E-ISBN: 978-93-7020-232-0
IIP Series, Chapter 1

CURRENT RESEARCH TRENDS IN ARID AGRICULTURE

Abstract

Arid regions, which are characterized by minimal precipitation and sparse vegetation, make up about 41.3 per cent of the global land mass. These areas present serious obstacles to human existence and are home to over 2.1 billion people worldwide. These areas are known for high temperature, water scarcity, poor soil fertility and low biodiversity. These issues can be addressed through sustainable resource management and application of cutting-edge technology, including smart irrigation, protective cultivation, integrated weed control, balanced fertilization and biotechnological breakthroughs. Protective cultivation practices like polyhouses and net houses play a vital role in optimizing crop production by regulating the microenvironment in arid regions where water resources are scarce. Protective cultivation also includes practices such as hydroponics, precision agriculture and integrated crop management strategies. Water productivity in arid regions can be improved by practicing smart irrigation which uses Internet of Things (IoT) and artificial intelligence (AI) to deliver water precisely, thereby enhancing yields and fertilizer use efficiency. Advanced weed management approaches, including cover cropping, allelopathy, genetic engineering and remote sensing are combating herbicide resistance and improving soil health. Soil conservation techniques such as contour ploughing, mulching, windbreaks, afforestation and agroforestry practices can mitigate erosion and boost soil fertility. Geographic Information Systems (GIS) and remote sensing technologies are in extensive use for assessing and mitigating land degradation, promoting ecological stability and sustainability in arid regions. Biotechnological tools, Marker-assisted selection (MAS) and CRISPR Cas9 gene editing offer targeted solutions for developing arid-adapted crop varieties, ensuring sustainable agricultural productivity and resilience to abiotic stresses in the challenging environment of arid

Authors

Keshav
Division of Agronomy
ICAR – Indian Agricultural Research Institute, Jodhpur Hub, India
kkhowde@gmail.com

Akarapu Sagar
Division of Agronomy
ICAR – Indian Agricultural Research Institute, Jodhpur Hub, India
sagarakarapu11@gmail.com

Mukesh Kumar
Division of Genetics and Plant Breeding
ICAR – Indian Agricultural Research Institute, Jodhpur Hub, India
parmarmukesh1199@gmail.com

Ehsas Pachauri
Division of Genetics and Plant Breeding
ICAR – Indian Agricultural Research Institute, Jodhpur Hub, India
pachauri.ehsas2411@gmail.com

Rahul
Division of Agronomy
ICAR – Indian Agricultural Research Institute, Jodhpur Hub, India
rahuldhakad939@gmail.com

regions. MAS expedites breeding by identifying genetic markers linked to traits like drought, heat and salinity tolerance. CRISPR Cas9 facilitates precise genetic modifications, enhancing stress tolerance by manipulating water-use efficiency and stress response genes. Collectively, all these modern technologies provide solutions for the sustainable development of arid regions.

Keywords: arid; resource management; sustainability; ecological stability; innovative technologies

I. INTRODUCTION

The word "arid" comes from the Greek word "arere", which has the meaning "to be dry". Arid refers to a geographical area that receives minimal rainfall, typically less than 250 mm annually. This leads to sparse vegetation, making agriculture challenging and precarious human habitation. Geographers and climatologists define arid zones as regions where precipitation falls short of potential evapotranspiration rates. Arid regions face escalating natural resource scarcity, a situation expected to worsen due to climate change and human influences on weather patterns [1]. Arid regions encompass nearly 60.9 million sq. km., constituting nearly 41.3 per cent of the total land surface and providing home to over one-third of the global population (approximately 2.1 billion individuals). These lands provide essential ecosystem services for people's livelihoods. Based on aridity index arid regions are classified into four categories: hyper-arid, arid, semi-arid and dry subhumid. The primary distinction is drawn between deserts, which comprise hyper-arid and arid regions, and semi-deserts, which are semi-arid. Hyper-arid areas account for 6.6 per cent of global land area, whereas dry areas account for 10.6 per cent. Semi-arid areas cover all continents and account for 15.2 per cent of worldwide land surface, while dry sub-humid areas account for 8.7 per cent of the global land area [2].

India is home to the largest subtropical desert in the world, which spans 31.7 million hectares, accounting for 20 per cent of the country's land area. This desert is situated between 24° and 29° N latitude and 70° and 76° E longitude, with the majority located in Rajasthan (62 per cent). It also extends into Gujarat (19 per cent), Andhra Pradesh (10 per cent), as well as parts of Punjab and Haryana (9 per cent). The largest expanse is found in western Rajasthan, covering 19.62 million hectares, followed by northwestern Gujarat with 2.16 million hectares [3]. These areas have a high aridity index, frequent droughts, intense solar radiation, extreme temperature fluctuations, low and erratic precipitation, high wind speeds and dust storms. Additionally, they have poor soil fertility, high soil pH, high infiltration rates, limited groundwater resources, saline groundwater for irrigation and reduced biodiversity [4]. Desertification is the main challenge in arid areas, caused by wind erosion, water erosion, waterlogging and salinity. The degradation of permanent pastures has led to the depletion of fodder resources, constraining livestock farming, which has been an important aspect of the region's economy throughout history. In recent times, industrial waste and mining activities have also been contributing to desertification. Despite the harsh circumstances, the area supports an enormous human and livestock population, as well as varied array of animals and flora. However, the growing human and livestock populations and ongoing development activities are putting strain on the limited natural resources of the region.

Smart irrigation systems can save about 80 per cent of the water, which also aims at saving time and energy by automatically providing water and helping in water conservation [5]. Recent advances in weed control technologies, including cover crops, allelopathic weed control, genetically modified varieties, remote sensing and unmanned aerial vehicles (UAVs), have substantial impact on food production by reducing crop input requirements and minimizing negative environmental effects, steering us toward more sustainable agricultural systems [6]. As arid soils are characterized by poor soil fertility, the integrated approach to soil nutrient management, which includes crop rotation, enhancing soil organic content, and soil test-based fertility management, has an enormous impact on soil fertility and crop growth [7]. Land degradation poses a significant challenge in arid regions due to climate change and human activities, including over-exploitation, which leads to soil degradation. To address this issue, various management practices, such as developing shelter beds and windbreaks, implementing conservation agriculture and adopting agroforestry techniques can effectively combat soil degradation and improve soil productivity [8].

Developing new plant varieties with improved genotypic potential is necessary to tackle the agricultural issues in arid regions, it can be achieved by the help of biotechnological approaches. Marker-assisted selection (MAS) helps to develop drought-tolerant, salinity-tolerant and heat stress-tolerant varieties. It makes the process more efficient by making selections at the genetic level. This is done by using marker analysis [9]. Marker-assisted selection (MAS) in selection programs allows for accuracy in selecting DNA polymorphism of important traits. However, it cannot modify the DNA sequence for improvement [10]. Genome editing is a cutting-edge technique for improving plants with modification at the DNA level [11]. The genome editing technique is based on site-directed nucleases (SDNs), including mega-nucleases, Zinc-finger nucleases (ZFN), transcription activator like effector nucleases (TALEN) and clustered regularly interspaced short palindromic repeats (CRISPR)/CRISPR-associated (Cas) system [12]. Genome editing technology can modify DNA with precision, enabling us to make plants more adaptable to the harsh conditions of arid agriculture. Sustainable resource management practices are vital for addressing the challenges faced in the arid zone. By implementing innovative technologies and adopting conservation measures, it is possible to mitigate the effects of desertification, protect valuable resources, and ensure the long-term sustainability of this unique ecosystem.

II. SMART IRRIGATION

Water scarcity poses a significant challenge for farming in arid regions, primarily due to climate variability, inconsistent rainfall and elevated temperatures. Implementing a smart irrigation system can enhance water use efficiency and boost crop productivity in these areas [13] by supplying water in the appropriate amounts, at the right times and in targeted locations [14]. Such systems integrate hardware, software and firmware [15], all interconnected through various computational methodologies, including deep learning (DL) and artificial intelligence (AI) [16].

