



## Abiotic Stress Management in Agriculture: Insights from Conservation Practices



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**A**GRICULTURAL systems across the world are increasingly under pressure because of abiotic stresses like drought, extreme temperatures, and salinity, which have adverse effects on crop yields and food security in the world. Traditional farming activities tend to increase these pressures by impoverishing soils and making ecosystems weaker. This review examines the importance of conservation agriculture (CA) as a sustainable method of abiotic stress mitigation through these fundamental principles of minimum soil disturbance, crop rotation, and cover cropping. CA can help to alleviate the negative impact of abiotic stresses, as well as increase agricultural productivity and sustainability by improving soil structure, nutrient balance, moisture retention, and supporting biodiversity, resulting in a beneficial microclimate in the root zone. This review summarizes the existing body of knowledge on how CA can be used to increase agricultural productivity sustainably and provide case studies showing successful experiences of CA use in various crops to counter abiotic stresses. The eco-physiological mechanisms associated with the impacts of CA on the mitigation of abiotic stress in plants are also discussed in this analysis. The implications of these insights underscore the necessity of integrating CA into comprehensive strategies to ensure food security amidst evolving global climate conditions.

**Keywords:** Biodiversity, CO<sub>2</sub> emissions, Crop residues, Crop rotation, Organic carbon, Climate change, Vulnerability.

### 1. Introduction

Abiotic stresses refer to non-living environmental factors that adversely affect the growth, development, and yield of plants. These stresses encompass various conditions like drought, salinity, extreme temperatures (both heat and chilling), flooding, and heavy metal toxicity. As essential components of the environment, these factors can significantly hinder the physiological and biochemical processes vital for plant survival, thereby threatening agricultural productivity and ecosystem stability worldwide (Mareri et al., 2022; Khan et al., 2025). Abiotic stress conditions significantly reduce global agricultural production, with the impacts ranging from 54% to 82%. Abiotic stressors have an adverse effect on crop growth, particularly during the reproductive stage, which leads to reduced global crop yield (Oshunsanya *et al.*, 2019). Through disturbance of seed germination, vegetative growth, dry matter generation, and its transport to reproductive organs, abiotic stresses also cause a variety of biotic challenges that result in low crop productivity (Mareri et al., 2022). About 90% of all arable land worldwide is susceptible to one or more of the above stressors, causing annual losses of 70 percent of the yields of major food crops (Waqas et al., 2019). With increasing climate change, there is a necessity to have effective management practices that can make the agricultural systems more resilient.

Conservation agriculture (CA) is a system of agronomic technology management that offers the ability to minimize soil disturbance, ensure long-term soil cover, and promote spatiotemporal crop species diversity. One study showed that some of the positive effects of CA are the reduction of greenhouse gas emissions due to labor, energy, and mineral nitrogen savings in agricultural production (Alam et al., 2019), an increase in the biological activity of soils (Bohoussou et al., 2022), and, consequently, long-term yield and productivity (Thierfelder & Mhlanga, 2022). CA approaches have contributed to the production of abundant harvests in addition to augmenting gross margins in agricultural crops (Bell et al., 2018). Applications of CA systems are now

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Received: 14/08/2025; Accepted: 24/09/2025

DOI: 10.21608/EJSS.2025.414023.2319

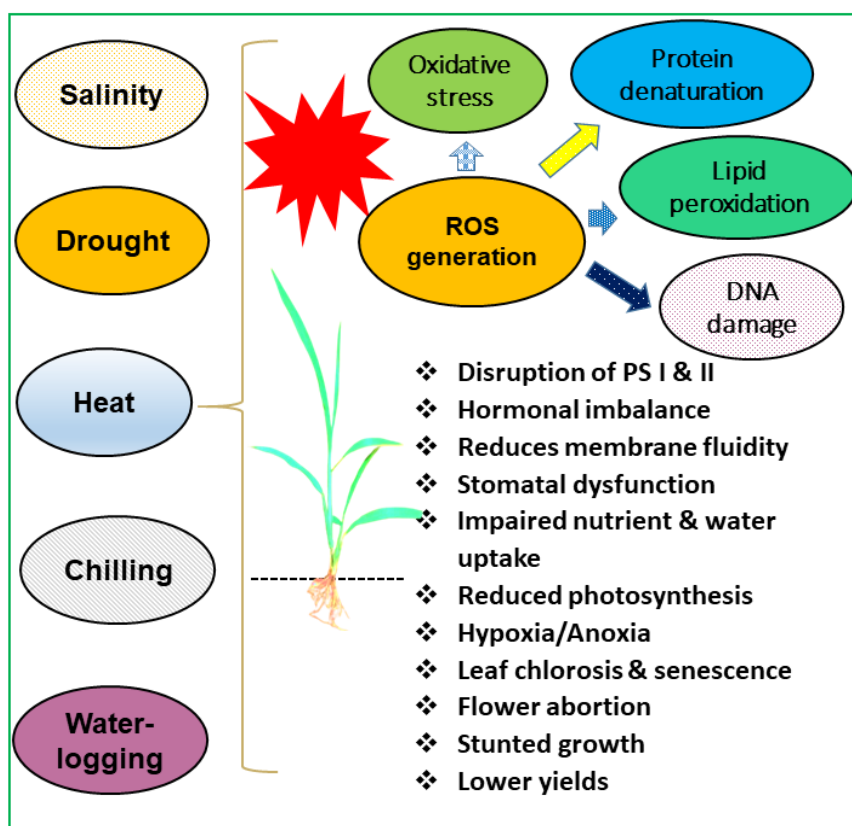
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widespread on all continents, and the agricultural activities exposed to CA treatment are broad (Farooq *et al.*, 2024). Some of them include rainfed and irrigated crops, annual crops, perennial plantations, orchards, integrated crop-livestock systems, agroforestry, rangeland and pasture management, rice-based crops, and organic farming (Kassam *et al.*, 2022). Nevertheless, certain obstacles remain, such as low adoption rates, inefficient equipment among small-scale farmers, competition with crop residues, and the necessity to overcome traditional preconceptions against tillage (Dev *et al.*, 2023; Savari *et al.*, 2025). In spite of these challenges, CA has been opined to provide a potential solution to sustainable farming practices and food security (Joshi *et al.*, 2021). It is also one of the solutions to problems with abiotic stress since it makes farming sustainable, brings health to the soil, and provides robustness to the ecosystem. With the growing number of environmental strains threatening agricultural productivity, the potential of CA to reduce soil erosion and degradation and increase carbon sequestration is massive.

This review attempts to provide a critical discussion of the importance of CA in managing abiotic stress. It will discuss how CA practices can make soil and plants more resilient to abiotic stress and present case studies of how CA practices have been successfully applied in abiotic stress management under various agroecological conditions. Finally, the review will conclude on the relevance of CA as a key approach to sustainable agricultural systems, given the perpetually increasing abiotic stressors.

## 2. Various Abiotic Stresses and Their Impact on Plants

Climatic stresses are rapidly becoming a threat to global food production, and they have substantial consequences on food supply. About 90% of arable land is vulnerable to a single or a combination of abiotic stress (Nehra *et al.*, 2024). Stressors such as salinity, drought, high heat and cold, and floods have a negative impact on the lifespan, yield, and biomass accumulation of crops (Yadav *et al.*, 2020). These environmental stresses can also cause crop yield losses of between about 51% and 82% in significant food staples that are vital in the achievement of global food security (Nehra *et al.*, 2024). Abiotic stresses, including inadequate water availability, severe temperatures, a lack of soil amendments, and/or an increase in harmful ions, soil hardness, and excessive light, can limit plant growth in various ways (Zhang *et al.*, 2022). Specifically, these stresses induce oxidative damage, disrupt nutrient uptake, and impair photosynthesis, ultimately reducing biomass, crop quality, and crop yield (Kumari *et al.*, 2022; Zhang *et al.*, 2023) (**Figure 1**).



**Fig. 1.** Effects of various abiotic stresses on plants, spanning from cellular responses to phenotypic changes

## 2.1. Salinity

Salinity is considered the most harmful abiotic stress impacting the plant life cycle. Around 7% of the global soil surface is affected by salinity (Hopmans et al., 2021). It is estimated that salinity stress contributes to roughly 20% of the potential decrease in crop yields (Pandit et al., 2024). Salinity stress, along with the resulting harm to the plant, can occur as a result of excessive buildup of soluble ions (such as  $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ ) in the rhizosphere (Shams et al., 2023). When the concentration of ions in the plant is lower than that of the original irrigation water, ions can build up in the water (Shams et al., 2023). Salinity stress leads to metabolic and physiological disturbances in plants, impacting their growth, development, productivity, and overall quality (Shrivastava & Kumar, 2015). It hampers plant growth by reducing the water potential in leaves, resulting in physiological and morphological alterations, the production of reactive oxygen species (ROS), ion toxicity, heightened osmotic stress, and modifications in biochemical activities (Rana et al., 2019; Pandit et al., 2024; Bayoumi et al., 2025). Salt stress influences seed germination, survival rates, morphological traits, photosynthesis, and respiration in plants (Atta et al., 2023; Ikbal et al., 2024). An EC level below  $1 \text{ dS m}^{-1}$  is generally considered suitable for optimal growth for many crops. However, as EC levels increase, the tolerance of crops to salinity decreases (Machado & Serralheiro, 2017). To give an example, barley (*Hordeum vulgare*) is fairly tolerant to salinity, with a decrease in yield observed at EC values exceeding  $4 \text{ dS m}^{-1}$  (Dhima et al., 2021). Wheat (*Triticum aestivum*) possesses a salinity tolerance of up to approximately  $3 \text{ dS m}^{-1}$  (Gheisary et al., 2025). Conversely, rice (*Oryza sativa*) is more susceptible to salinity, and its negative impact can be observed at an EC level of approximately  $6 \text{ dS m}^{-1}$ , in particular, during the stage of the onset of the reproductive phase (Rana et al., 2019).

