metabolites were identified. Alkaline stress caused differential accumulation of 114 and 89 non-volatile metabolites in the alkali-sensitive and alkali-tolerant varieties, respectively, while 16 and 20 volatile metabolites also showed significant changes.

More importantly, alkaline stress altered pathways related to phenylpropanoid biosynthesis, flavonoids, flavone and flavonol biosynthesis, valine/leucine/isoleucine biosynthesis, arginine and proline metabolism, tryptophan metabolism, and ascorbate metabolism. This means that metabolic reprogramming in millet grains involves both primary and secondary metabolism. Branched-chain amino acids, arginine, and proline reflect changes in nitrogen metabolism and osmotic regulation, while phenylpropanoid and flavonoid pathways are closely associated with antioxidant activity and the accumulation of functional compounds.

From an agricultural perspective, these findings have dual significance. On one hand, alkaline stress may reduce yield or alter grain filling processes. On the other hand, moderate stress may increase the content of certain phenolic acids, flavonoids, amino acid derivatives, and organic acids, making broomcorn millet a promising raw material for functional foods produced on saline-alkali land. Therefore, broomcorn millet production in saline-alkali areas should not only pursue "stress resistance and yield maintenance," but also explore the combined goal of "stable yield plus improved functional quality." For example, in mildly to moderately saline-alkali soils, varieties that can maintain yield while accumulating higher levels of phenolic acids and flavonoids could provide valuable raw materials for functional millet rice, millet flour, and fermented foods.

5.3 Antioxidant and functional metabolites

The accumulation of antioxidant metabolites in broomcorn millet is an important link connecting stress resistance with its development as a functional food ingredient. Under stress conditions, metabolites such as phenolic acids, flavonoids, amino acids and their derivatives, and organic acids increase in millet grains, and the metabolic changes are more obvious in alkali-sensitive materials. This suggests that alkaline stress induces a more active antioxidant metabolic network in millet grains, although the response intensity and direction differ among varieties.

Xiang et al. (2023) investigated changes in phenolic composition and antioxidant activity during the germination of three millet varieties. The study found that total phenolic content and total flavonoid content increased significantly as germination progressed. After six days of germination, free total phenolic content increased by 6.30~8.66 times, while bound total phenolic content increased by 77.65%~116.18%. At the same time, compounds such as feruloyl quinic acid and N, N′-bis-(p-coumaroyl)-putrescine were reported for the first time during millet germination.

The functional metabolites of broomcorn millet show strong plasticity. Saline-alkali stress in the field can reshape grain metabolism, while postharvest processes such as germination and fermentation can further release or generate antioxidant active compounds. In agricultural applications, a complete chain of "saline-alkali cultivation-variety selection-germination processing-functional food development" can be established. For example, germination treatment of millet harvested from saline-alkali soils may further increase phenolic acid and flavonoid contents, supporting the development of antioxidant cereal powders, germinated millet beverages, and low-GI composite foods.

5.4 Nutritional and health value of broomcorn millet

The nutritional value of broomcorn millet should not only be understood from the traditional perspective of "coarse grains." It should also be analyzed within the dual framework of climate-resilient food crops and functional food ingredients. Broomcorn millet is rich in protein and dietary fiber, and some nutritional indicators are superior to those of common cereals. Its gluten-free characteristics and relatively low glycemic index make it suitable for people with gluten intolerance, type 2 diabetes, and cardiovascular metabolic risks (Pavithra and Rawat, 2024).