An automatic smart irrigation system uses field-based measurements, remote sensing and multiple sensory systems to monitor and control valves (Figure 1) and regulates the activation and deactivation of pumps within an irrigation control framework, which includes Android mobile applications [17] . Smart irrigation ensures precise water delivery at optimal intervals for crops, thereby enhancing water use efficiency (WUE), increasing yields, reducing fertilizer consumption, lowering labour expenses and conserving energy [18, 19]. Various monitoring systems are utilized to enhance the effectiveness of irrigation systems by tracking key climatic parameters such as precipitation, evapotranspiration, solar radiation, canopy and air temperature [20]. Smart irrigation systems have the potential to enhance crop yields and optimizing resource allocation by integrating data from diverse sources. These systems facilitate better decision-making by considering various factors, such as soil hydraulic properties, variations in soil and climate, plant responses to water stress and fluctuations in weather patterns [21,5]. This comprehensive approach ultimately leads to significant water savings and increased agricultural productivity [22, 23]. Smart irrigation is advocated as an effective strategy for managing soil variability and achieving economic benefits by addressing the irrigation requirements of specific crops [24]. Some notable smart irrigation technologies include:

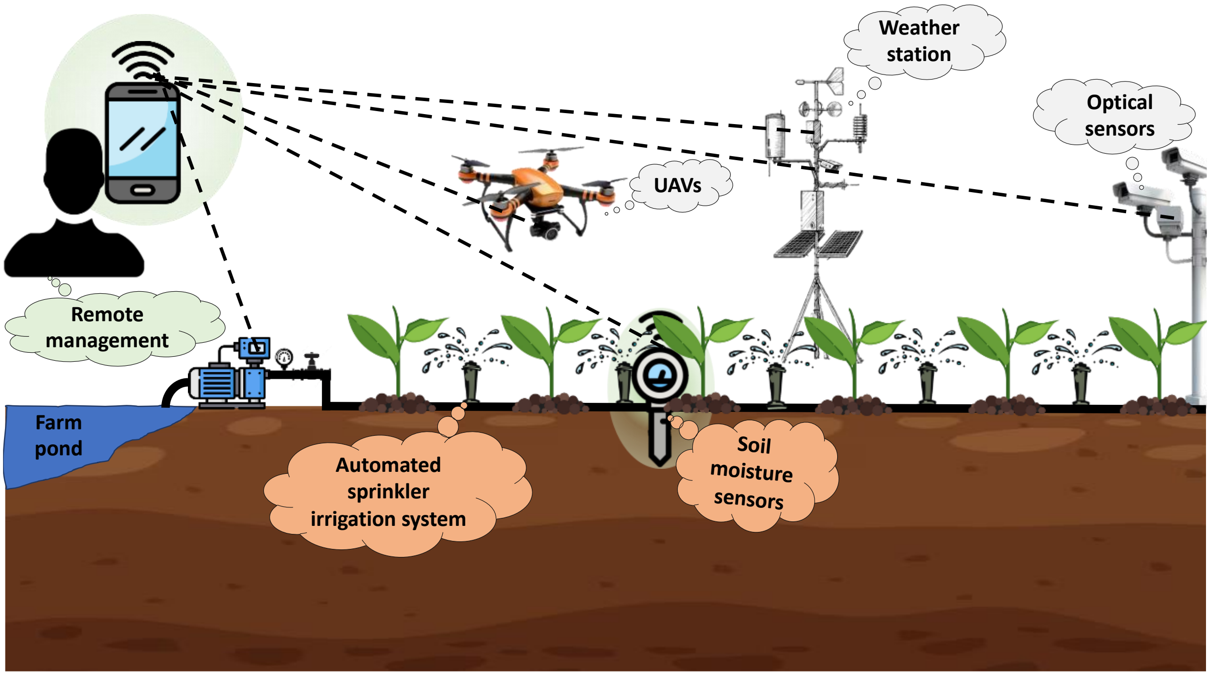

Figure 1: An overview of different components of the smart irrigation model.

- Model Predictive Irrigation Systems
- Smart drip irrigation using IoT
- Variable-Rate Irrigation (VRI)

The high cost of sophisticated smart irrigation devices poses challenges for farmers. Furthermore, tailor-made commercial smart irrigation systems create challenges in terms of control and adaptability. There is a need to develop user-friendly and affordable devices at the community level. In arid regions, numerous farmers lack formal education and would benefit from training through hands-on demonstrations of smart irrigation systems conducted by knowledgeable extension workers. In addition, governments should consider providing incentives to farmers to encourage the widespread adoption of such technologies.

III. MODERN WEED MANAGEMENT APPROACH

The primary focus of extensive tillage was primarily on weed management. However, nowadays, weed control relies more on herbicides. The repeated and frequent application of herbicides for managing weeds during fallow periods, pre-seeding and post-harvest has developed herbicide resistance in several species of weeds. The anticipated effects of climate change and rising CO_2 levels in the atmosphere are also expected to enhance the growth and photosynthesis of numerous weed species, consequently enhancing their competitiveness against crops [25, 26]. The effectiveness of various herbicides can be affected by environmental elements such as CO_2 levels, temperature, light, and relative humidity [27], [28]. Recent studies indicate that global warming may induce phenotypic and genetic shifts within weed populations, leading to higher risk of non-target-site herbicide resistance due to the metabolic adaptations of various weed species. For instance, the effectiveness of glyphosate was found to be reduced in weeds grown under high CO_2 levels [29]. Similarly, decreased efficacy has been observed for mesotrione on *A. palmeri*, while glyphosate has shown reduced effectiveness on *B. scoparia* and *C. album* and dicamba's impact on *B. scoparia* has also lessened with rising temperatures (30-40°C) [30, 31, 32]. The modern approach to controlling weed invasion employs various methods, including cover cropping, crop rotation, mulching, mechanical weeding, biological herbicides, genetic engineering, remote sensing and the use of UAVs *etc*. for precise herbicide application.

A. Cover cropping

Cover cropping to manage weeds is not a recent development. It involves using plant residue to conserve soil moisture, modify the soil microenvironment and affect the persistence of weed seeds[33, 34]. Cover crops can also reduce weed growth in semi-arid regions through their allelopathic properties[35]. However, it is important to thoroughly investigate the allelochemical characteristics, their release time, and their impact on germination and longevity of weed seed and soil microorganisms. Using cover crops to suppress weeds can reduce the need for herbicides and the risk of weed resistance [36]. This can improve the effectiveness of chemical control and increase revenue for growers by producing high-quality forage [37, 38, 39]. Cover crops help in reducing soil compaction, nutrient loss and erosion while enhancing nitrogen fixation [41], soil structure, and the protection of crop seedlings. They help conserve soil moisture by reducing evaporation from the soil surface [38, 33, 42].These factors significantly contribute to the economic viability and sustainability of semiarid agricultural systems.

Studying the effects of various cover crop management practices is essential. This includes selecting appropriate species, timing the planting and termination, utilizing suitable seeding rates and implementing effective termination techniques, which impact population dynamics. Research should also focus on seed mortality, dormancy, germination patterns, and emergence. It is also important to explore the other benefits of cover crops, such as allelopathy, the attraction of beneficial insects or pollinators, and the creation of habitats for weed seed predators. The primary goal is to develop more robust weed management systems that can slow the development of herbicide-resistant weeds. Long-term field studies should validate the key aspects of environmental sustainability and economic viability when incorporating cover crops into weed management in the region.

B. Allelopathic Weed Management

The allelopathic potential of crops can be used to reduce the competitiveness of resistant weeds. Selective breeding has been used to improve the allelopathic capabilities of crops, taking into account the genetic diversity found in cereals [35, 43]. Using traditional breeding methods, highly effective weed-suppressive rice varieties have been developed, such as the Kouket-sumochi and IR24 hybrids, which effectively suppress weeds like jungle rice and red rice [*Oryza sativa* L.]. Additionally, the recent enhancement of crops' allelopathic potential through genetic modification represents a significant advancement in agrobiotechnology.