Irrigation water salinity poses serious risks to agricultural productivity and sustainability (Demo et al., 2025). Using saline water for irrigation leads to the buildup of salts and alkaline substances in farmland. This buildup can cause soil salinization and alkalinity. It also raises the osmotic pressure in the soil solution, making it hard for plants to absorb water through their roots. Additionally, toxic ions in the water can cause damage (Yavuz et al., 2022). Higher salt concentrations in irrigation sources directly reduce water quality. This reduction can lead to lower crop yields, slower plant growth, decreased nutrient uptake, and increased vulnerability to pests and diseases (Yavuz et al., 2023). Elevated salt levels cause osmotic stress in plants, which limits their ability to take in water and leads to nutrient imbalances (Tarolli et al., 2024). This stress can result in lower germination rates, stunted growth, and reduced harvests, ultimately threatening food security (Machado & Serralheiro, 2017). In addition, increased salinity can harm soil structure and disrupt microbial activity, which further affects plant health (Demo et al., 2025). Sensitive crops often face physiological and metabolic issues, resulting in symptoms like chlorosis and necrosis (Atta et al., 2023). Overall, salinity stress poses a significant threat to crop growth and yield, and ways of limiting negative effects and maximizing crop resilience are required (Acharya et al., 2024).

## 2.2. Drought

One of the significant environmental issues caused by temperature changes, light intensity, and the decrease in precipitation is drought stress (Seleiman et al., 2021). It is one of the most intense stresses that impacts plant productivity. Water is very important in most physiological processes in a plant, as it constitutes about 80 to 95 percent of the fresh biomass of a plant (Ahluwalia et al., 2021). As a result, drought has been considered the major abiotic stress in most plants, particularly in areas that are likely to experience water deficits (Ahluwalia et al., 2021). Bista et al. (2018) reported that even in fertilized areas, environmental variables like lack of moisture can result in nutrient deficits because the physiochemical characteristics of the soil can affect the mobility and uptake of particular nutrients. Additionally, stomatal closure brought on by drought lowers transpiration (Bista et al., 2018). As a result, the reduction in transpiration rate, imbalance in active transport, and membrane permeability all restrict the amount of nutrients that can be transported from the roots to the shoot, which lowers the roots' capacity for absorption. In short, water scarcity adversely affects both crop yield and quality (Salehi-Lisar et al., 2016). Various practices can be implemented to mitigate the issue, including water conservation, soil management, and the use of drought-resistant crops (Wang & Ren, 2025).

## 2.3. Elevated Temperature

It is projected that worldwide air temperatures will increase by approximately  $0.2^\circ\text{C}$  every ten years, resulting in a rise of  $1.8$  to  $4.0^\circ\text{C}$  above current levels by the year 2100 (IPCC, 2007). Scientists are becoming increasingly concerned about this forecast, as elevated temperature is known to impact the vital functions of living organisms, either directly or by altering their surrounding environment. Plants, being sessile, cannot relocate to better conditions; therefore, their growth and development are significantly impaired, often to the point of death, due to elevated temperatures (Ding & Yang, 2022; Omran et al., 2025). Both prolonged and sudden heat waves have a negative effect on the growth and development of crop plants. It is anticipated that heat waves and other extreme temperature conditions will have a greater detrimental impact on plant growth than rises in the mean temperature will (Ding & Yang, 2022). Heat stress (HT) in various cultivated plant species leads to lower germination rates,

poor plant emergence, weak seedlings, and stunted radicle and plumule growth. High temperatures cause water loss from cells, which reduces cell size and overall growth (Moore et al., 2021; Ding & Yang, 2022). When plants face HT during the reproductive and grain filling stages, it can lower cereal crop yield by decreasing the number of fertile spikelets, shortening the grain filling period, and harming sink activity (Shrestha et al., 2022). Heat stress (HT) can lead to reduced photosynthesis, impaired metabolism, and increased production of ROS, ultimately resulting in cellular damage and reduced plant performance (Yu et al., 2024). Photosynthesis is very sensitive to heat. High temperatures can significantly reduce its effectiveness, particularly in C<sub>3</sub> plants, by damaging chloroplast structures like thylakoid membranes and decreasing photosystem II activity (Moore et al., 2021). HT causes changes in chloroplasts, such as thylakoid disorganization and pigment loss, which disrupt the photosynthesis process (Dhokne et al., 2022; Yu et al., 2024). Extreme high temperatures can quickly damage or kill cells, leading to a breakdown of cellular structures (Dhokne et al., 2022). It disrupts proteins, membranes, RNA, and cytoskeleton components in different ways. This instability interferes with enzymatic activities and creates metabolic imbalances that affect overall physiological functions (Moore et al., 2021; Kim et al., 2023).

To mitigate heat stress in plants, management strategies such as using shade, adjusting sowing time, mulching, adjusting irrigation, and employing heat-tolerant plant varieties can be used.

## 2.4. Chilling Stress

Chilling stress is the exposure of crops to temperatures that are below their threshold level, which differs across species. This temperature tends to be between 0 °C and 5 °C, but in some hardier varieties, including some winter wheat, temperatures of up to −15 °C can also be tolerated (Devi et al., 2023). At temperatures below these threshold levels, the physiological processes of the plants are disturbed, causing poor growth, ineffective photosynthesis, and high susceptibility to diseases (Mukhopadhyay et al., 2018). It limits productivity by slowing down metabolic reactions and reducing water uptake. Chronic cold stress may result in direct damage to plant tissues—it can lead to cell death and growth suppression (Wu et al., 2022). Furthermore, cold stress may cause a delay in flowering and fruit set, leading to a shortened growing season and reduced yield (Shi et al., 2022). Low temperatures can make cell membranes rigid. This rigidity reduces fluidity, causes electrolyte leakage, and disrupts cellular functions (Qari et al., 2022; Qian et al., 2025). Damage to roots and weakened membrane integrity hinder a plant's ability to take in water and essential nutrients, causing wilting and stunted growth (Yu et al., 2025). It also increases harmful signaling molecules like MDA and ROS, leads to osmolyte accumulation such as proline, and changes the activities of antioxidant enzymes like SOD, CAT, and POD (Song et al., 2021).

## 3. Impact of Abiotic Stresses on Soil Health and Productivity

Among stress factors, salinity, drought, excessive heat, and pollution have a significant impact on the health of global soil (Kumari et al., 2022). Such abiotic environmental stresses disrupt the soil ecosystem, soil structure, the availability of microbial populations and nutrients, production, and plant growth (Rahim et al., 2025) (**Table 1**). Recent research findings show that abiotic stresses play a major part in crop production sustainability with respect to soil dynamics (Kumari et al., 2022; Rahim et al., 2025). The physico-chemical properties of the soil are negatively impacted since excess quantities of soluble salts accumulate as a result of salinity stress (Devkota et al., 2022). High levels of salinity subject the plant to osmotic stress and alter the diversity of microbes, which play a key role in the mineralization of nutrients (Devkota et al., 2022). Extreme salinity also leads to degradation of soil structure by breaking up clay particles, leading to low infiltration and aeration, which further reduces the growth of plants (Devkota et al., 2022). Abiotic stresses can include drought stress or lack of water, which are the most common agricultural stresses. These factors contribute to a decrease in soil moisture level, which means that the processes of organic matter degradation and the activity of microorganisms are lowered (Lin et al., 2025). Drought stress results in unstable soil aggregates through long-evolution stress and is linked with soil aeration and water-holding capacity (Jat et al., 2020). This leads to poor cycling of nutrients, which limits the availability of nutrients that plants need and reduces productivity (Li, 2024). HT increase evaporation rates and deplete soil moisture content (Mikó et al., 2025). HT harms soil health by raising soil temperature, which leads to less moisture and affects root-soil contact. This ultimately lowers nutrient uptake and crop productivity (Mishra et al., 2023). For example, in *Lens culinaris*, exposure to 37 °C resulted in lower levels of Zn and Fe compared to ambient temperature conditions (El Haddad et al., 2021). Excessive temperature (high and low) affects soil microbial populations and chemical rates ((Bas & Killi, 2024). Specifically, enhanced temperatures can encourage organic matter decomposition but can also cause water loss, further aggravating climate-like drought in the area (Tang et al., 2024). On the one hand, low temperatures slow down the speed of microbial activity, reducing the rates of microbial nutrient mineralization, hence limiting plant nutrition (Schnecker et al., 2023). Changes in temperature alter enzymatic activities in soils, and these have a general effect on soil fertility. In summary, the basic mechanisms that maintain soil health (i.e., organic matter decomposition, nutrient recycling, and biological variety) are harmed through abiotic stresses. These shifts lower soil productivity, threaten food security, and represent a challenge to sustainable agriculture. Knowledge about

such effects is therefore vital in devising adaptive management, including soil amelioration, crop selection, and sustainable irrigation, in order to overcome the negative consequences and make soil resilient to current environmental changes and dynamics (Teng et al., 2024).

