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Trehalose as a metabolic signalling hub: Coordinating carbon-nitrogen balance and stress responses in plants

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Intricacies of the subject

Trehalose is a non-reducing disaccharide that functions as a multifunctional component of plant metabolic regulation and environmental adaptation. Although present at relatively low concentrations in most vascular plants, trehalose metabolism is associated with carbohydrate homeostasis, cellular protection, photosynthetic performance, nitrogen utilization and abiotic stress responses. Its relevance to carbon–nitrogen (C-N) coordination arises from the dependence of nitrogen assimilation on carbon-derived skeletons, cellular energy and reducing power. Exogenous trehalose has been reported to enhance nitrate and ammonium assimilation, activities of key nitrogen-assimilatory enzymes, chlorophyll content, photosynthesis and growth under nitrogen limitation. Trehalose-associated responses to drought, salinity, temperature extremes and heavy-metal stress further involve osmotic adjustment, reactive oxygen species (ROS) homeostasis, antioxidant defence and preservation of cellular integrity. Trehalose-6-phosphate (T6P), an intermediate of trehalose biosynthesis, has an established role in carbon-status signalling, particularly through its relationship with sucrose and SnRK1; however, T6P and trehalose have distinct functions. This article focuses primarily on trehalose and summarizes its roles in carbon metabolism, C-N coordination, nitrogen assimilation, photosynthetic fitness, plant growth and abiotic stress adaptation. Collectively, available evidence supports trehalose as a metabolic hub that contributes to the integration of carbon availability, nitrogen utilization and stress responses.

Introduction

Plant growth and productivity depend on continuous coordination between carbon acquisition and nitrogen utilization. Photosynthesis provides carbohydrates, energy and reducing power, whereas nitrogen is required for amino acids, proteins, chlorophyll, nucleic acids and numerous metabolic enzymes. This interdependence becomes particularly important under environmental stress, when limitations in photosynthesis, nutrient acquisition, water availability and redox balance can occur simultaneously. Sugars therefore function not only as metabolic substrates but also as regulators of plant metabolism and resource allocation. Trehalose is a non-reducing disaccharide composed of two glucose molecules linked by an α, α-1,1 glycosidic bond. In plants, trehalose is synthesized through the trehalose-6-phosphate synthase (TPS) and trehalose-6-phosphate phosphatase (TPP) pathway and degraded by trehalase. Unlike desiccation-tolerant organisms, most vascular plants maintain relatively low trehalose concentrations; nevertheless, changes in trehalose metabolism can strongly influence plant development, metabolism and stress responses (Lunn *et al.*, 2014). Tre is therefore better considered a multifunctional metabolic regulator and cellular protectant than simply an osmolyte or stress marker. Its physiological effects are associated with carbohydrate regulation, cellular stability, photosynthetic maintenance, nitrogen metabolism, antioxidant defence and adaptation to adverse environments. Among these functions, its relationship with C-N metabolism provides an important basis for understanding how trehalose-associated regulation can influence plant physiological fitness.

Trehalose modulates carbon–nitrogen coordination

Trehalose metabolism is closely connected with primary carbohydrate metabolism and may contribute to carbon–nitrogen (C-N) coordination. Trehalose is synthesized through the TPS–TPP pathway and degraded by trehalase, linking its metabolism with cellular carbon status. T6P, an intermediate of this pathway, functions primarily as a carbon-status signal through the sucrose-SnRK1 system and is distinct from trehalose. Photosynthetic carbon enters glycolysis and the TCA cycle, generating energy and 2-oxoglutarate (2-OG), a key carbon skeleton for N assimilation. Nitrate is reduced to nitrite by nitrate reductase (NR) and subsequently to ammonium by nitrite reductase (NiR), followed by incorporation into amino acids through the GS/GOGAT pathway. Thus, efficient N assimilation requires adequate carbon supply and respiratory metabolism, while N availability supports chlorophyll and photosynthetic protein synthesis. Consistent with this interdependence, Lin *et al.*, (2017) reported that exogenous trehalose enhanced nitrate and ammonium assimilation and increased NR, GS and GOGAT activities in N-deficient tobacco, accompanied by higher total leaf N, chlorophyll, photosynthetic rate and biomass. These findings suggest that trehalose promotes metabolic conditions favourable for N assimilation under N limitation, although the responses may involve coordinated changes in carbon, energy and redox metabolism rather than direct activation of N-assimilatory enzymes. This metabolic relationship indicates that efficient nitrogen assimilation depends on adequate carbon availability and respiratory metabolism. Conversely, nitrogen availability influences chlorophyll formation and the synthesis of photosynthetic proteins, thereby affecting subsequent carbon fixation. Experimental evidence supports a role for trehalose in this coordination. Lin *et al.*, (2017) reported that exogenous trehalose improved nitrate and ammonium assimilation in nitrogen-deficient tobacco and increased the activities of NR, GS and GOGAT. Trehalose treatment was also associated with increased chlorophyll, total leaf nitrogen, photosynthetic rate and biomass. These findings indicate that trehalose can promote metabolic conditions favourable for nitrogen assimilation under N limitation. However, they do not establish that trehalose directly activates individual N-assimilatory enzymes; the observed responses may involve coordinated changes in carbon status, energy metabolism, redox balance and metabolic demand (Fig. 1).