C. Genetic Modification

The use of herbicide-tolerant crops, which account for 83% of genetically modified (GM) crops [44], is designed to endure herbicides such as imidazolinone, glufosinate, bromoxynil, glyphosate and dicamba [44, 45]. The introduction of these herbicide-tolerant varieties, including rice, sugar beet, corn, canola, alfalfa, brassica, cotton, and soybean, has transformed weed management practices in the United States, Canada, and several other countries [45, 46, 47]. While these advancements have notably enhanced weed control, there are concerns regarding the potential transfer of resistant genetic traits from these crops to related weed species.

D. Remote Sensing and UAVs

Site-specific weed management is a progressive approach to achieving proficient, cost-effective and environmentally sustainable weed control. Automated drones equipped with stationary high-resolution cameras are an effective modern approach for collecting data and controlling weeds [48]. The inherent advantages of these UAVs include their ability to maneuver at low altitudes, quick deployment, frequent high-resolution imaging capabilities, effectiveness in operating despite cloud cover, adaptable positioning options, and economic viability [49]. Collectively, these characteristics make UAVs practical tools for future automated weed management efforts [50, 51]. But, the effectiveness and economic viability of these systems in real-world conditions need to be studied through scientific research. Remote sensing is another modern technology that helps in decision-making and is used in agriculture to ensure precise management of inputs and to identify the presence of weeds [52]. It involves identifying weed patches, creating maps and promptly controlling them using machine vision while considering the economic feasibility (Figure 2) [53]. The variability in weed infestation across a space is the basis for implementing these systems. Weeds frequently establish concentrated patches in agricultural fields, making remote sensing an invaluable tool for minimizing herbicide usage and lowering production costs by improving the precision of herbicide application [54]. This technique utilizes the differential spectral reflectance between weeds and surrounding vegetation, such as crops, in conjunction with the spectral resolution of the instruments used [55]. These two elements are essential for effectively mapping weed distribution through remote sensing.

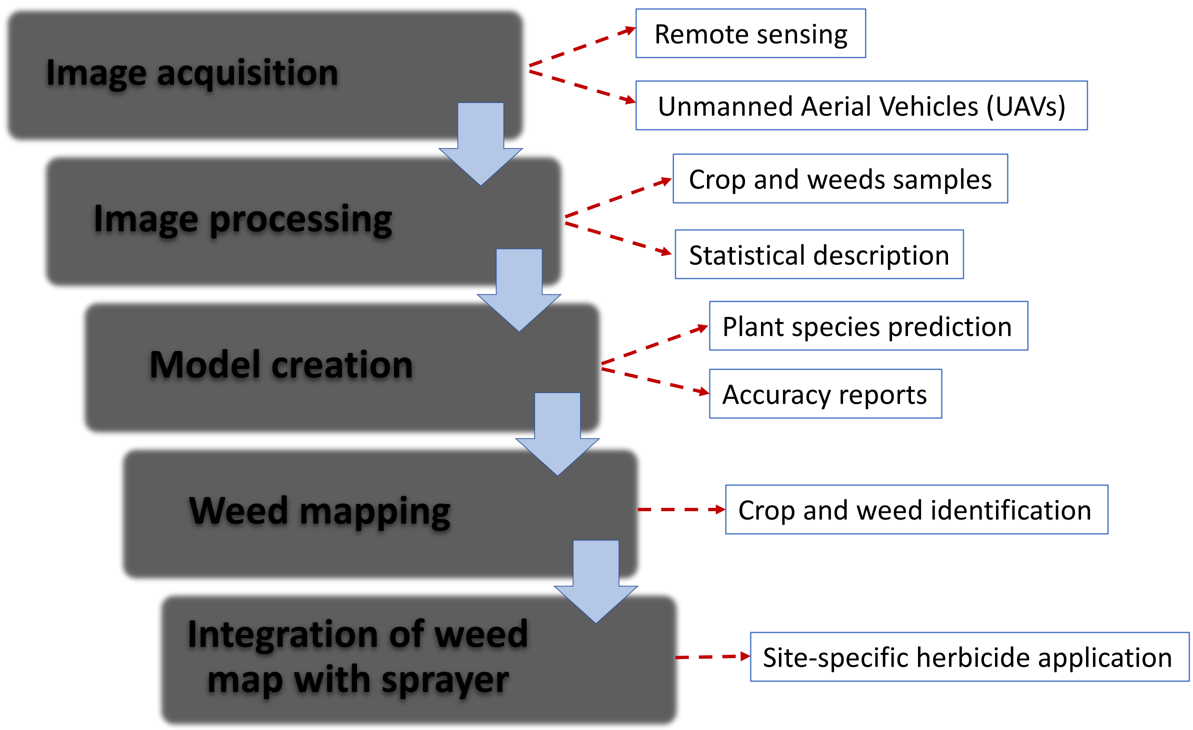

Figure 2: Site-specific weed management using Remote Sensing (RS) and UAVs.

In the modern agricultural era, achieving sustainable weed management requires the use of integrated strategies. These strategies may involve utilizing stacked gene crops in addition to a rotational application of herbicides to ensure effective weed control in various cropping systems.

IV. INTEGRATED NUTRIENT MANAGEMENT

The soils of arid zones are characteristically low in organic matter and most of the nutrient reserve is found in unweathered mineral forms. Nutrient adsorption and retention of these soils is very low due to the presence of clay and silt in lower quantities. These soils are also alkaline in nature with high pH values which contain higher amounts of soluble salts and calcium content [56]. The organic matter and humus content in arid soils tend to be lower due to sparse vegetation and increased decomposition rates caused by high temperatures. Therefore, it is essential to enhance soil organic content through the adoption of management practices such as applying farmyard manure and compost, cultivating green manure crops and implementing crop residue management techniques like mulching. These practices ultimately improve various soil characteristics, including organic content, nutrient levels, microbial activity and water retention capacity. The application of biofertilizers can complement chemical fertilizers as they play a vital role in maintaining soil fertility by enhancing nutrient availability, as well as providing antibiotics, hormones like auxins and cytokinins, and vitamins that enrich the root rhizosphere [57].

Soil test-based fertility management is another efficient method for enhancing the productivity of agricultural soils with significant geographical variability brought about by the interaction of physical, chemical and biological processes [7]. To balance the nutrient input and output in the root zone, real-time nutrient management tools such as LCC, SPAD, optical sensors, crop canopy spectrum, reflectance, GIS, *etc*. can be employed.

V. PROTECTIVE CULTIVATION

Protective cultivation is a cropping methodology aimed at optimizing production while conserving resources by modulating the microenvironment surrounding the plant throughout its growth cycle. This involves the use of modern structures such as poly-houses, screen houses, net houses and tunnels, as well as protective measures like windbreaks, irrigation and mulches to cultivate crops in a controlled environment and protect them from adverse weather conditions [58]. Protective cultivation finds significant application in arid and semi-arid regions, where it addresses challenges such as elevated temperatures, diminished soil fertility, limited biomass generation, prevalent strong winds, and intense solar irradiation [59, 60, 61]. One of the primary drivers for adopting protective cultivation in such regions is the pronounced scarcity of water resources. Protected cultivation offers a way around most of the problems associated with crop cultivation within arid environments [62]. It encompasses a spectrum of sustainable agricultural practices, including hydroponic cultivation, precision agriculture techniques, integrated pest management (IPM), integrated nutrient management (INM), utilization of grafted robust planting material, facilitation of high-quality seed production, and judicious utilization of water and other resources to mitigate the impacts of climate change and reduce greenhouse gas emission [63]. Moreover, the integration of high-tech agricultural methodologies facilitates heightened yield potentials within confined land areas, fosters avenues for entrepreneurial endeavors, and augments export opportunities.