**Table 1. Impacts of different abiotic stresses on soil properties and soil health.**

| Indicators                  | Effects                                                                                                                                                            | References           |
|-----------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| Soil texture                | In a saline condition, dispersion of clay particles occurred due to the presence of Na <sup>+</sup> .                                                              | Luo et al., 2024     |
| Soil structure and porosity | Na <sup>+</sup> and Cl <sup>-</sup> ions disrupt soil aggregates, leading to a decrease in porosity of 10-30%.                                                     | Demo et al., 2025    |
| Bulk density                | Bulk density can increase from 1.2 to 1.6 g/cm <sup>3</sup> in saline soils due to dispersion.                                                                     | Wang et al., 2024    |
|                             | Generally increases (by 10–20%) due to soil compaction during drought periods.                                                                                     | Jat et al., 2020     |
| Nutrient availability       | N, P, and K availability is reduced by 20-50% in saline soils due to precipitation and complexation.                                                               | Theresa et al., 2025 |
|                             | Drought stress decreased mineralization, leading to a reduction in N (3.78%), P (9.18%), and K availability.                                                       | Bista et al., 2018   |
|                             | Under anaerobic conditions, NO <sub>3</sub> levels decrease by 50–70%; available P and K can decline by 20–40% with the accumulation of certain nutrients.         | El-Latif, 2015       |
| Soil organic carbon (SOC)   | Salinity reduces the breakdown of organic material and nutrient cycling. Organic carbon can decline by 10-30% in saline conditions.                                | Zhou et al., 2025    |
|                             | Declines by 3.3% over prolonged drought periods.                                                                                                                   | Deng et al., 2021    |
|                             | Elevated temperatures accelerate microbial respiration, decomposing organic carbon. SOC can decrease by 8.7 %–14.8 % after prolonged exposure to high temperature. | Tang et al., 2024    |
| Microbial biomass           | Osmotic stress and toxicity inhibit beneficial microbial populations. Microbial biomass can decrease by 40-60% in saline soils.                                    | Rath et al., 2019    |
|                             | Shortage of moisture significantly limits microbial activity and growth (up to 22%); cell lysis due to osmotic stress.                                             | Qu et al., 2023      |
|                             | In waterlogging conditions, O <sub>2</sub> deprivation inhibits microbial activity; microbial biomass carbon is reduced.                                           | Das et al., 2025     |

#### 4. Principles of CA

CA is a management approach to farming systems that is considered one of the primary ways to achieve sustainable agriculture and protect the environment and land more effectively (Cárceles Rodríguez, 2022; Farooq et al., 2024). According to FAO, CA is a method that integrates long-term soil cover (at least 30% soil cover between planting and harvesting), minimal or no tillage (NT), and crop species mixtures, including legumes (FAO, 2015). Developed in the 1930s in the United States to overcome soil degradation caused by water and wind erosion (Holland et al., 2004), CA is characterized by the use of three interrelated principles that are adopted along with regionally specific agricultural management (FAO, 2015; Cárceles Rodríguez et al., 2022; Ahmed et al., 2024). These three tenets include permanent soil cover, minimum soil disturbance, and crop rotation. These components have a synergistic effect in promoting soil health, water management, and agricultural system sustainability (Jat et al., 2020; Farooq et al., 2024) (**Figure 2**). CA systems are established worldwide and cover a diverse array of agricultural practices. This includes both rainfed and irrigated farming, such as annual crop cultivation, perennial and orchard systems, plantation and agroforestry systems, combined crop-livestock operations, pasture and rangeland management, rice-based systems, and organic farming methods (Kassam et al., 2022; Farooq et al., 2024).

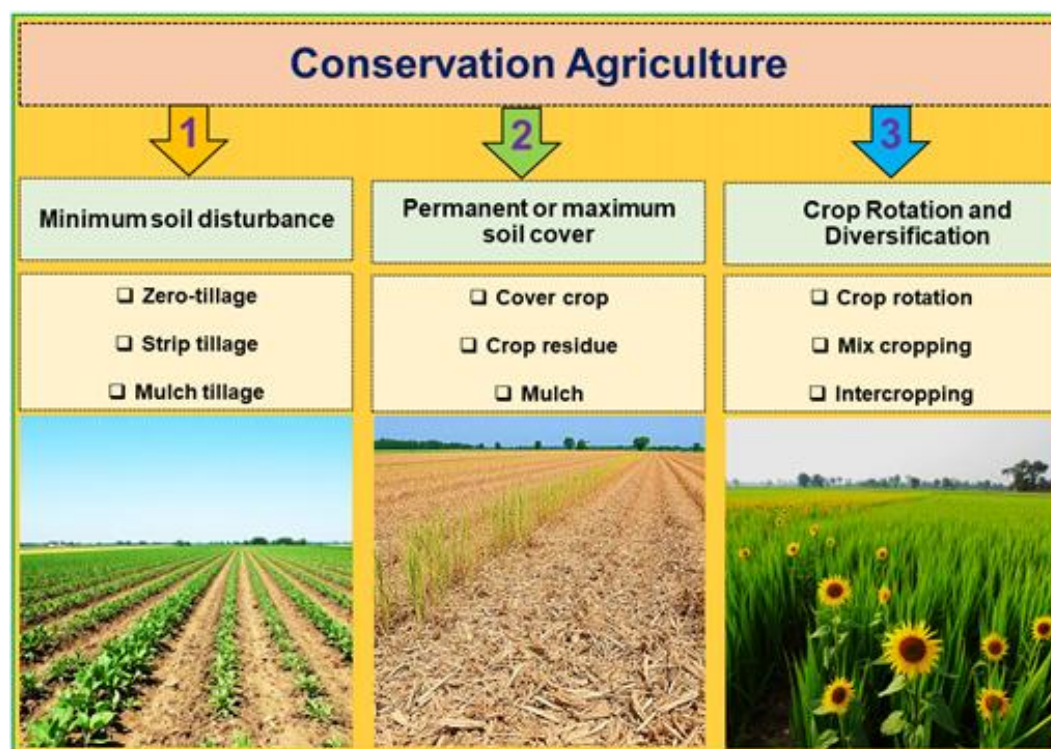


Fig. 2. Three core principles of CA.

#### 4.1. Crop Residue Management

Crop residue management is a technique that involves covering at least 30% of the soil surface with organic leftover material from the previous crop during planting (Erenstein, 2002). Returning crop residues to the field following harvest is a widely recognized beneficial practice worldwide for enhancing soil health indicators (Sarker et al., 2022). Three reasons make a permanent soil cover necessary: it shields the soil from the destructive effects of rain and sunlight; it provides "food" to the soil's microorganisms on a constant basis; and it alters the microclimate in the root zone to encourage the growth of soil microbes (Sharma et al., 2023). Additionally, residues left from harvested crops significantly influence crop yields by affecting the soil's physical, chemical, and biological properties, as well as enhancing the quality of both water and soil (Sarker et al., 2022).

#### 4.2. No-till Farming

No-till farming is an agricultural method where crops are cultivated without disturbing or turning over the soil through plowing or tillage. As of now, the no-till systems are numerous and include: pure no-till (no tillage), strip tillage (tillage restricted to narrow strips where the seed is planted), and mulch tillage (minimal disturbance and cover crops) (Dang et al., 2020; Dev et al., 2023). The most common ones are direct sowing of crops on undisturbed soil with special equipment and no-till seed drills to reduce soil erosion and the loss of water (Ma et al., 2025). The area under no-till farming has increased to around 20–30% of the total crop area globally, especially in North America, South America, and Australia (FAO, 2015). It has been well documented that no-till farming enhances soil quality in various aspects, such as soil fertility, soil structure, and soil biological properties. As a comparison, it has been demonstrated that mulch no-till enhances yield, reduces runoff, and enhances water infiltration compared to tilled soils (Du et al., 2022).

