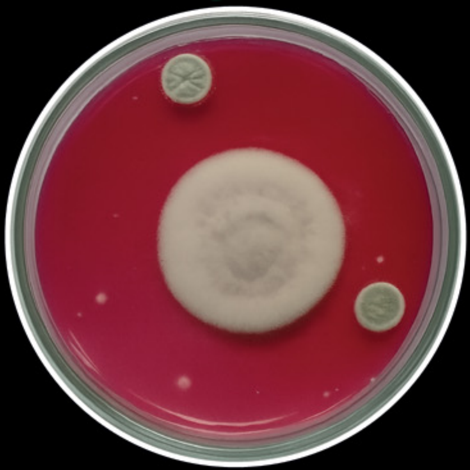
# Decoding Plant–Environment–Microbiome Interactions in Stress-Resilient Agriculture



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**Deepti Srivastava[1], P. Smriti Rao[1], Sandeep Kumar Singh[1], Deepak Kumar[2], Md Shamim[3], Kumari Vandna[1], Md Abu Nayyer[4], Saba Siddiqui[1], and Mohammed Haris Siddiqui[1]**

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## 5.1 Introduction

Due to sessile nature, plants are subject to a range of various environmental stresses, which significantly affect their growth capacity, development, and productivity. Soil salinity, heavy metal (HM) toxicity, drought, and high and low temperatures are most often the sources of serious consequences. These stresses modify the morphological and physiological responses, which ultimately decrease the development and production of plants. For example, drought stress that occurs due to temperature dynamics, light intensity, and low rainfall reduces water supply, causing osmotic stress and loss of turgor pressure (Seleiman et al., 2021) whereas salinity stress encourages ionic imbalance and toxicity (Atta et al., 2023). Proteins can be denatured at both low and high temperatures, disrupting the cellular balance (Zheng et al., 2024). Heavy metals in contrast bind to important biomolecules and interfere with variety of metabolic processes of plants (Wang et al., 2018). In response to these assorted and regularly overlapping pressures effect, plants have developed a wide range of systems to recognize, respond, and mitigate the impacts caused by abiotic challenges. These systems are commonly classified as morphoanatomical traits and physiological processes that combine into an advanced adaptive strategy. For the absorption of water and nutrients, a developed root architecture is essential. Under drought conditions, plants usually grow deeper and wider and the expanded root systems penetrate deep into soil layers for uptake and fulfillment of water requirements. The surface area for absorption is increased by extensive root branching and root hair multiplications (Comas et al., 2013). In addition, abiotic stresses often modify the size, shape, and structure of leaves. For example, during drought, the size of leaves is significantly reduced causing excessive water loss through transpiration. To overcome such losses, some plants produce thicker cuticles and high-density trichome and reflect excess light (Cutler et al., 2010). In addition to structural changes, stomata also regulate gas exchange and water loss. Under stress, plants adjust stomatal aperture to balance water retention and $CO_2$ uptake. This includes stomatal density alterations and the formation of specialized stomatal structures (Hetherington and Woodward, 2003). Internal tissue modifications, such as the formation of aerenchyma (air gaps in roots), improve oxygen diffusion in submerged conditions. Like this, during salt stress, lignification and suberization of cell walls boost mechanical strength while reducing permeability to harmful ions (Colmer and Voesenek, 2009). Apart from these morphological alterations, plants also adjust their physiological mechanisms to endure or manage diverse abiotic stressors. Under drought and salinity stress situations, plants store appropriate solutes such as proline, glycine, betaine, and carbohydrates to maintain cellular osmotic balance. These osmolytes shield enzymes and biological components from stress damage (Ashraf and Foolad, 2007). Reactive oxygen species (ROS), often produced in response to abiotic stresses, oxidatively damage the cells. However, the extensive antioxidant defense system consisting of enzymes such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POX), synthesized under stress protect plants from oxidative damage (Maury et al., 2020; Nadarajah, 2020; Ali et al., 2024; Qamer et al., 2021;

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