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Unraveling the mechanisms of biochar and steel slag in alleviating lithium stress in tomato (*Solanum lycopersicum* L.) plants via modulation of antioxidant defense and methylglyoxal detoxification pathways

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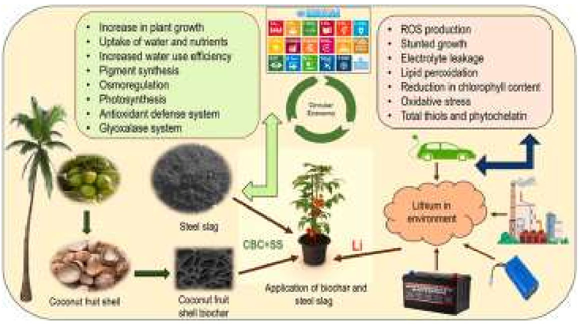
Highlights

- Coconut shell biochar and steel slag increased tomato plant growth under Li stress.
- Accumulation of osmolytes under combined CBC and SS treatment, strengthened ROS scavenging mechanisms.
- Li stress increased thiol and phytochelatin contents in roots and shoots.
- Biochar and steel slag reduced oxidative damage by altering antioxidant defense.

Abstract

With progress in technology, soaring demand for lithium (Li) has led to its release into the environment. This study demonstrated the mitigation of the adverse effects of Li stress on tomato (Solanum *lycopersicum* L.) by the application of waste materials, namely coconut shell biochar (CBC) and steel slag (SS). To explore the impact of Li treatment on tomato plants different morphological, biochemical parameters and plant defense system were analyzed. Tomato plants exposed to Li had shorter roots and shoots, lower biomass and relative water contents, and showed decreases in physiological variables, as well as increases in electrolyte leakage and lipid peroxidation. However, the application of CBC and SS as passivators, either singly or in combination, increased growth variables of tomato and relieved Li-induced oxidative stress responses. The combined CBC and SS amendments reduced Li accumulation 82 and 90% in tomato roots and shoots, respectively, thereby minimizing the negative impacts of Li. Antioxidant enzymes SOD, CAT, APX and GR reflected 4, 5, 30, and 52% and glyoxalase enzymes I and II 7 and 250% enhancement in presence of both CBC and SS in Li treated soil, with a concurrent decrease in methylglyoxal content. Lithium treatment triggered oxidative stress, increased enzymatic and non-enzymatic antioxidant levels, and induced the synthesis of thiols and phytochelatins in roots and shoots. Hence, co-amendment with CBC and SS protected tomato plants from Li-induced oxidative damage by increasing antioxidant defenses and glyoxalase system activity. Both CBC, generated from agricultural waste, and SS, an industrial waste, are environmentally benign, safe, economical, and non-hazardous materials that can be easily applied on a large scale for crop production in Li-polluted soils. The present findings highlight the novel reutilization of waste materials as renewable assets to overcome soil Li problems and emphasize the conversion of waste into wealth and its potential for practical applications.

Graphical abstract



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Introduction

The rapid expansion of industrial and mining activities, reliance on synthetic fertilizers, use of wastewater in agricultural fields, unpredictable climatic perturbations, release of landfill leachates, and unsafe waste disposal practices are responsible for land degradation and negatively affect global crop yields. Lithium (Li), also known as white gold or green energy metal, is widely used in different industries for the fabrication of electric devices, mobile phones, batteries, lubricants, nuclear reactors, pharmaceuticals, glass, and ceramics (Pavon et al., 2022). These Li applications boost the global energy economy, and Li demand is predicted to be triple by 2025 due to the advent of new technologies and the desire to achieve sustainable development goals of decarbonization and greenhouse gas reductions by increasing the electrification of vehicles (Bolan et al., 2021; Garcia et al., 2023). Worldwide production of Li is currently >600,000 tons, or three times greater than in 2000 (Hayyat et al., 2021). Due to its mobility and highly soluble nature, Li can leach into water resources. It is also readily absorbed by plants; therefore, it can enter in food chain and pose hazards to the health of animals, humans, and ecosystems (Tanveer et al., 2019). It ranges from 1 to 200 $mg\,kg^{-1}$ and between 0.01 and 0.02 $mg\,L^{-1}$ in soil and surface and marine waters, respectively (Torok et al., 2021). Lithium levels in plants range between 0.15 and 6000 $mg\,kg^{-1}$ (Kavanagh et al., 2018). Due to its small radius and greater polarizing capacity, Li^+ shares characteristics with nutritional elements and can replace sodium (Na), potassium (K), and calcium (Ca) in plants by using the same transport systems (Naeem et al., 2021). Lithium decreases plant growth and interrupts different biochemical processes by reducing nutrient uptake, carbon assimilation, photosynthesis, and enzyme function (Shahzad et al., 2016; Shakoor et al., 2023).

Extensive use of Li in different fields, improper Li waste recycling or dumping, and chemical Li spillage during manufacturing processes are responsible for Li entry into water and soils and pose serious environmental threats. Therefore, Li elimination from polluted areas is a challenging task (Bolan et al., 2021; Martins et al., 2022). Various strategies, such as excavation, soil washing, and thermal desorption, have been applied for the remediation of metal pollutants, but all these methods are expensive, labor-intensive, prone to generating secondary pollutants, and unsuitable for field applications. In recent years, the use of soil additives, such as compost, fly ash, steel slag, and biochar (BC), has been considered to be an efficient strategy to increase soil fertility and crop yield in contaminated