#### 4.3. Crop rotation and Diversification

Other CA practices that can be employed to increase sustainable farming systems include crop rotation and crop diversification (Sun et al., 2018). Crop rotation involves the production of different crops in a particular order over a variety of growing seasons, and crop associations are the production of two or more crops simultaneously (Shah et al., 2021). Simple rotation, i.e., cereals to legumes; complex crop rotation systems, i.e., utilization of diverse crops, including maize, beans, and potatoes; and cover cropping, i.e., planting of crops that are not harvested to fertilize and preserve the soil, are the simplest forms of crop rotation (Sun et al., 2018; Shah et al., 2021). The practice interrupts the pest and disease cycle, reduces soil erosion, and improves soil health as a result of a greater range of use and resupply of nutrients (Kassam et al., 2022). As an example, the biological binding of nitrogen in the soil can be done by alternating legumes with cereals, which decreases the need to

implement chemical fertilisers (Kebede et al., 2021). Crop rotation can increase crop yields by 10–20% and reduce chemical inputs, and as such, environmental impact (Sehgal et al., 2023). Diversification is synonymous with crop rotation in that it brings in new crops into a farming system. This reduces economic risk and enhances adaptability to climatic fluctuations because it is not based on a monoculture (Ahmed et al., 2024). Diversity also increases biodiversity, which activates beneficial insects and microorganisms in the soil that aid the health of crops (Rahman et al., 2024). Together, crop rotation and diversification enhance the stability of the soil, organic matter, and water-holding capacity and lead to higher yields using less input.

## 5. Role of CA for Sustainable Agricultural Productivity

### 5.1. Agronomic and Economic Benefits

Sustainable intensification is also becoming accepted as an activity that must be adopted to achieve sustainable agriculture (Asante et al., 2025). In contrast to conventional agriculture, there are several significant differences between CA and conventional agriculture as a means of less harmful agriculture (**Tables 2 & 3**). CA is supposed to help improve the soil sustainability and decrease its negative effect on the ecosystem and the long-term sustainability of agricultural land. It is believed that in the world, the overall farmland operated using CA practices is about 180 million ha or about 12.5 percent of worldwide arable land (Kassam et al., 2022). The most developed countries where CA is implemented are the USA, Brazil, Argentina, Australia, and Canada. Practices of CA are also increasingly attracting interest in India and Pakistan in South Asia (Kassam et al., 2022). Concisely, CA is increasingly gaining popularity in most parts of the globe as an alternative to traditional and organic farming.. Statistics indicate that no-till farming can increase soil organic carbon to 5.85 Mg ha<sup>-1</sup> over conventional tillage within 11 years, contributing to reducing the impacts of climate change (Wang et al. 2020). Additionally, farmers adopting no-till practices often experience a fuel saving of 3.9 gallons acre<sup>-1</sup> (Dang et al., 2020) and a 50% decrease in labor (Corbeels et al., 2015) compared to traditional methods.

**Table 2. Key agronomic and economic benefits of CA.**

| Parameter               | Agronomic/Economic output                                                                                                                                                                                                                 | References                 |
|-------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|
| Yield                   | CA practices can lead to higher (10-20%) or comparable yields over time.                                                                                                                                                                  | Su et al., 2021            |
| Irrigation needs        | Promotes better water retention, reducing irrigation needs. Water savings of 25-30%.                                                                                                                                                      | Nandan et al., 2021        |
| Labor requirements      | CA can reduce labor requirements by 20-50%, primarily due to decreased tillage and fewer passes over the field.                                                                                                                           | Dev et al., 2023           |
| Fuel requirements       | Fuel savings of approximately 25-30% when adopting zero tillage compared to conventional tillage methods.                                                                                                                                 | Aravindakshan et al., 2015 |
| Time savings            | Reducing multiple tillage passes shortens planting and harvest times. CA could reduce planting time by 15-20 days during the planting season.                                                                                             | Nyagumbo et al., 2017      |
| Fertilizer expenditures | CA practices augment soil health and organic matter, improving nutrient availability. Reports showed that with better soil structure and microbial activity, farmers could reduce fertilizer inputs by 10-20% without sacrificing yields. | Feng et al., 2022          |
| Weed control            | CA relies on integrated weed management techniques, including cover crops and residue management, which suppress weeds. A reduction in weed biomass was found under CA systems compared to conventional tillage.                          | Cordeau, 2022              |
| Disease outbreaks       | Crop diversification in CA practice can reduce the reproduction of soil-borne diseases.                                                                                                                                                   | Zhang et al., 2025         |
| Insect outbreaks        | Diversified plants reduce the severity and frequency of insect outbreaks, such as the BPH in rice, by maintaining proper ecological balance.                                                                                              | Ali et al., 2021           |

**Table 3. Key environmental/ecological benefits of CA.**

| Parameter                      | Environmental/ecological benefits                                                                                                                                                                                           | References                 |
|--------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|
| Soil organic carbon            | CA practices enhance soil organic content and facilitate nutrient recycling. Implementing no-till farming can raise soil organic carbon levels by up to 5.85 Mg ha <sup>-1</sup> over conventional tillage within 11 years. | Wang et al. 2020           |
| Soil erosion                   | Maintains soil cover and reduces runoff, preventing erosion rates (up to 80%).                                                                                                                                              | Savari et al., 2025        |
| Nitrate leaching               | Cover crops significantly reduce nitrate leaching by up to 56% in comparison to conventional practices through improving soil structure and increasing nitrogen uptake efficiency.                                          | Thapa <i>et al.</i> , 2018 |
| Surface runoff reductions      | CA practices improve soil water retention and infiltration, leading to reduced surface runoff of 16%.                                                                                                                       | Du et al., 2022            |
| CO <sub>2</sub> emissions      | Reduced/no tillage and organic matter retention increase soil carbon sequestration, reducing net CO <sub>2</sub> emissions. The no-till practices can sequester about 0.2–0.5 t ha <sup>-1</sup> of carbon annually.        | Karki et al., 2025         |
| Increase in soil biodiversity  | CA improves soil biodiversity by offering essential habitats and nutrients. No-till and cover cropping can increase earthworm populations by up to 196% compared to conventional tillage.                                   | Seibutis et al., 2025      |
| Increase in microbial activity | A 71% increase in microbial biomass was observed in no-till systems due to higher microbial activity and improved nutrient cycling.                                                                                         | Srouf et al., 2020         |
| Downstream water pollution     | CA minimizes sediment, nutrients, and agrochemicals in downstream water pollution by reducing runoff and leaching.                                                                                                          | Shivendra et al., 2023     |

## 5.2. Soil Health Improvement

One of the key advantages of CA is the significant enhancement of soil health. By reducing tillage, CA minimizes soil erosion and maintains soil structure, leading to increased organic matter content (Ma et al., 2025). According to Lal (2015), no-till systems can increase soil organic carbon stocks by 0.2 to 0.5 t ha<sup>-1</sup> annually, promoting nutrient retention and soil fauna. Additionally, retaining crop residues shields the soil surface from compaction and compaction-related yield losses, which, in conventional systems, can decrease yields by up to 30% (Sarker et al., 2022). CA also leads to better soil health through increased soil aggregation, organic carbon, and enzymes, which have a positive effect on the carbon-nitrogen cycle, soil stability, and crop productivity. When integrated practices such as crop rotation and residue management are combined with conservation tillage, there is a high likelihood of long-term sustainability of soil management (Sangotayo et al., 2023). In Mexico, Kabiri et al. (2016) revealed that after a long-term of NT maize (six years), microbial biomass (MBM), soil enzymes, and soil organic carbon (SOC) were all increased relative to conventional tillage. Overall, CA contributes to making soil management sustainable by sustaining a biologically active, resistant soil ecosystem.

## 5.3. Water Conservation

CA increases the efficiency of water use. Retaining crop residues particularly enhances water infiltration and decreases evaporation, thus leading to better soil moisture storage (Sarker et al., 2022). Research has shown that CA practice may lead to 20–30% greater water use efficiency than conventional tillage (Ghosh et al., 2025). Also, the ability of CA to increase soil porosity allows crops to access deeper soil moisture when it is dry (Eze et al., 2020). Such practices have been proven to increase yields by 15–25% due to improved water availability in semi-arid regions (Lal, 2015). There is also less surface runoff and soil erosion that contributes to water conservation, and that is why CA can be adopted as a possible solution in water-limited realities, especially in the world affected by climate change (Ghosh et al., 2025).

## 5.4. Enhanced Biodiversity

CA also promotes biodiversity on many levels. The conservation of crop residues on the land and reduced soil plowing could create an optimum environment for soil inhabitants such as earthworms, insects, and beneficial microbes that contribute substantially to nutrient cycling and soil health (Ma et al., 2025). Superficially, the multi-cropping system and cover of residues provide food and homes to pollinators and beneficial insects, which

create more robust agro-ecosystems (Ali et al., 2021). When crop rotation is diversified, fauna and flora in the soil are also diversified (Sharma et al., 2023). Legumes have also been included in crop rotations and mixtures due to their capability to interrupt the life cycles of pest species, reduce off-site pollution, and elevate biodiversity (Mng'ong'o et al., 2025). The research study by the IITA has found that the population of beneficial insects is 40% higher on farms where CA is practiced than on conventional farms (IITA, 2019). This increased biodiversity decreases chemical input requirements and escalates ecosystem services, which ultimately facilitates sustainable farming systems.