As we face the compounding challenges of population growth, climate change, limited land availability, and increased demand for essential resources like land and water, along with rising consumer expectations for high-quality agricultural products, it is crucial to implement significant advancements in crop production technologies, especially in protected cultivation [64]. The integration of high tech in controlled environment agriculture, such as robotics artificial intelligence for fruit harvesting, precise fruit maturity detection, selective fruit picking, and the implementation of IoT or sensor-based irrigation scheduling, has the potential to improve the crop productivity and income of local farmers. Polyhouse structures enhance water and fertilizer usage efficiency, boost yields, produce quality, off-season production of high-value crops and the production of virus-free seedlings and hybrid seeds, resulting in higher income by faceting higher prices.

The state of Maharashtra is at the forefront of protected cultivation in India, followed by Karnataka and Himachal Pradesh. Other states engaged in protected cultivation include Punjab, Uttarakhand, Haryana, Uttar Pradesh, Gujarat, Rajasthan, Jharkhand, Jammu & Kashmir, Delhi, West Bengal, Orissa, Bihar, and Madhya Pradesh (GOI 2018) [65]. Farmers typically cultivate roses, gerbera, and carnations as flowers, and capsicum, tomato, and cucumber as vegetable crops. However, protected cultivation in India is still in its early stages, with only 0.2 per cent penetration, significantly lower compared to the Netherlands, Turkey, and Israel. In the arid and semi-arid regions of India, the adoption of protective cultivation faces several challenges. These include high initial investment costs, lack of awareness, limited access to subsidies, high wages for skilled labour, expensive transportation, inadequate local marketing facilities, insufficient supply chain management, and market price fluctuations [66, 58]. Due to the capital-intensive nature of this technology, there is a concern that only large, educated, and progressive farmers will adopt it [67]. To address this issue, substantial subsidies and quotas are being allocated to small and marginal farmers to encourage the widespread adoption of protective cultivation. Additionally, financial and marketing support is being provided to ensure better quality input supply and maximize earnings from agricultural produce. Both central and state governments have implemented various programs and schemes aimed at fostering and advancing protective cultivation, with the National Horticulture Mission (NHM) being a key initiative. Through this program, farmers are eligible for 50 per cent subsidy on the establishment of protective cultivation structures and 50 per cent subsidy on planting materials of flowers and vegetables cultivated under protective structures.

VI. LAND DEGRADATION

Land degradation can be defined as a piece of land losing its ability to produce due to factors including soil erosion caused by wind and water, humus loss, nitrogen depletion, secondary salinization, dilution and deterioration of the plant cover, and biodiversity loss. In addition, it results in a decline in the productivity of land in terms of economy and biodiversity, which is caused by several factors such as climate change and human dominance, which destroys ecosystems. The area under land degradation in India was about 97.85 million ha which is 29.77% of the total geographical area of the country [68]. The extent of land degradation is vast, occupying over 23% of the Earth's landmass, increasing at a rate of 5-10 million hectares per year and impacting roughly 1.5 billion people worldwide. To avert such harmful processes, comprehensive and immediate effort is required to prevent land degradation [8]. Land degradation neutrality (LDN) is one of the sustainable development goals among 17 goals which was adopted by the UN General Assembly in September 2015 which demands that nations promote sustainable use of the ecosystem, combat desertification and reduce the loss of biodiversity and land degradation. The main aim of LDN is to maintain the land resources base so that it can continue to provide ecosystem services while enhancing the resilience of the communities that rely on the land. By 2030, India hopes to repair 26 million hectares of degraded land [69].

Many different approaches can be used to restore land degradation, depending on its type, degree, and nature. Most types of land degradation are recoverable with the addition of organic matter, soil additives to improve the topsoil and cover crops and green manure to encourage the growth of new vegetation. It requires accurate, evaluated and scientifically proven technologies and methodologies for sustainable land management that combine the ecological, economic and social aspects of land use to avoid and address current land degradation. Soil conservation techniques which include contour ploughing, strip cropping, cover crops, mulching, bunding and terracing aid in mitigating soil erosion. Minimum tillage which is part of conservation agriculture can help in the conservation of soil resources by reducing soil erosion, improving soil health, increasing crop yield, promoting environmental sustainability and contributing to soil carbon sequestration [70]. In the long run, afforestation activities contribute to ecological restoration and the mitigation of climate change in addition to improving the condition of the soil by carbon sequestration, water regulation, nutrient cycling and soil erosion control. In the age of climate change, increased ecological stability and sustainability are ensured by afforestation and sustainable forest management (SFM) techniques on degraded land. Therefore, in degraded and wasteland areas, including problem soils like saline, waterlogged, marshy, coastal, and sandy land, afforestation activities must be implemented. Improved scientific afforestation techniques, reinforced by SFM techniques, can help remediate problematic soil [71].

Planting windbreaks and shelterbelts along the boundaries is necessary to reduce wind velocity and decrease wind erosion. The best planting arrangement is a row of trees and shrubs across the direction of the wind. On the leeward side, it reduces wind speed by 60–80%. The amount of protection offered to the soil depends on the height of a tall tree and the length of the windbreak. On the windward side, windbreaks and shelterbelts offer protection from desiccating winds up to five to ten times the height of a tall tree, and up to thirty times on the leeward side [72]. Agro-forestry has been suggested as one of the viable solutions for land degradation because of its positive influences on soil fertility, mainly due to tree components. The inclusion of suitable and desirable species of trees in agroforestry can result in significant improvement in soil fertility by enhancing the organic matter content of the soil, which stimulates the activity of micro-organisms in the root zone, improving efficient nutrient cycling within the systems and reducing soil erosion [73]. Currently, GIS and remote sensing are employed to study the different sources of land degradation as these technologies are effective and profitable for assessing spatial distribution, land cover dynamics and investigating land degradation [69].

VII. MARKER-ASSISTED SELECTION

Arid regions, characterized by limited precipitation and harsh environmental conditions, present unique challenges for agricultural practices and research. High solar radiation, low moisture availability and soil salinity are major constraints for plant growth and development in arid agriculture. Marker-assisted selection (MAS) is a technique in plant breeding that uses morphological, biochemical, or DNA markers to select agriculturally significant characteristics indirectly. This approach improves the effectiveness of selection for the characteristics of interest in breeding programs [74]. Molecular markers are utilized to generate genetic marker maps. With data from the map position of desirable characteristics linked to genetic markers, the MAS facilitates the enhancement of targeted traits in crops. However, the success of MAS depends upon the desired trait's genetic information and its correlation with a molecular marker [75].

Molecular markers have some advanced benefits: low cost, easy selection and generation advancement. The rapid advancements in genetic research, combined with the widespread accessibility of sequenced genomes due to decreasing costs associated with second and third-generation sequencing techniques, have resulted in a wealth of molecular markers. Marker-assisted selection (MAS) is gaining prominence as it improves the efficiency of plant breeding by allowing for the targeted transfer of specific genomic regions of interest and expediting the recovery of genome segments that harbor desirable traits [76]. A single locus controlling a trait of interest can be introduced precisely and effectively using MABC, all while maintaining essential characteristics of the RP [77]. The technique known as MABC involves the use of markers to minimize the length of the donor segment that contains a target locus, select target loci, and/or speed up the recovery of the RP genome during backcrossing [78, 79]. The desired result is an enhanced line that contains only the desired gene from the donor parent, with the recipient parent line existing across the entire genome. Reducing the number of backcrosses needed to recover the RP phenotype was one of the early advantages of using molecular markers in plants to speed up the backcrossing process (Figure 3) [80].

