



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(6): 218-221
Received: 22-04-2026
Accepted: 28-05-2026

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Effect of terminal heat stress on wheat and mustard crops in Northern States of India: A review

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i6Sc.5778>

Abstract

Terminal heat stress has emerged as one of the major abiotic constraints affecting crop productivity in the Indo-Gangetic plains of northern India. Wheat (*Triticum aestivum* L.) and mustard (*Brassica juncea* L.) are the dominant rabi crops cultivated across Punjab, Haryana, Uttar Pradesh, Rajasthan and Madhya Pradesh. Rising temperatures during reproductive stages accelerate crop phenology, shorten grain filling duration and reduce assimilate accumulation. Previous studies reported that wheat yield declines by approximately 6% for every 1 °C increase in temperature, particularly when temperatures exceed 31 °C during grain filling (Asseng *et al.*, 2015; Lobell *et al.*, 2011). Terminal heat stress disrupts photosynthesis, reduces chlorophyll stability and impairs enzyme activities involved in starch synthesis (Farooq *et al.*, 2011; Prasad *et al.*, 2008). Similarly, mustard productivity declines due to reduced silique formation, impaired seed filling and decreased oil accumulation under high temperature conditions (Angadi *et al.*, 2000; Chauhan *et al.*, 2011). Climate change and delayed sowing in rice–wheat systems have increased the incidence of terminal heat stress in northern India. This review synthesizes current research on the physiological, biochemical and agronomic impacts of terminal heat stress on wheat and mustard crops and discusses potential mitigation strategies for sustaining crop productivity under climate change.

Keywords: Terminal heat stress, wheat, mustard, Indo-Gangetic plains, climate change, grain filling, crop productivity

Introduction

Wheat is the second most important cereal crop globally and plays a crucial role in ensuring food security in India. The Indo-Gangetic plains account for a major share of national wheat production and represent one of the most productive agricultural regions in the world (Ortiz *et al.*, 2008) ^[19]. Mustard is also an important oilseed crop widely cultivated in northern India due to its adaptability to cool winter conditions (Chauhan *et al.*, 2011) ^[6].

However, climate change has significantly altered temperature patterns in these regions. Rising global temperatures and frequent heat waves have increased the incidence of heat stress during critical crop growth stages (IPCC, 2021). Terminal heat stress occurs when crops experience elevated temperatures during flowering, grain filling or seed development stages (Farooq *et al.*, 2011 and Megha *et al.*, 2024) ^[9, 4]. These high temperatures accelerate crop maturity, shorten grain filling duration and ultimately reduce crop yield (Asseng *et al.*, 2015) ^[3].

Heat stress during flowering in wheat causes pollen sterility, reduced grain number and decreased kernel weight (Prasad *et al.*, 2008) ^[21]. In mustard, high temperature stress during flowering in mustard causes reduced fertility, flower and fruit abortion with loss in seed yield (Young *et al.*, 2004; Singh *et al.*, 2014) ^[30, 25]. Similarly, high temperatures reduce silique formation and seed development, leading to significant yield losses (Angadi *et al.*, 2000) ^[2]. Terminal heat stress caused significant reduction in seed yield/plant (Sharma *et al.*, 2022) ^[26]. Therefore, understanding the impact of terminal heat stress on wheat and mustard crops is critical for developing effective adaptation strategies.

Climate Change and Occurrence of Terminal Heat Stress

Recent climate studies indicate that average temperatures in the Indo-Gangetic plains have increased significantly over the last few decades (Lobell *et al.*, 2011) ^[14]. Climate projections

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suggest further warming of 1.5–2.0 °C by mid-century, which could severely affect crop productivity (IPCC, 2021). Terminal heat stress has become more frequent due to delayed sowing in rice–wheat cropping systems and shortened winter seasons (Aggarwal *et al.*, 2006) ^[1]. Simulation studies using crop models have predicted wheat yield reductions of 10–18% under future climate scenarios in South Asia (Asseng *et al.*, 2015; Zhao *et al.*, 2017) ^[3, 31].