### 5.5. CA on Soil Microbial Activity

Microbial communities play a critical role in the breakdown of organic matter and the release of key nutrients, including nitrogen and phosphorus, back to plants. An augmented SOM due to CA practices is also advantageous to soil microbes because it serves as a food source. This can lead to an increase in microbial biomass and diversity, and eventually, general soil health (Sangotayo et al., 2023; Enebe *et al.*, 2025) (**Table 4**). CA practices, by promoting microbial activity and increasing soil enzyme production, lead to better nutrient mineralization, thereby improving soil fertility (Al-Shammari, 2024; Shultana et al., 2025). Diverse crop rotations and cover crops in California enhance soil microbial diversity, which in turn improves soil health and resilience. Crop rotation is crucial because it allows soil microorganisms to have a diversified "diet" and can be "recycled" by crops that are grown alternately. Different crops release different types and amounts of carbon and other resources into the soil through their roots and residues. This variety of resources supports a wider range of microbes, including fungi, bacteria, and other microorganisms (Sun *et al.*, 2024). Reduced tillage practices enhance soil health by maintaining soil structure, which in turn supports beneficial organisms. This approach minimizes soil disturbance, leading to improved soil aggregation and reduced compaction. The resulting better aeration and increased pore space create a more favorable environment for the proliferation of these beneficial microbes (Sher et al., 2024).

**Table 4. Microbial activity under different CA practices.**

| Sl. No. | CA                                                                    | Microbial activity                                                                                                                                                                                                                                                                                                                                                                                         | Reference            |
|---------|-----------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------|
| 1       | Crop residue retention under no tillage                               | No-tillage promotes a richer variety of bacterial and fungal communities, supporting the proliferation of beneficial microbes like arbuscular mycorrhizal fungi that enhance nutrient availability and overall plant growth.                                                                                                                                                                               | Srour et al., 2020   |
| 2       | Mulch (30% crop residue)                                              | Applying crop residue mulches resulted in enhanced bacterial functional capabilities, particularly those related to amino acid transport and metabolism, along with improved energy generation and transformation processes.                                                                                                                                                                               | Zhang et al., 2020   |
| 3       | Ridge tillage (RT) with residue management on the ridges and furrows. | RT increased the population of <i>Acidobacteria</i> , <i>Gemmatimonadetes</i> , and <i>Proteobacteria</i> compared to conventional tillage. The increments were 10.85%, 2.95%, and 3.21%, respectively. Similarly, the populations of Chytridiomycota, Ascomycota, and Cercozoa increased by, 27%, 38% and 77%, respectively.                                                                              | Liu et al., 2022     |
| 4       | Strip tillage (ST)                                                    | ST was identified as the most effective cultivation method for enhancing the microbial biomass in Chernozem soil. The fungi, arbuscular mycorrhiza, and bacterial biomasses were significantly higher in the ST compared to the plowing tillage. ST elevated the overall bacterial population by 49.0%, enhanced the number of active bacteria by 27.0%, and boosted both active and total fungi by 37.0%. | Kovács et al., 2024. |
| 5       | Reduced tillage & alley cropping                                      | RT and alley cropping increased the proportion of beneficial bacteria. RT practice exhibited a greater proportion of the Solirubrobacteraceae family, along with increased presence of the genera <i>Streptomyces</i> and <i>Solirubrobacter</i> .                                                                                                                                                         | Özbolat et al., 2023 |

## 6. Role of CA Practices on Mitigating Abiotic Stress in Important Crops

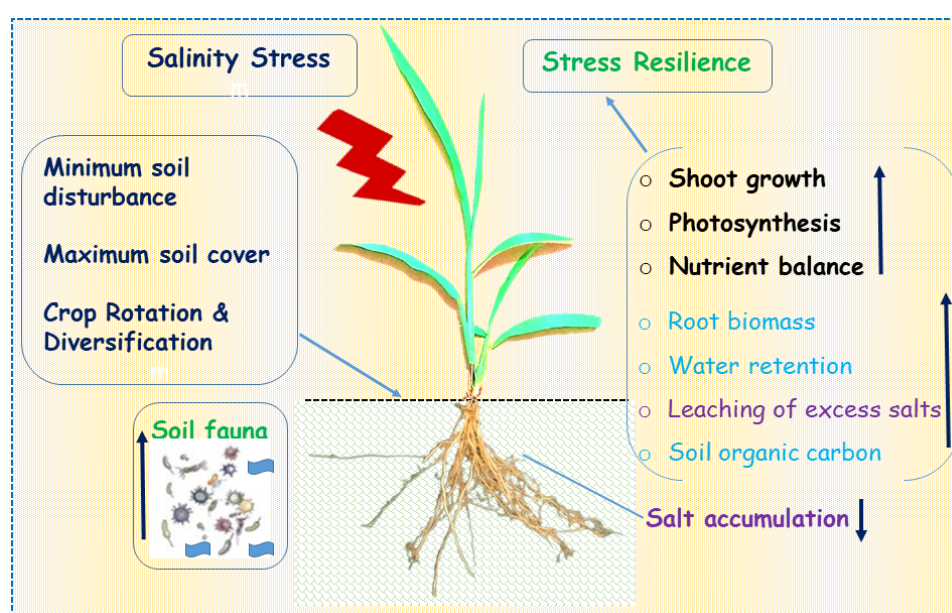
Abiotic stresses, such as salinity, drought, cold, elevated temperatures, and waterlogging, significantly reduce crop yields globally, with potential losses ranging from 50 to 82% in major food crops (Nehra et al., 2024). CA, characterized by agronomic methods such as cover cropping, residue management, and zero tillage, offers sustainable solutions to boost crop resilience against these stresses (Michler et al., 2019). At its core, CA encompasses minimizing soil disturbance by practicing reduced tillage, preserving soil cover with crop residues or cover crops, and implementing crop rotation or diversification (FAO, 2015; Rodríguez et al., 2022). All these principles enhance the health of the soil, water retention, and biodiversity, which in turn enhance plant resistance to abiotic stresses (Jat et al., 2020). The use of legume cover crops can increase soil moisture content, suppress weeds and soil erosion, alleviate drought, and improve soil fertility (Kassam et al., 2022). Residue management has the capability of sustaining soil moisture, soil temperature, and soil organic matter, which have the capacity to enhance the abiotic stress endurance of plants (Sarker et al., 2022). In the meantime, no-till also minimizes soil disturbance, maintains soil integrity, and enhances water infiltration and water-holding capacity, hence abating drought- and heat-related susceptibility (Ma et al., 2025). These practices have been applied in different agro-ecological zones and crops across the world. In India, the zero-tillage rice-wheat cropping system has contributed to the conservation of water, along with a decrease in input costs, hence making it resistant to drought and heat (Vashisht et al., 2025). In America, reduced tillage of soybean and maize has been extensively employed, and this has brought about improvements in soil health and alleviated drought (Khangura et al., 2023). In Australia, it is also a natural component of dryland farming systems that leads to the preservation of residue and cover cropping, enhancing moisture retention and crop yield in arid conditions (Kelly et al., 2020). The adoption of CA practices not only permits maintaining the level of productivity but also contributes to the mitigation of climate change due to the capture of carbon and greenhouse gas emissions (Rahman et al., 2021). The scope also addresses smallholder farmers in Africa and Southeast Asia, where cost-effective CA practices can help maintain resilience against erratic rainfall patterns and variations in temperature, which in turn can ensure livelihoods (Kassam et al., 2022).