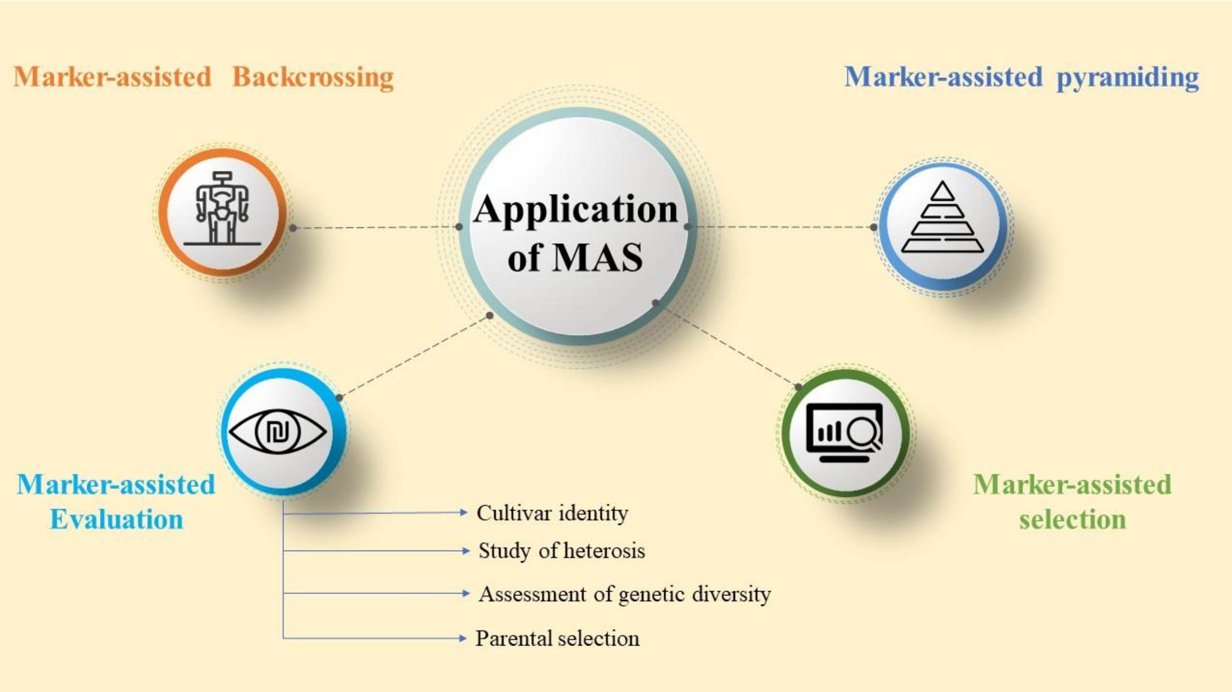

Figure 3: Applications of Marker Assisted Selection (AMS).

Gene pyramiding is the process of integrating two or more genes from various parental lines into a single genotype, which allows for the expression of multiple genes that confer resistance to both abiotic and biotic stresses. The success of gene pyramiding is influenced by several factors, including the number of genes being transferred, the diversity of gene and flanking markers, the number of selected populations in each breeding generation, the specific characteristics of the genes and germplasm involved, and the breeders' proficiency in accurately identifying the target genes. Gene pyramiding has become more accurate and dependable for the creation of stress-tolerant cultivars due to marker-assisted approaches [81].

VIII. CRISPR TECHNOLOGY IN ARID AGRICULTURE

Crop improvement focuses on enhancing crop yield, resistance to biotic and abiotic stresses, quality, and nutritional value. Consequently, scientists and breeders have shifted their emphasis from merely increasing production to improving quality. The combination of speed breeding, genomic-assisted breeding, and advanced genome editing tools has enabled the rapid manipulation and generation of multiple crop cycles, significantly accelerating the plant breeding process, especially in arid regions of the globe.

Recently, genome editing (GE) technology has been found to offer precise modifications to plant genomes. GE can induce predictable and inheritable mutations at specific genome sites with minimal off-target effects and no integration of foreign genes. GE-mediated DNA modifications include deletions, insertions, single-nucleotide substitutions (SNPs), and large fragment substitutions. Four site-directed nucleases (SDN) families are integral to this process: homing endonucleases (HEs), Zinc-Finger Nucleases (ZFNs), Transcription Activator-Like Effector Nucleases (TALENs), and CRISPR-associated proteins (Cas). These nucleases typically create double-strand breaks (DSBs) in DNA, which are repaired by the plant's endogenous systems through nonhomologous end joining (NHEJ) or homologous-directed recombination (HDR). NHEJ often introduces small indels around the cleavage site, while HDR uses homologous sequences or exogenous templates for precise repair, enabling large insertions or fragment replacements.

ZFNs and TALENs were successful, nonetheless, the main obstacles facing researchers and manufacturers were the complexity, cost, and duration of protein engineering. 2012 saw the discovery by J Doudna and E Charpentier that, with the correct template, CRISPR/Cas-9 could modify any desired DNA [82]. This second-generation genome editing technology is easier to design, and execute and more cost-effective. CRISPR remains the most effective genome editing technology across all fields as of right now.

A. Background

The unique arrangement of short, partially repeated DNA sequences found in prokaryotic genomes is referred to as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeat). In prokaryotes, CRISPR, along with the associated protein Cas-9, serves as an adaptive defense mechanism against viruses and bacteriophages [83, 84]. In 1987, Japanese scientist Ishino and his colleagues unexpectedly uncovered these distinctive repeating palindromic DNA sequences interspersed with spacers while studying a gene for alkaline phosphatase in Escherichia coli, leading to the identification of CRISPR. However, the true potential of this discovery became evident in 2012 when J. Doudna and E. Charpentier demonstrated that CRISPR/Cas-9 could be harnessed to modify any DNA sequence with remarkable precision.

The distinctive arrangement of short, partly repeated DNA sequences present in prokaryote genomes is known as CRISPR (Clustered Regularly Interspaced Short Palindromic Repeat). In prokaryotes, CRISPR and the protein it is linked with (Cas-9) provide an adaptive defense mechanism against viruses or bacteriophages [83, 84]. Ishino, a Japanese scientist, and his colleagues were studying a gene for alkaline phosphatase when they unintentionally discovered peculiar repeating palindromic DNA sequences broken up by spacers in Escherichia coli. This led to the discovery of CRISPR in 1987. But its real caliber could be understood in 2012 when J Doudna and E Charpentier discovered that CRISPR/Cas-9 could be utilized to modify any desired DNA with utmost precision.

B. Components of CRISPR Cas

The CRISPR/Cas system can be classified into Class I (types I, III, and IV) and Class II (types II, V, and VI) based on the structures and functions of their respective Cas proteins. Class II systems utilize a single Cas protein, while Class I systems consist of multi-subunit Cas protein complexes. Among them, the Type II CRISPR/Cas-9 system has been extensively studied and applied in genetic engineering due to its relatively straightforward structure. The two fundamental components of the CRISPR/Cas-9 system are guide RNA (gRNA) and CRISPR-associated (Cas-9) proteins. Cas-9 is categorized as a genetic endonuclease and features a large, multi-domain structure that cleaves target DNA to create a double-strand break.

The Cas9 protein is composed of two primary sections: the nuclease (NUC) lobe and the recognition (REC) lobe. The NUC lobe consists of the RuvC and HNH domains, which are responsible for cleaving each single-stranded DNA strand, as well as the domain that interacts with the protospacer adjacent motif (PAM), providing PAM specificity and initiating the binding process to the target DNA [85, 86]. In contrast, the REC lobe is comprised of the REC_1 and REC_2 domains, which engage with guide RNA. Guide RNA is made up of two essential components: CRISPR RNA (crRNA) and trans-activating CRISPR RNA (tracr-RNA). The tracr-RNA serves as a long loop that acts as a binding scaffold for the Cas9 nuclease, while the crRNA is a 16 to 20 base pair sequence that identifies the target DNA by pairing with the corresponding target sequence. In prokaryotes, the role of guide RNA is to specifically target viral DNA. However, in gene editing applications, it can be synthetically designed to target nearly any desired gene sequence by combining tracr-RNA and crRNA to create a single guide RNA (sgRNA) [85].