Trehalose, photosynthesis, growth and cellular protection

The close relationship between carbon and nitrogen metabolism ultimately influences photosynthetic performance and plant growth.

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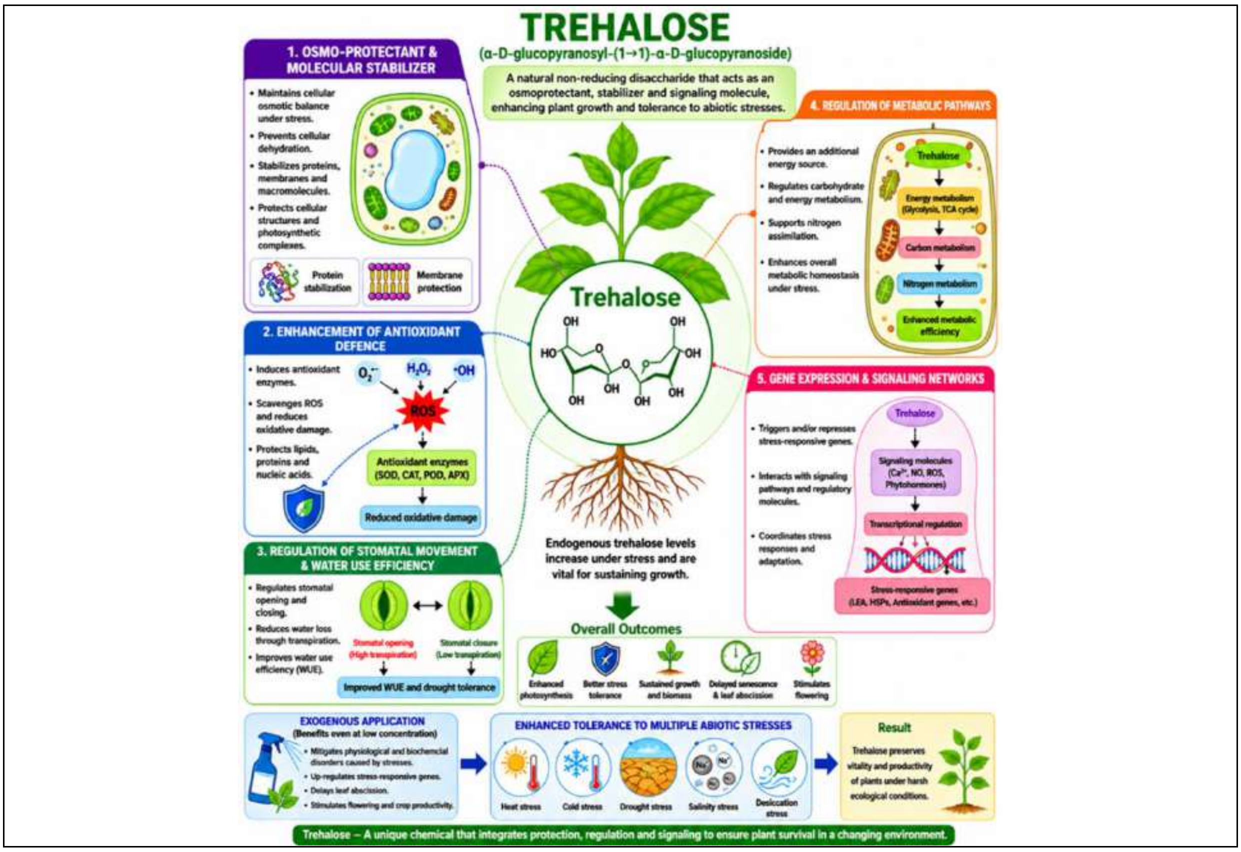
Nitrogen supports chlorophyll, Rubisco and other components of the photosynthetic apparatus, while photosynthesis provides carbon substrates and energy required for nitrogen assimilation. Maintenance of this reciprocal relationship is therefore essential for physiological fitness. Trehalose-associated regulation can contribute to this process by supporting carbohydrate homeostasis and cellular stability. Trehalose possesses physicochemical properties that can protect proteins and membranes under dehydration and other adverse conditions. However, its role extends beyond direct molecular stabilization. Trehalose-associated responses involve changes in carbohydrate metabolism, antioxidant defence, water relations and stress-responsive processes, indicating broader metabolic acclimation (Lunn *et al.*, 2014; Hassan *et al.,* 2023). Trehalose-associated effects on photosynthesis and growth have been observed particularly under stress conditions. Exogenous trehalose improved photosynthetic characteristics, water relations and oxidative defence in drought-stressed maize (Ali and Ashraf, 2011). Such responses suggest that trehalose can help preserve photosynthetic activity when environmental limitations disrupt normal carbon assimilation. The effect of trehalose on growth is nevertheless context dependent. Plant species, tissue type, developmental stage, environmental conditions and the extent of trehalose metabolic alteration can influence the magnitude and direction of the response. Trehalose should therefore not be considered a universal growth-promoting molecule; its beneficial effects are more appropriately interpreted as part of a coordinated metabolic adjustment to specific nutritional or environmental constraints.