### 6.1. Salinity Management

It is projected that about 10.7% of the global land area under irrigation is influenced by salinity, much of which is in developing nations (FAO, 2024). Salinity can also cause negative impacts on crop growth, yield, soil structure, and soil fertility (Tarolli et al., 2024). Tillage (reduced tillage or no-till) can prevent salinization of the soil because it minimizes soil disturbance and the formation of capillary action that promotes the movement of salts to the soil surface (Yao et al., 2023; Tarolli et al., 2024). Moreover, conservation of crop residues helps increase water intake and reduce water evaporation, thus diluting soil salts and promoting a favorable environment that stimulates the growth of healthy plants (Sarangi et al., 2020). The protective barriers also contribute to cover crops because they assist in regulating the concentration of salt by preventing the surface of the soil from being exposed to direct sunlight and minimizing evaporation (Quintarelli et al., 2022). Researchers have established that retention of residue can significantly reduce soil salinity by increasing infiltration of water and reducing evaporation of water on the surface (Shawkhatuzamman et al., 2023). Kundu et al. (2022) asserted that salinity can be alleviated through crop rotation, introduction of salt-tolerant crops to boost biological activity and nutrient cycling in the soil. An example is CA-based practices in cotton-wheat systems; it enhances sustainability measures such as an increase in yields, water productivity, and energy use efficiency in irrigated drylands and alleviates soil salinity (Devkota et al., 2022). Research has demonstrated that reduced tillage enhances soil aggregation and reduces soil evaporation, which restricts the salt concentration at the soil surface (Lal, 2015) (**Table 5**). CA-based practices such as no-tillage and residue retention combined with optimal nitrogen application per hectare demonstrated the highest potential for enhancing sustainability and resilience. In short, CA decreased the salt level in the cotton-wheat system (Devkota et al., 2022). Moreover, CA systems increase SOM, which helps in binding salts, avoiding their build-up within the root zone (**Figure 3**). Soil erosion exacerbates salinity by removing the topsoil layer and exposing saline subsoil. CA practices, like reduced tillage and retention of crop residues, minimize erosion and protect the soil surface. Research by Kundu et al. (2022) highlighted that reduced tillage and soil cover significantly lower erosion rates, thereby mitigating salinity. In sum, the use of salt-tolerant crop varieties combined with CA practices further enhances resilience to salinity stress.

**Table 5. CA practices to alleviate the adverse effects of salt stress in important crops.**

| Crop            | CA practice                                                                                                                | Mitigation effect                                                                                                                                                                                                                                                | Reference                  |
|-----------------|----------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------|
| Rice            | Crop residue mulch (5600 kg ha <sup>-1</sup> straw mulching)                                                               | Reduces evaporation, minimizes exchangeable Na <sup>+</sup> buildup, and improves soil moisture retention.                                                                                                                                                       | Yuan et al., 2022          |
| Wheat           | Sub-soil plastic film mulch (PMF)                                                                                          | PMF more effectively reduced salinity in shallow soils, leading to a substantial increase in crop yield compared to the control..                                                                                                                                | Wang et al., 2024          |
| Barley          | Cover cropping (legumes, grasses)                                                                                          | Enhances leaching of salts, improves soil organic matter, and reduces salinity stress.                                                                                                                                                                           | Cabello-Leiva et al., 2015 |
| Soybean         | Biodiversification through the use of cover crops, such as grasses or a combination of grasses and legumes.                | Improves soil quality and boosts soybean production by 10%.                                                                                                                                                                                                      | Souza et al., 2025         |
| Maize           | Traditional tillage combined with comprehensive straw mulching throughout the fallow period.                               | An increase of 10.3% in soil moisture, 17.8% in soil organic matter, and 11.3% in grain yield was achieved. Applying straw mulch throughout the fallow period is advised as an effective method to maintain soil health in saline rain-fed agricultural systems. | Zhang et al., 2022         |
| Sunflower       | Deep tillage with straw mulch and burying of a maize straw layer (12 t ha <sup>-1</sup> ) (SM + SL)                        | SM + SL considerably increased the soil moisture at the 0–40 cm depth. SM + SL increased the sunflower shoot biomass by 4.8% compared to conventional practice in a salt-affected area.                                                                          | Zhao et al., 2014          |
| Wheat & sorghum | Deficit irrigation at 60% of crop water needs, combined with rice straw mulching under reduced tillage practices. (CWR+RT) | CWR+RT showed the potential in preserving soil health and conserving fresh irrigation water while sustaining the yield of the sorghum-wheat cropping system.                                                                                                     | Soni et al., 2021          |
| Sugarcane       | Cover crops                                                                                                                | Improves soil structure and minimizes the buildup of surface salts.                                                                                                                                                                                              | Kishore et al., 2024       |
| Cotton          | Wheat straw mulch, farm yard manure mulch.                                                                                 | Mulching significantly increased soil water contents by 32% and decreased soil salt contents by 67% compared to the control.                                                                                                                                     | Iqbal et al., 2024         |
| Wheat-Alfalfa   | Crop rotation                                                                                                              | Crop rotation by alternating salt-resistant crops with salt-sensitive crops helps to disrupt the salt accumulation cycle.                                                                                                                                        | Cuevas et al., 2019        |

**Fig. 3. A schematic diagram showing the eco-physiological processes underlying the effects of CA on salinity stress mitigation in plants.**

## 6.2. Drought Management

CA helps crops withstand drought stress by creating an ecosystem that is more robust and moisture-conserving. In spite of shifting climatic trends, maintaining soil structure and organic matter also makes it possible to use water resources more efficiently, which increases agricultural production. These methods increase soil water retention, lower evaporation, and improve soil health in general (**Table 6**). CA practices improve soil properties, increase water infiltration by 0.7-7.9 times, and enhance soil moisture retention by 11-31% in comparison with conventional tillage (Thierfelder and Steward, 2022). These improvements lead to greater adaptive capacity during dry spells and heat stress, particularly on light-textured soils (Thierfelder and Steward, 2022). Studies in Mozambique, Zimbabwe, and Zambia have shown that CA practices can boost maize and legume yields compared to conventional tillage, especially in drought-prone environments (Thierfelder *et al.*, 2016). Applying a mulch layer on the soil surface reduces evaporation and helps sustain an optimal water balance (Ramos *et al.*, 2024). The synergistic effect of minimal soil disturbance, retention of crop residues, and diverse crop rotations can gradually enhance soil carbon levels, thereby increasing water retention capacity, particularly in sandy soils (Xiao *et al.*, 2025). It has been noted that the use of CA techniques increases infiltration and the accessibility of water in the soil, thereby increasing the resistance of crops to dry spells during the season and reducing the possibility of crop failure (Ramos *et al.*, 2024). In addition, soil-water management strategies like CA have been observed to conserve water and reduce the risk of drought, which results in significantly higher yields of maize and wheat in the semi-arid regions of Kenya and Ethiopia (Cornelis *et al.*, 2019). Crop residue mulch, cover crops (forages), and bare-fallow avoidance can also help retain soil and water and enhance surface SOC levels (Lal, 2015). Crop rotation with deep-rooted cover crops enhances soil porosity and organic matter content, which collectively improve the soil's water-holding capacity. Overall, CA provides a sustainable agricultural method that lessens the effects of water shortage, which is crucial for the proper management of drought stress.