C. Mechanism of CRISPR/ Cas 9

The mechanism is generally divided into three steps (figure 4):

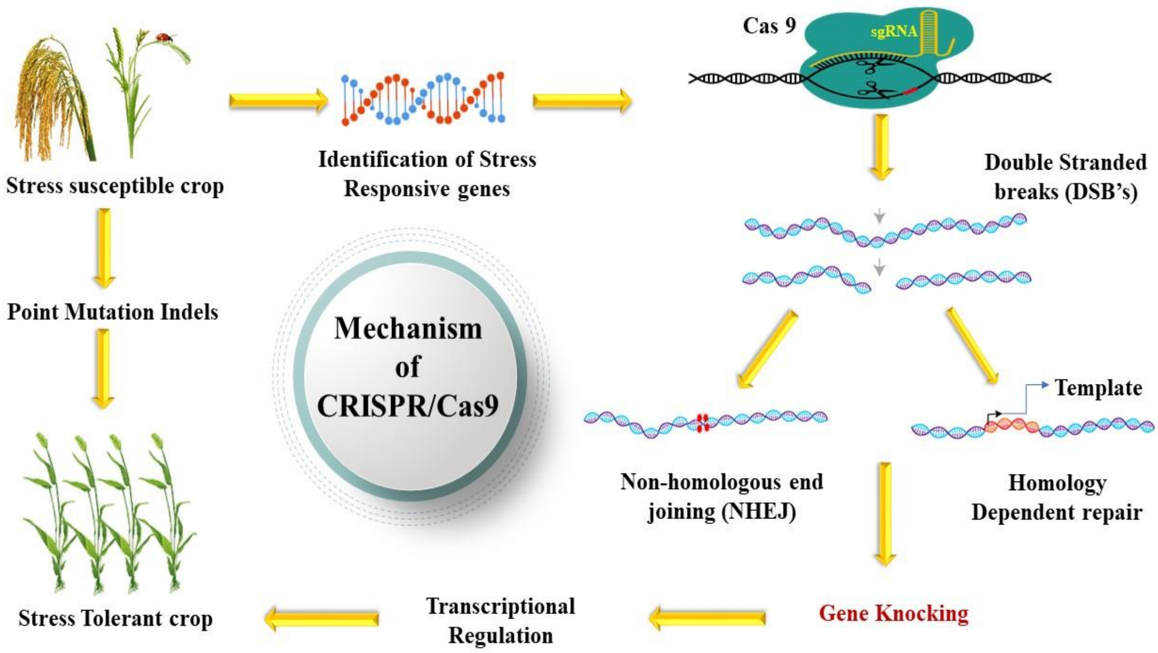

Figure 4: Mechanism of CRISPR Cas9.

1. **Recognition:** The Cas9 protein remains inactive without sgRNA; thus, the designed sgRNA directs Cas9 to recognize the target sequence in the gene of interest through its 5' crRNA complementary base pair component [87].

2. **Cleavage:** Double-strand breaks (DSBs) are induced by the Cas9 nuclease at a position three base pairs upstream of the protospacer adjacent motif (PAM). The PAM sequence is a conserved region of the DNA located downstream of the cleavage site, typically comprising 3-5 base pairs. Cas9 recognizes the PAM sequence in the form of 5′-NGG-3′. Upon identifying the target site with the appropriate PAM, Cas9 initiates local DNA melting, followed by the formation of an RNA-DNA hybrid. This process activates the Cas9 protein for DNA cleavage. The HNH domain is responsible for cleaving the complementary strand, while the RuvC domain cleaves the non-complementary strand, resulting in the formation of predominantly blunt-ended DSBs [88, 89].

3. **Repair:** Double-stranded break repair mechanisms generally follow two types of pathways: *i.e.,* Non-homologous end joining (NHEJ) and homology-directed repair (HDR).

In the absence of homologous DNA from external sources, non-homologous end joining (NHEJ) enzymatically ligates DNA fragments to repair double-strand breaks (DSBs). NHEJ is active throughout the entire cell cycle and serves as the primary and most efficient cellular repair mechanism. However, it is prone to errors that can lead to premature stop codons or frameshift mutations due to small random insertions or deletions (indels) occurring at the site of cleavage. In contrast, homologous recombination (HR) is highly accurate and requires a homologous DNA template. This mechanism is most active during the late synthesis and G_2 phases of the cell cycle. HR performs precise gene insertion or replacement by utilizing a donor DNA template that shares sequence homology with the designated DSB location [90], [91].

D. Applications of CRISPR Cas in Arid Agriculture

1. **Gene Editing for Drought Resistance:** By targeting genes involved in water use efficiency and root growth, certain crops that maintain productivity with less water can be developed.

2. **ABA Pathway Modification:** Abscisic acid (ABA) is a plant hormone that plays a crucial role in drought response. CRISPR can modify ABA-related genes to enhance drought resistance.

3. **Heat Stress Resistance:** By editing genes that help plants manage heat shock proteins, the ability of crops to survive and produce yields under high temperatures can be enhanced [92].

4. **Salt Tolerance Genes:** In arid regions, soil salinity can be a significant problem. CRISPR-Cas can be used to develop crops that are more tolerant to high salt levels by editing genes responsible for salt stress responses. Modifying genes involved in ion transport and sequestration can help plants manage high-salinity environments better [92].

5. **Biotic Stress Resistance:** Arid environments make crop plants more susceptible to pests and diseases. By targeting and editing genes involved in the plant's immune response crop losses due to such causes can be reduced [92].

6. **Nitrogen and Phosphorus Use Efficiency**: Since soil nutrient levels are low in arid lands CRISPR-Cas can improve nutrient uptake and use efficiency by targeting genes involved in nutrient transport and metabolism and also enhances the efficiency of symbiotic relationships between plants and nitrogen-fixing bacteria or mycorrhizal fungi can improve nutrient acquisition in poor soils.

IX. CONCLUSIONS

To address the challenges of the arid zone, sustainable resource management practices need to be implemented. One such practice is smart irrigation, which involves the use of advanced techniques such as high-tech soil moisture sensors, IoT, artificial intelligence, machine learning, drip irrigation and sprinklers to ensure efficient water use and minimize water loss through evaporation. This not only helps in conserving water but also prevents soil erosion caused by excessive irrigation. Effective weed management is another important aspect of sustainable resource management in the arid zone. Weeds compete with cultivated crops and natural vegetation for nutrients, water, sunlight and other resources leading to reduced crop productivity. Adopting integrated weed management strategies, which include the use of manual removal, cover cropping, crop rotation, allelopathy, bioherbicides, robotics, UAVs, genetic engineering and herbicides, can help in controlling weed growth and protecting valuable resources. Balanced fertilization by using organic fertilizers, crop rotation, biofertilizers, crop residue management and foliar nutrition also improves soil fertility and productivity in the arid zone. These practices help replenish soil nutrients and prevent nutrient imbalances that can lead to crop failure. Furthermore, land and water conservation measures are important components of sustainable resource management in the arid zone. Implementing measures like contour ploughing, terracing and afforestation helps to reduce soil erosion and water runoff. Constructing check dams and reservoirs can also aid in water conservation and recharge groundwater resources.

Biotechnological approaches, such as MAS and CRISPR also help in arid agriculture by improving plants to withstand the challenges of an arid climate. In marker-assisted breeding, a plant is chosen early in its development for participation in a breeding program based on DNA markers linked to desired qualities. This method greatly reduces the time needed to find varieties in a breeding program that express the desired characteristics. Clustered regularly interspaced short palindromic repeats associated with Cas endonuclease (CRISPR/Cas) genome editing emerged as a cutting-edge technique for accurate and efficient genetic modification of plant genomes. To identify and modify genes linked to stresses that are produced in an arid agricultural climate, CRISPR genome editing techniques are employed. Through the insertion of several gene types via CRISPR, plants can be made more resilient to stress by expressing more stress proteins and antioxidant enzymes.

REFERENCES

[1] R. Ray *et al.*, "Extreme rainfall deficits were not the cause of recurring colonial era famines of southern Indian semi-arid regions," *Sci. Rep.*, vol. 11, no. 1, p. 17568, Sep. 2021, doi: 10.1038/s41598-021-96826-2.