Effect of Terminal Heat Stress on Wheat

Physiological Effects

High temperature stress significantly affects physiological processes in wheat plants. It reduces photosynthetic efficiency by damaging chloroplast structures and inhibiting photosystem II activity (Mathur *et al.*, 2014) ^[15]. Heat stress also accelerates leaf senescence, resulting in reduced chlorophyll content and decreased photosynthetic rate (Farooq *et al.*, 2011) ^[9]. Studies have shown that high temperature during grain filling reduces starch accumulation in wheat grains by inhibiting key enzymes involved in carbohydrate metabolism (Nandan *et al.*, 2020) ^[17]. Additionally, heat stress increases respiration rate and reactive oxygen species (ROS) production, leading to oxidative damage in plant cells (Mittler, 2006) ^[16].

Effects on Grain Development and Yield

Grain development in wheat is highly sensitive to temperature during the reproductive stage. Elevated temperatures reduce grain filling duration and decrease grain weight (Reynolds *et al.*, 2010) ^[22]. Experiments have shown that wheat yield declines significantly when temperatures exceed 30–32 °C during grain filling (Prasad *et al.*, 2008) ^[21]. Climate change due to elevated CO₂ concentration in the atmosphere would stimulate biomass production in crops particularly C3 crops like wheat. But simultaneously increasing heat stress due to elevated temperature and resulted moisture stress will reduce yield of crops. Sensitivity of wheat towards variations in temperature gets established by Info-Crop wheat model. It confirmed that rise in temperature reduces growth and negatively impacts yield determining parameters in wheat crop (Dubey *et al.*, 2020) ^[7]. Delayed planting might have exposed the crop to higher temperatures during reproductive stages, causing reduction in duration of grain filling phase, kernel size, biomass, tiller number, etc. During the lowering and grain- filling stages, high temperatures can adversely affect wheat yield and quality, primarily through the phenomenon known as 'terminal heat stress'. This stress disrupts pollination, reduces grain number, and lowers grain size and protein content by shortening the grain filling period (Yadav *et al.*, 2025) ^[9].

Wheat Yield Losses Due to Heat Stress in Northern India

State	Yield loss (%)	Research findings
Punjab	15–25	Heat waves reduced yield significantly
Haryana	10–19	Grain weight reduction
Uttar Pradesh	11–21	Yield losses in several districts
Rajasthan	4–5 q/ha reduction	Observed in climate-resilient villages
Madhya Pradesh	10–15	Early maturity under heat stress

Heat waves in Punjab, Haryana and Uttar Pradesh caused wheat yield declines ranging from 10–25% in several districts.

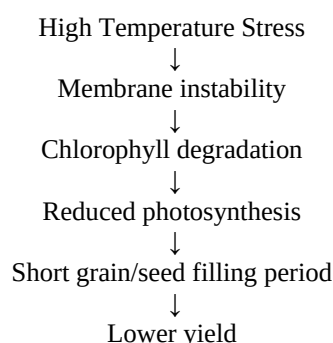
Mustard Yield Reduction under Terminal Heat Stress

State	Yield loss (%)	Observation
Uttar Pradesh	14–18	Reduced siliqua formation
Rajasthan	10–15	Reduced seed weight
Haryana	12–18	Reduced oil content

Terminal heat stress reduced mustard yields by 10–18% in several regions of northern India. (Bal, S.K., *et al.*, 2022) ^[5] Field studies in north-western India have reported yield losses of 20–35% under severe terminal heat stress conditions (Lobell *et al.*, 2011; Asseng *et al.*, 2015) ^[14, 3]. Such reductions pose a serious threat to food security in the region.

Rising temperature during March–April in the Indo-Gangetic plains exposes wheat crops to terminal heat stress during grain filling. Temperature increases of 2–3 °C during late rabi season have been reported across northern India (Asseng *et al.*, 2015; Lobell *et al.*, 2011) ^[3, 14].

Physiological Mechanism of Heat Stress in Wheat and Mustard



Heat stress disrupts photosynthesis and metabolic processes, leading to reduced grain filling and yield losses in wheat and mustard (Farooq *et al.*, 2011; Hasanuzzaman *et al.*, 2013) ^[9, 11]. Studies revealed that high-temperature stress caused some level of injuries at the seedling stage. Based on the analysis of variances, the main effect of individual cultivars with biochemical parameters such as chlorophyll content, catalase, peroxidase, superoxide dismutase activity and proline content were significantly influenced in mustard (Sakpal *et al.* 2023) ^[23].