**Table 6. Strategies implemented by CA to alleviate the negative impacts of drought stress on important crops.**

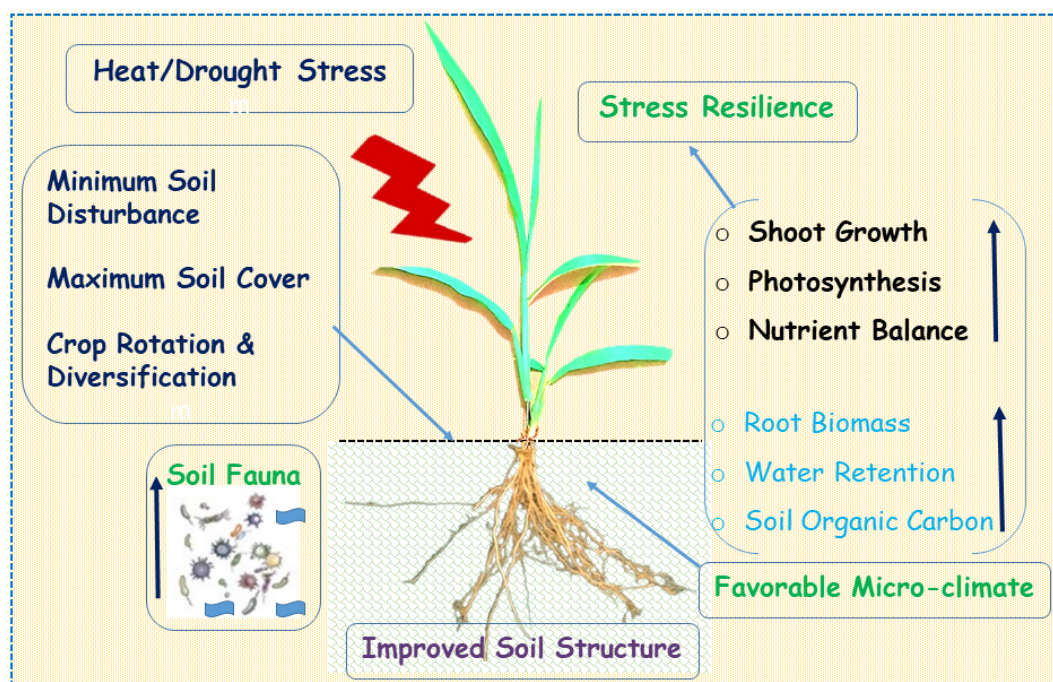
| Crop                                                                       | CA practice                                                       | Mitigation effect                                                                                                                                                                                                                                                                                                     | Reference                       |
|----------------------------------------------------------------------------|-------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------|
| Rice                                                                       | Biodegradable film mulching in dry direct-seeded conditions (BFM) | BFM significantly improved soil moisture regulation, expanded leaf area, and boosted rice productivity and water use efficiency relative to the control.                                                                                                                                                              | Zhao <i>et al.</i> , 2024       |
|                                                                            | Straw mulching under non-flooded conditions                       | Non-flooded cultivation combined with straw mulching enhances growth and physiological responses under drought conditions.                                                                                                                                                                                            | Ria <i>et al.</i> , 2025        |
| Potato, Sweet Pepper, Eggplant, Tomato, Legumes                            | Mulching                                                          | Both organic and plastic mulching improve soil structure, aeration, and aggregation, which enhances soil infiltration capacity, increases water holding and retention capacity, and stimulates better root growth.                                                                                                    | Saputra <i>et al.</i> , 2025    |
| Spring wheat                                                               | No tillage and straw mulching                                     | No-tillage combined with straw mulching improves dry matter accumulation of spring wheat by enhancing soil physicochemical characteristics and regulating stress-tolerance compounds, thereby promoting yield development.                                                                                            | Du <i>et al.</i> , 2023         |
|                                                                            | Efficient irrigation                                              | Sprinkler and drip irrigation optimize the microclimate, thus lowering soil and canopy temperature and optimizing transpiration, which helps mitigate drought stress.                                                                                                                                                 | Yadav <i>et al.</i> , 2022      |
| Maize                                                                      | No-tillage and straw (NTS)                                        | NTS can improve the soil structure and soil fertility across various depths, and reduce drought effects and grain yield reduction.                                                                                                                                                                                    | Deng <i>et al.</i> , 2023       |
| Faba bean                                                                  | Non-tillage                                                       | The higher levels of mycorrhizal colonization in roots, especially under no-till practices, may be beneficial for plants in coping with drought stress.                                                                                                                                                               | Madejón <i>et al.</i> , 2023    |
| Pearl millet, Cowpea, Potato, Pea, Barley, Maize, Wheat, Soyabean, Legumes | Reduced tillage                                                   | Reduced tillage through ploughing, harrowing, or disking, which enhances soil structure, soil moisture, and better root penetration.                                                                                                                                                                                  | Wittwer <i>et al.</i> , 2023    |
| Wheat, Legumes                                                             | Timely sowing or planting                                         | Early maturing variety in sowing early can escape drought stress in the flowering stage. Early sowing increases 0.4 t ha <sup>-1</sup> yield.                                                                                                                                                                         | Deihimfard <i>et al.</i> , 2023 |
| Cowpea-babycorn, Potato-Legume, Maize-Soyabean                             | Inter-cropping                                                    | Intercropping increases crop growth rate, relative water content, and chlorophyll content of both crops and significantly reduces canopy temperature and soil temperature due to shading and increased soil cooling through moisture retention. The yield of cowpea and babycorn increased 28% and 17%, respectively. | Bijarnia <i>et al.</i> , 2024   |

### 6.3. Heat Stress Management

CA offers several benefits for temperature management, primarily through its influence on soil and local climate conditions. By altering soil properties and processes, CA can mitigate temperature extremes and improve soil health, which in turn supports sustainable agricultural practices (**Figure 4**) (**Table 7**). Mulching with crop residues insulates the soil, reducing temperature fluctuations and maintaining a stable microclimate around the root zone (Acharya et al., 2019; Li et al., 2021). This temperature reduction is caused by the presence of stubble on the surface of the soil and the soil being wetter as a result of less evaporation. This temperature stabilization of the soil is important to crops such as maize, which need particular temperature ranges to germinate and grow well. Also, conservation activities support an increase in microbial levels required to maintain soil health and nutrient cycling, which further boosts agricultural productivity (Ma et al., 2025). High-temperature stress had adverse impacts on the yields of non-stress-tolerant maize varieties in cropping systems that do not involve legume rotation. Nonetheless, the practice of CA contributed to reducing this negative effect in comparison with conventional control practices (Komarek et al., 2021). CA has been found to reduce local warming during extreme temperature events by about 1 °C in mid-latitude areas through increased transpiration and increased soil moisture retention (Hirsch et al., 2018). It was found that CA enhances soil health through elevated soil organic carbon and microbial biomass that are essential in maintaining soil structure and fertility under warming conditions, which contributes to improved resilience to climate warming, as indicated by higher crop yields and microbial diversity (Teng et al., 2024). Even though the use of CA can be highly beneficial in terms of temperature control, it may not be effective depending on the climate in a particular region and the type of farming activities used.

### 6.4. Cold Stress Management

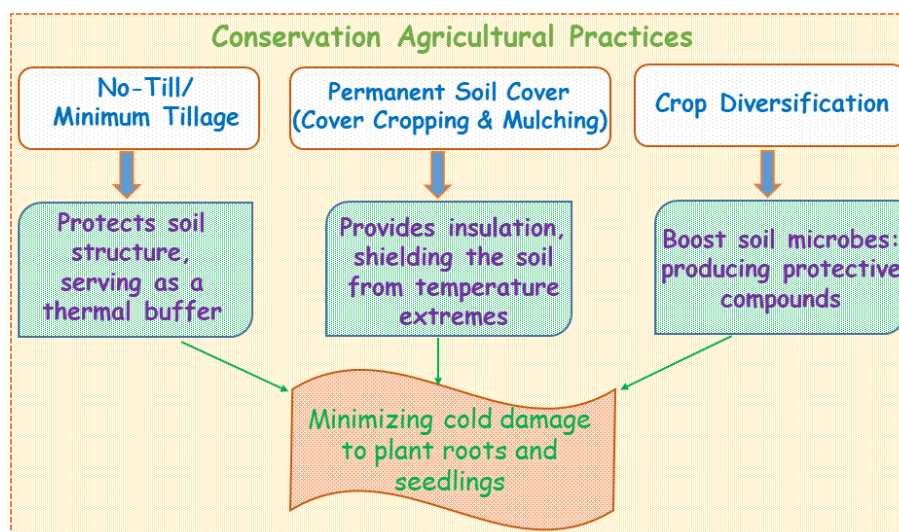
CA practices can successfully reduce the adverse impacts of cold stress on different crops (Karki & Gyawaly, 2021). Cover crops provide an insulating layer that buffers soil and plant tissues against low temperatures, reducing plant damage (Yang et al., 2021) (**Figure 5**). Additionally, organic mulches, like straw or leftover crop materials, insulate the soil surface, moderating temperature fluctuations and protecting root systems (Mamun et al., 2013). Crop diversification and rotation help select cold-tolerant varieties and break pest and disease cycles, further strengthening crop growth under cold stress conditions (Sehgal et al., 2023). Timing of planting is optimized to avoid peak cold periods, and conservation tillage facilitates better soil warming (Du et al., 2023). Implementing these CA practices not only reduces cold-induced damage across a variety of crops, such as wheat, maize, soybeans, and vegetables, but also promotes sustainable production systems (Qu & Feng, 2022) (**Table 8**).



**Fig. 4.** A schematic diagram showing the eco-physiological processes underlying the effects of CA on heat/drought stress mitigation in plants.

**Table 7. CA practices to alleviate the adverse impacts of high temperature stress in important crops.**

| Crops                                          | CA practice                                                         | Impacts on heat stress mitigation                                                                                                                                                                                                                                                                                | Reference                    |
|------------------------------------------------|---------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------|
| Wheat, Lentil, Faba bean, Chick pea, Legumes   | Raised bed systems and zero tillage, adjusting planting time        | 15-20 days of early sowing or planting helps to escape the heat stress during the flowering to post-flowering stage. Moreover, Furrow irrigated raised bed techniques and zero tillage systems have the potential to lower the canopy temperature by 1.5 to 3.0 °C.                                              | Dubey et al., 2019           |
| Wheat                                          | Irrigation                                                          | Sprinkler and drip irrigation optimize the microclimate, thus lowering soil and canopy temperature and optimizing transpiration, which helps mitigate heat stress. Wheat yield increased by 22–59% due to irrigation.                                                                                            | Yadav et al., 2022           |
|                                                | Adjusting mulching practices and sowing schedules for late planting | Farmyard manure (10 t ha <sup>-1</sup> ) combined with rice straw mulch (4 t ha <sup>-1</sup> ) mitigates the negative impact of terminal heat stress, and enhances the wheat grain yield and water use efficiency under late planting.                                                                          | Balwinder-Singh et al., 2016 |
|                                                | Cover crop (sorghum )                                               | Stimulate growth under heat stress. During the sowing period of winter wheat, surface soil moisture experienced a 4% rise when grown with an optimal summer cover crop.                                                                                                                                          | Zhang et al., 2023           |
| Maize                                          | Cover crops                                                         | Improves heat tolerance by increasing the absorption of nitrogen and zinc.                                                                                                                                                                                                                                       | Mariscal-Sancho et al., 2023 |
| Wheat, Potato, Cotton                          | Mulching                                                            | Soil surface mulching promotes better aeration, resists temperature fluctuation, maintains the soil moisture, and improves root growth, thus helping to minimize canopy temperature via transpiration cooling and reducing heat stress.                                                                          | Acharya et al., 2019         |
| Cowpea-babycorn, Potato-Legume, Maize-Soyabean | Inter-cropping                                                      | Intercropping increases crop growth rate, relative water content, and chlorophyll content of both crops and significantly reduces canopy temperature and soil temperature due to shading and increased soil water content and soil cooling. The yield of cowpea and babycorn increased 28% and 17% respectively. | Nyawade et al., 2020         |
| Citrus                                         | Straw Mulching                                                      | Straw mulching techniques can enhance citrus fruit production even under severe temperature extremes.                                                                                                                                                                                                            | Visconti et al., 2024        |