Fig. 1 : Integrated role of trehalose in plant carbon metabolism, carbon-nitrogen coordination, nitrogen assimilation, photosynthetic performance, growth and abiotic stress adaptation



Trehalose-mediated abiotic stress adaptation

Abiotic stresses such as drought, salinity, temperature extremes and heavy-metal toxicity disrupt water relations, photosynthesis, nutrient metabolism, membrane stability and cellular redox balance. Trehalose-associated responses across these stresses show considerable functional overlap, particularly in the maintenance of osmotic balance, ROS homeostasis, antioxidant defence and cellular integrity. Under drought, reduced water availability promotes stomatal closure, restricts CO_2 assimilation and increases the risk of oxidative damage. Exogenous trehalose has been associated with improved photosynthetic performance, water relations and antioxidant defence under water deficit (Ali and Ashraf, 2011). Salinity imposes both osmotic and ionic stress, and trehalose-associated responses include improved osmotic adjustment, protection of cellular structures, antioxidant regulation and maintenance of photosynthetic function (Hassan *et al.*, 2023). Temperature extremes can destabilize proteins and membranes and interfere with photosynthetic metabolism. Exogenous trehalose has been reported to improve physiological and antioxidant responses to heat stress in tea plants, indicating a role in maintaining cellular and metabolic stability under elevated temperature. Heavy-metal stress provides another example of integrated trehalose-mediated protection. In Vigna radiata exposed to chromium, exogenous trehalose improved growth and photosynthetic performance, mineral nutrient uptake and antioxidant enzyme activity while reducing oxidative damage (Elkelish *et al.*, 2024). ROS regulation is an important component of these responses. ROS are both damaging agents at excessive concentrations and essential signalling molecules at controlled levels. Therefore, trehalose is more accurately described as a modulator of ROS homeostasis and antioxidant defence rather than simply a ROS scavenger. Maintaining redox balance allows plants to limit oxidative damage while retaining ROS-dependent signalling.

Conclusion

Trehalose is a multifunctional metabolic regulator involved in carbohydrate homeostasis, C-N coordination, photosynthetic performance, cellular protection and abiotic stress adaptation. By supporting carbon-derived energy and skeletons required for N assimilation, trehalose-associated regulation can enhance N metabolism, photosynthesis and growth under limiting conditions. Its stress-protective effects involve osmotic adjustment, ROS homeostasis, antioxidant defence and maintenance of cellular stability. Overall, trehalose functions as a metabolic hub that contributes to physiological resilience, nutrient-use efficiency and plant productivity under changing environmental conditions.

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