Effect of Terminal Heat Stress on Mustard

Physiological Responses

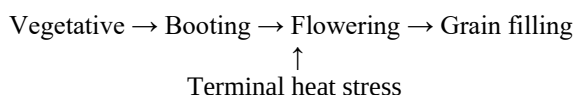
Mustard crops are sensitive to high temperatures during flowering and seed development stages. Heat stress reduces chlorophyll content, disrupts membrane stability and decreases photosynthetic efficiency (Angadi *et al.*, 2000) ^[2]. These physiological changes reduce biomass accumulation and reproductive success. Survival percentage differed with the application of heat/temperature treatments. It was found that the highest survival percentage (32.3–75.1%) was recorded at 30 °C, while it was found lowest (15.2–48.3%) at 40 °C (Sakpal *et al.* 2023) ^[23].

Growth and Yield Effects

High temperature stress reduces the number of siliqua per plant, seed size and oil content in mustard crops (Chauhan *et al.*, 2011) ^[6]. Experimental studies have reported yield reductions of 20–

30% under late sowing and heat stress conditions (Kumar *et al.*, 2016) ^[13].

Impact of Terminal Heat Stress on Wheat Growth Stages



Wheat is most sensitive to heat stress during flowering and grain filling stages when high temperature reduces pollen viability and grain weight (Prasad *et al.*, 2008; Reynolds *et al.*, 2010) ^[21, 22].

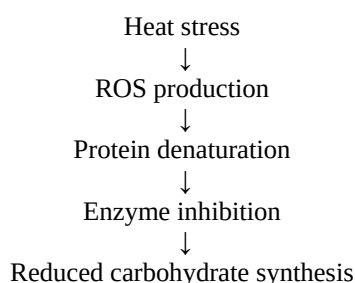
Physiological Mechanisms of Heat Stress

Heat stress affects plants through several physiological and biochemical mechanisms including:

- membrane instability
- enzyme denaturation
- oxidative stress
- reduced photosynthesis

Heat stress increases the accumulation of reactive oxygen species such as hydrogen peroxide and superoxide radicals, which damage cellular components (Mittler, 2006) ^[16]. Plants respond by activating antioxidant defense systems including superoxide dismutase and catalase enzymes (Hasanuzzaman *et al.*, 2013) ^[11].

Biochemical Responses of Crops to Heat Stress



High temperature induces oxidative stress in plants, increasing reactive oxygen species (ROS) that damage cellular structures and reduce crop productivity (Mittler, 2006; Hasanuzzaman *et al.*, 2013) ^[16, 11].

Adaptation Strategies

To mitigate these effects, it is crucial for farmers to adapt their agricultural practices based on accurate weather forecasts, enabling timely and effective management of crops. Additionally, the strategic use of certain chemicals, such as growth regulators and antioxidants, can help alleviate the negative impact of elevated temperatures on the wheat crop during critical growth stages (Yadav *et al.*, 2025) ^[9].

Several strategies can reduce the impact of terminal heat stress on crop productivity.

Adaptation Strategies for Terminal Heat Stress

Agronomical practices

Agronomic and breeding strategies can mitigate terminal heat stress impacts and improve crop resilience (Reynolds *et al.*, 2010; Aggarwal *et al.*, 2006) ^[22, 1]. Agronomic practices, including nutrient management and the use of beneficial microbes, play a critical role in boosting plant resilience to heat stress (Pillai and Walia 2024) ^[20].

Early sowing

Early sowing allows crops to escape high temperatures during reproductive stages (Aggarwal *et al.*, 2006) ^[1].

Heat-tolerant varieties

Breeding programs aim to develop wheat varieties with improved heat tolerance and stable yield under stress conditions (Reynolds *et al.*, 2010) ^[22].

Improved irrigation and nutrient management

Proper irrigation and balanced fertilization enhance plant growth and reduce heat stress damage (Farooq *et al.*, 2011) ^[9].

Conclusion

Terminal heat stress is an increasingly significant challenge for wheat and mustard production in northern India. Rising temperatures during reproductive stages disrupt physiological processes, reduce grain filling duration and significantly decrease crop yield. Studies indicate that wheat yields may decline by up to 35% under severe heat stress conditions, while mustard productivity also decreases due to impaired seed development. Developing heat-tolerant cultivars, adjusting sowing dates and adopting climate-smart agronomic practices will be essential for sustaining crop productivity under future climate scenarios.

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