**Fig. 5. A schematic diagram showing the eco-physiological processes underlying the effects of CA on heat/drought stress mitigation in plants.**

**Table 8. CA practices for alleviating the adverse effects of cold stress in different crops.**

| Crops        | CA method                                              | Mitigation effects                                                                                                                                                                                                 | Reference           |
|--------------|--------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------|
| Rice         | 25% rice husk as tray media with 75% loamy soil        | The husk acted as an insulator and increased the temperature in the root zone, resulting in improved seedling growth under low temperature conditions.                                                             | Mamun et al., 2013  |
| Wheat        | Plastic film mulching (PFM)                            | Soil temperature prior to the jointing stage was elevated by PFM application, leading to an increase in winter wheat yield in semiarid rainfed regions experiencing cold stress.                                   | Li et al., 2021     |
|              | 80% surface of straw mulching (SSM)                    | SSM increased the yield of buckwheat due to the improvement of soil organic matter and temperature use efficiency.                                                                                                 | Qu & Feng, 2022     |
| Wheat        | Planting and sowing time in reduced tillage conditions | Early sowing or planting of short-duration varieties helps to escape the cold stress during the flowering to post-flowering stage.                                                                                 | Hassan et al., 2021 |
| Sweet Pepper | Mulching                                               | Mulching improves soil temperature, leaf membrane stability, relative water and chlorophyll content, and photosynthesis, reduces leaf water loss, which mitigates cold stress. Yield of capsicum increased 82-87%. | Singh et al., 2019  |

### 6.5. Waterlogging Stress Management

The management of agricultural land to alleviate flood risks and surface runoff is essential for ensuring both economic viability and environmental integrity. Various CA practices such as straw mulching, no-tillage practices, ridge-farming, contour farming, and the implementation of bunds and buffer strips have consistently demonstrated efficacy in curtailing surface runoff by improving infiltration, decelerating water flow, and capturing sediments and nutrients (Singh et al., 2025). Cover crops have proven to be quite effective in mitigating the effects of recurrent floods. It has been empirically shown that cover crops, specifically those planted after the main harvest, are effective at controlling peak flow during winter and early spring floods (Hovis et al., 2021). In post-flooding situations, rapid establishment of cover crops has shown the potential to improve the growth of beneficial soil microbes, accelerate the cycling of nutrients, and improve the condition of the soil (Basche et al., 2016). It has also been documented that straw mulch has aided in enhancing the infiltration rate and establishing adhesive properties against erosive forces (Wang et al., 2023). According to Singh et al. (2025), runoff can be mitigated through cover crops as they provide a sort of shield over the surface of the soil, which can help in lessening the extent of surface runoff as well as the velocity of water flow. When applied in conservation methods such as no-tillage, ridge farming, and stubble mulch farming, the reduction in surface runoff has been proven to be very significant (Du et al., 2022). The study concluded that no-till practices disrupt soil, leading to minimal disturbance of the soil, improvement of filtration mechanisms, and reduced flooding (by up to 16%). Likewise, creating ridges and performing tillage along the contours formed barriers that slowed overland flow. This extension of surface detention time subsequently enhanced the period available for water to infiltrate the soil. Contour farming resulted in a 10% decrease in runoff compared to planting crops at a right angle to the incline (Farahani et al., 2016). Bunds were also recognized as effective in runoff management due to their capacity to retain water across slopes.

### 7. Mechanisms of Plants' Acclimation to Abiotic Stress Through CA Practices

CA has emerged as a sustainable approach to mitigate the adverse effects of different abiotic stresses, including salinity, drought, heat, cold, and waterlogging by promoting resource-efficient and resilient farming systems (Michler et al., 2019; Kumara et al., 2020). Key mechanisms include improvements in soil structure, water retention, and nutrient balance, aided by CA practices such as reduced tillage, cover cropping, and crop diversification, though creating a favorable microclimate in the root zone (**Figures 3, 4 & 5**). Reduced tillage, minimizing soil disturbance and promoting the development of stable soil aggregates. These aggregates increase soil porosity, creating a porous matrix that facilitates better water infiltration and retention (Schlüter et al., 2020). The better the soil structure, the less sealing and crusting occur on the surface, and the more rainwater can percolate into the soil profile. This enhanced infiltration decreases surface runoff and erosion, preserves the integrity of the topsoil, and prevents the loss of nutrients (Sittig & Sur, 2024). In addition, stable aggregates enrich the air in the soil, creating positive microbial activity that further stabilizes the soil and makes it fertile, which leads to resiliency to abiotic stresses like drought (Jat et al., 2023). Such soil moisture dynamics are critical for plant survival during dry spells and have a large influence on CA practices. In this regard, cover crops

and additions of organic matter are important. The cover crops shade the soil surface from direct sunlight and wind and hence minimize the rate of evaporation (Çerçioğlu *et al.*, 2025). Their root systems also facilitate water retention and soil porosity, originally adequately sustaining water over a longer duration (Farmaha *et al.*, 2021). The incorporation of organic matter into soil, in the form of crop residues and compost, increases the level of organic carbon in the soil, thus increasing the water-holding capacity because it enriches the soil structure and porosity (Parewa *et al.*, 2023). This organic matter functions as a sponge, retaining water in the pores of the soil and supplying plants during periods of water deficiency.

The preservation of soil moisture is also achieved through crop rotation since it disrupts the pest cycle and limits the occurrence of diseases, causing healthier root systems that can seek moisture in lower soil levels (Shah *et al.*, 2021). A multiplicity of root systems exists between different types of cropping systems, which increases the porosity and water-retaining abilities of the soil across depths, thus cushioning crops against drought (Liang *et al.*, 2023; Zou *et al.*, 2024). In conclusion, it is possible to surmise that the primary mode of action of CA practices in alleviating abiotic stresses is by enhancing soil structure and water management. Reduced tillage improves aggregation and infiltration in the soil, and cover crops, organic amendments, and crop diversification have a synergistic impact to enhance soil moisture retention. These processes contribute to a resilient agro-ecosystem that is capable of withstanding the ill effects of abiotic stress and leading to sustainable agricultural productivity and a healthy environment.

## 8. Conclusion

Conservation agriculture has become an innovative method of contemporary agricultural operations, providing lasting solutions to the adverse impacts of abiotic stress factors on crops such as salinity, drought, high temperature, and soil erosion. Limited soil disturbance, maintaining soil cover year-round, crop rotation or alternation, and diversification are all examples of how farmers can vary the agricultural system in place to minimize abiotic stress and enhance the soil, use fewer water resources, and enhance biodiversity on the farm. The mechanisms through which CA reduces abiotic stress demonstrate the complexity of the interconnection of soil chemistry and water-holding capacity with nutrient cycling. The outcome of CA practices is healthier crops able to better tolerate climatic variations due to the ability of the soil to infiltrate and retain water. Not only do these practices enhance the physical, chemical, and biological characteristics of the soil, but they also result in better cycling of nutrients and buildup of organic matter, which are vital in crop stress resistance. Along with this, CA reduces erosion, retains both moisture and modulates soil temperature, which offers a more stable growing environment, allowing plants to thrive under stressed growing conditions. The initiation of CA principles is becoming extremely vital to the attainment of food security, improvement of agricultural yields, and the realization of environmental sustainability due to the rising abiotic stresses that have been prompted by climate change. Incorporation of CA in farming systems will enable farmers to manage abiotic stresses better, hence ensuring the long-term viability and sustainability of agriculture in the face of the changing climate.

## Declarations

### Ethics approval and consent to participate

**Consent for publication:** The article contains no such material that may be unlawful, defamatory, or which would, if published, in any way whatsoever, violate the terms and conditions as laid down in the agreement.

**Availability of data and material:** Not applicable.

**Competing interests:** The authors declare that they have no conflict of interest in the publication.

**Funding:** Not applicable.

**Authors' contributions:** Conceptualization: AKH, AKMMI and MMR; formal analysis: MMR, SAU, SN, and RS, TKR; investigation: AKMMI and AKH; resources: MMR, AKH, RS and AKMMI; writing—original draft preparation: MMR, SAU, RS, TKR, SN and AKMMI; writing—review and editing: AKH, MSH and SC. All authors have read and agreed to the published version of the manuscript.

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