[2] "2010–2020: UN Decade for Deserts and the Fight against Desertification." Accessed: May 28, 2024. [Online]. Available: https://www.un.org/en/events/desertification_decade/whynow.shtml#

[3] M. Gaur and V. Squires, "Geographic Extent and Characteristics of the World's Arid Zones and Their Peoples," in *Climate Variability Impacts on Land Use and Livelihoods in Drylands*, 2018, pp. 3–20. doi: 10.1007/978-3-319-56681-8_1.

[4] "Special Report on Climate Change and Land — IPCC site." Accessed: May 28, 2024. [Online]. Available: https://www.ipcc.ch/srccl/

[5] E. A. Abioye *et al.*, "A review on monitoring and advanced control strategies for precision irrigation," *Comput. Electron. Agric.*, vol. 173, p. 105441, Jun. 2020, doi: 10.1016/j.compag.2020.105441.

[6] A. Monteiro and S. Santos, "Sustainable Approach to Weed Management: The Role of Precision Weed Management," *Agronomy*, vol. 12, p. 118, Jan. 2022, doi: 10.3390/agronomy12010118.

[7] K. Majumdar, "Current Nutrient Management Approaches: Issues and Strategies," *Indian J. Fertil.*, vol. 10, pp. 14–27, May 2014.

[8] I. Stavi and R. Lal, "Achieving Zero Net Land Degradation: Challenges and opportunities," *J. Arid Environ.*, vol. 112, pp. 44–51, Jan. 2015, doi: 10.1016/j.jaridenv.2014.01.016.

[9] B. C. Y. Collard and D. J. Mackill, "Marker-assisted selection: an approach for precision plant breeding in the twenty-first century," *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 363, no. 1491, pp. 557–572, Aug. 2007, doi: 10.1098/rstb.2007.2170.

[10] S. Pandurangan, C. Workman, K. Nilsen, and S. Kumar, "Introduction to Marker-Assisted Selection in Wheat Breeding," in *Accelerated Breeding of Cereal Crops*, A. Bilichak and J. D. Laurie, Eds., New York, NY: Springer US, 2022, pp. 77–117. doi: 10.1007/978-1-0716-1526-3_3.

[11] K. Chen, Y. Wang, R. Zhang, H. Zhang, and C. Gao, "CRISPR/Cas Genome Editing and Precision Plant Breeding in Agriculture," *Annu. Rev. Plant Biol.*, vol. 70, no. Volume 70, 2019, pp. 667–697, Apr. 2019, doi: 10.1146/annurev-arplant-050718-100049.

[12] T. Gaj, C. A. Gersbach, and C. F. Barbas, "ZFN, TALEN, and CRISPR/Cas-based methods for genome engineering," *Trends Biotechnol.*, vol. 31, no. 7, pp. 397–405, Jul. 2013, doi: 10.1016/j.tibtech.2013.04.004.

[13] Z. F. Fawzy and S. I. Shedeed, "Climate Smart Agriculture and Intelligent Irrigation System for Management of Water Resources in Arid and Semi-Arid Regions – A Review," in *Water, Flood Management and Water Security Under a Changing Climate: Proceedings from the 7th International Conference on Water and Flood Management*, A. Haque and A. I. A. Chowdhury, Eds., Cham: Springer International Publishing, 2020, pp. 361–370. doi: 10.1007/978-3-030-47786-8_25.

[14] D. Gurjar, "Precision irrigation management: concepts and applications for higher use efficiency in field crops," 2019, p. 286.

[15] J. Neupane and W. Guo, "Agronomic Basis and Strategies for Precision Water Management: A Review," *Agronomy*, vol. 9, no. 2, Art. no. 2, Feb. 2019, doi: 10.3390/agronomy9020087.

[16] D. Bhavsar, B. Limbasia, Y. Mori, M. Imtiyazali Aglodiya, and M. Shah, "A comprehensive and systematic study in smart drip and sprinkler irrigation systems," *Smart Agric. Technol.*, vol. 5, p. 100303, Oct. 2023, doi: 10.1016/j.atech.2023.100303.

[17] "Zhu et al. - 2018 - Review of intelligent sprinkler irrigation technol.pdf." Accessed: May 28, 2024. [Online]. Available: https://pdfs.semanticscholar.org/020f/2b794db55686ce896c74fbb321a054be567c.pdf

[18] N. Sales, O. Remédios, and A. Arsenio, "Wireless sensor and actuator system for smart irrigation on the cloud," in *2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, Dec. 2015, pp. 693–698. doi: 10.1109/WF-IoT.2015.7389138.

[19] H. M. Al-Ghobari, F. S. Mohammad, and M. S. A. E. Marazky, "Assessment of smart irrigation controllers under subsurface and drip-irrigation systems for tomato yield in arid regions," *Crop Pasture Sci.*, vol. 66, no. 10, pp. 1086–1095, Sep. 2015, doi: 10.1071/CP15065.

[20] G. Bitella, R. Rossi, R. Bochicchio, M. Perniola, and M. Amato, "A Novel Low-Cost Open-Hardware Platform for Monitoring Soil Water Content and Multiple Soil-Air-Vegetation Parameters," *Sensors*, vol. 14, no. 10, Art. no. 10, Oct. 2014, doi: 10.3390/s141019639.

[21] L. García, L. Parra, J. M. Jimenez, J. Lloret, and P. Lorenz, "IoT-Based Smart Irrigation Systems: An Overview on the Recent Trends on Sensors and IoT Systems for Irrigation in Precision Agriculture," *Sensors*, vol. 20, no. 4, Art. no. 4, Jan. 2020, doi: 10.3390/s20041042.

[22] A. Yari, C. Madramootoo, S. Woods, and V. Adamchuk, "Performance Evaluation of Constant Versus Variable Rate Irrigation: Variable Rate Irrigation," *Irrig. Drain.*, vol. 66, Mar. 2017, doi: 10.1002/ird.2131.

[23] "Sensors | Free Full-Text | Smart System for Bicarbonate Control in Irrigation for Hydroponic Precision Farming." Accessed: May 28, 2024. [Online]. Available: https://www.mdpi.com/1424-8220/18/5/1333

[24] B. Boman, S. Smith, and B. Tullos, "Control and Automation in Citrus Microirrigation Systems," *EDIS*, vol. 2002, no. 1, Dec. 1969, doi: 10.32473/edis-ch194-2002.

[25] P. Waryszak, T. I. Lenz, M. R. Leishman, and P. O. Downey, "Herbicide effectiveness in controlling invasive plants under elevated CO2: Sufficient evidence to rethink weeds management," *J. Environ. Manage.*, vol. 226, pp. 400–407, Nov. 2018, doi: 10.1016/j.jenvman.2018.08.050.

[26] B. A. Bradley, D. M. Blumenthal, D. S. Wilcove, and L. H. Ziska, "Predicting plant invasions in an era of global change," *Trends Ecol. Evol.*, vol. 25, no. 5, pp. 310–318, May 2010, doi: 10.1016/j.tree.2009.12.003.

[27] "Indicators of climate change in agricultural systems | Climatic Change." Accessed: May 28, 2024. [Online]. Available: https://link.springer.com/article/10.1007/s10584-018-2222-2

[28] A. Varanasi, P. V. V. Prasad, and M. Jugulam, "Chapter Three - Impact of Climate Change Factors on Weeds and Herbicide Efficacy," in *Advances in Agronomy*, vol. 135, D. L. Sparks, Ed., in Advances in Agronomy, vol. 135. , Academic Press, 2016, pp. 107–146. doi: 10.1016/bs.agron.2015.09.002.

[29] N. G. Koleva and U. A. Schneider, "The impact of climate change on the external cost of pesticide applications in US agriculture," *Int. J. Agric. Sustain.*, vol. 7, no. 3, pp. 203–216, Aug. 2009, doi: 10.3763/ijas.2009.0459.

