture availability so that the most drought-sensitive phases do not coincide with severe soil drying.

4.2 Effects of temperature and light conditions on physiological performance

Temperature and light conditions have major effects on legume physiological performance, and both factors interact strongly with water relations. Legume cover crop experiments that included jack bean (*Canavalia ensiformis*) showed that increasing light intensity significantly increased leaf, shoot, and root growth, while also increasing net assimilation rate, SPAD index, net photosynthesis, stomatal conductance, and transpiration (Baligar et al., 2020). These findings indicate that sword bean performance under different management systems will be highly sensitive to canopy light environment, especially in intercropping or shaded production settings where reduced irradiance can constrain carbon gain. Reduced light does not simply lower growth; it also changes leaf structure and biomass partitioning. Under shade, legumes developed thinner but larger leaves, had higher leaf-to-stem and leaf-to-total dry weight ratios, and accumulated more chlorophyll per unit area, yet final biomass still declined by about one-third relative to full sun. For sword bean, this suggests that shaded plants may show morphological adjustment that helps maintain light capture, but this acclimation is unlikely to fully offset losses in dry matter production where radiation is substantially limited.

Temperature stress imposes a parallel physiological burden because extreme heat alters water relations, photosynthesis, and reproductive metabolism. In legumes, high temperature increases transpiration and water loss, disturbs turgor and physiological processes, and impairs osmotic adjustment partly through damage to photosystem II, increased respiration, and reduced sugar concentrations. More generally, each legume species has specific minimum, maximum, and threshold temperatures, and extreme deviations can disrupt every stage of plant development and cause severe productivity loss. The interaction of temperature and light is especially important because hotter environments often increase evaporative demand at the same time that radiation drives canopy function. Greenhouse work on tropical perennial legumes was conducted near 30/28°C to reflect warmer tropical conditions, and the same study showed that increasing photosynthetic photon flux density improved water-use efficiency as well as nutrient-use efficiency across species (Baligar et al., 2020). This implies that sword bean physiological performance will be best when adequate radiation is matched with sufficient soil moisture, since light can promote carbon gain and efficiency, but high temperature without water supply is more likely to shift the balance toward dehydration and stress.

4.3 Adaptation mechanisms under abiotic stress conditions

Under abiotic stress, legumes activate integrated morphological, physiological, and biochemical defense systems