[30] R. D. DeGreeff, A. V. Varanasi, J. A. Dille, D. E. Peterson, and M. Jugulam, "Influence of Plant Growth Stage and Temperature on Glyphosate Efficacy in Common Lambsquarters (Chenopodium album)," *Weed Technol.*, vol. 32, no. 4, pp. 448–453, Aug. 2018, doi: 10.1017/wet.2018.38.

[31] A. S. Godar, V. K. Varanasi, S. Nakka, P. V. V. Prasad, C. R. Thompson, and J. Mithila, "Physiological and Molecular Mechanisms of Differential Sensitivity of Palmer Amaranth (Amaranthus palmeri) to Mesotrione at Varying Growth Temperatures," *Plos One*, vol. 10, no. 5, p. e0126731, May 2015, doi: 10.1371/journal.pone.0126731.

[32] J. Ou, C. R. Thompson, P. W. Stahlman, N. Bloedow, and M. Jugulam, "Reduced Translocation of Glyphosate and Dicamba in Combination Contributes to Poor Control of Kochia scoparia: Evidence of Herbicide Antagonism," *Sci. Rep.*, vol. 8, no. 1, p. 5330, Mar. 2018, doi: 10.1038/s41598-018-23742-3.

[33] B. Baraibar, M. C. Hunter, M. E. Schipanski, A. Hamilton, and D. A. Mortensen, "Weed Suppression in Cover Crop Monocultures and Mixtures," *Weed Sci.*, vol. 66, no. 1, pp. 121–133, Jan. 2018, doi: 10.1017/wsc.2017.59.

[34] A. Lawson, C. Cogger, A. Bary, and A.-M. Fortuna, "Influence of Seeding Ratio, Planting Date, and Termination Date on Rye-Hairy Vetch Cover Crop Mixture Performance under Organic Management," *PLOS ONE*, vol. 10, no. 6, p. e0129597, Jun. 2015, doi: 10.1371/journal.pone.0129597.

[35] H. P. Singh, D. R. Batish, and R. K. Kohli, "Allelopathic Interactions and Allelochemicals: New Possibilities for Sustainable Weed Management," *Crit. Rev. Plant Sci.*, vol. 22, no. 3–4, p. 239, 2003.

[36] "Cover crops and weed suppression in the U.S. Midwest: A meta-analysis and modeling study - Nichols - 2020 - Agricultural & Environmental Letters - Wiley Online Library." Accessed: May 28, 2024. [Online]. Available: https://acsess.onlinelibrary.wiley.com/doi/full/10.1002/ael2.20022

[37] A. Franzluebbers and J. Stuedemann, "Crop and cattle responses to tillage systems for integrated crop-livestock production in the Southern Piedmont, USA," *Renew. Agric. Food Syst.*, vol. 22, Sep. 2007, doi: 10.1017/S1742170507001706.

[38] H. Blanco-Canqui *et al.*, "Cover Crops and Ecosystem Services: Insights from Studies in Temperate Soils," *Agron. J.*, vol. 107, no. 6, pp. 2449–2474, Nov. 2015, doi: 10.2134/agronj15.0086.

[39] "Managing Spring Planted Cover Crops for Livestock Grazing under Dryland Conditions in the High Plains Region - 0.309," Extension. Accessed: May 28, 2024. [Online]. Available: https://extension.colostate.edu/topic-areas/agriculture/managing-spring-planted-cover-crops-for-livestock-grazing-under-dryland-conditions-in-the-high-plains-region-0-309/

[40] G. Chen and R. Weil, "Penetration of cover crop roots through compacted soil," *Plant Soil*, vol. 331, pp. 31–43, Jun. 2010, doi: 10.1007/s11104-009-0223-7.

[41] C. M. White *et al.*, "Managing the trade off between nitrogen supply and retention with cover crop mixtures," *Agric. Ecosyst. Environ.*, vol. 237, pp. 121–133, Jan. 2017, doi: 10.1016/j.agee.2016.12.016.
[42] J. R. Teasdale and S. B. Mirsky, "Tillage and Planting Date Effects on Weed Dormancy, Emergence, and Early Growth in Organic Corn," *Weed Sci.*, vol. 63, no. 2, pp. 477–490, Jun. 2015, doi: 10.1614/WS-D-14-00112.1.
[43] "Manipulation of Allelopathic Crops for Weed Control | SpringerLink." Accessed: May 28, 2024. [Online]. Available: https://link.springer.com/book/10.1007/978-3-319-53186-1
[44] A. A. Bajwa, G. Mahajan, and B. S. Chauhan, "Nonconventional Weed Management Strategies for Modern Agriculture," *Weed Sci.*, vol. 63, no. 4, pp. 723–747, Dec. 2015, doi: 10.1614/WS-D-15-00064.1.
[45] H. J. Beckie *et al.*, "A decade of herbicide-resistant crops in Canada," *Can. J. Plant Sci.*, vol. 86, no. 4, pp. 1243–1264, Oct. 2006, doi: 10.4141/P05-193.
[46] S. O. Duke and S. B. Powles, "Glyphosate-Resistant Crops and Weeds : Now and in the Future," *Httpwwwagbioforummissourieduv12n34v12n34a10-Dukehtm*, 2009, Accessed: May 29, 2024. [Online]. Available: https://mospace.umsystem.edu/xmlui/handle/10355/6923
[47] W. A. Givens *et al.*, "Survey of Tillage Trends Following the Adoption of Glyphosate-Resistant Crops," *Weed Technol.*, vol. 23, no. 1, pp. 150–155, Mar. 2009, doi: 10.1614/WT-08-038.1.
[48] J. M. Peña, J. Torres-Sánchez, A. I. de Castro, M. Kelly, and F. López-Granados, "Weed Mapping in Early-Season Maize Fields Using Object-Based Analysis of Unmanned Aerial Vehicle (UAV) Images," *PLoS ONE*, vol. 8, p. e77151, Oct. 2013, doi: 10.1371/journal.pone.0077151.
[49] K. Anderson and K. J. Gaston, "138 Lightweight unmanned aerial vehicles will".
[50] C. Zhang and J. M. Kovacs, "The application of small unmanned aerial systems for precision agriculture: a review," *Precis. Agric.*, vol. 13, no. 6, pp. 693–712, Jul. 2012, doi: 10.1007/s11119-012-9274-5.
[51] J. Torres-Sánchez, F. López-Granados, A. I. D. Castro, and J. M. Peña-Barragán, "Configuration and Specifications of an Unmanned Aerial Vehicle (UAV) for Early Site Specific Weed Management," *PLOS ONE*, vol. 8, no. 3, p. e58210, Mar. 2013, doi: 10.1371/journal.pone.0058210.
[52] M. Gašparović, M. Zrinjski, Đ. Barković, and D. Radočaj, "An automatic method for weed mapping in oat fields based on UAV imagery," *Comput. Electron. Agric.*, vol. 173, p. 105385, Jun. 2020, doi: 10.1016/j.compag.2020.105385.
[53] A. M. Smith and R. E. Blackshaw, "Weed–Crop Discrimination Using Remote Sensing: A Detached Leaf Experiment1," *Weed Technol.*, vol. 17, no. 4, pp. 811–820, Oct. 2003, doi: 10.1614/WT02-179.
[54] M. H. M. Roslim *et al.*, "Using Remote Sensing and an Unmanned Aerial System for Weed Management in Agricultural Crops: A Review," *Agronomy*, vol. 11, no. 9, Art. no. 9, Sep. 2021, doi: 10.3390/agronomy11091809.
[55] Q. Du, N.-B. Chang, C. Yang, and K. R. Srilakshmi, "Combination of multispectral remote sensing, variable rate technology and environmental modeling for citrus pest management," *J. Environ. Manage.*, vol. 86, no. 1, pp. 14–26, Jan. 2008, doi: 10.1016/j.jenvman.2006.11.019.
[56] P. Kumar *et al.*, "Variability in arid soil characteristics," 2009, pp. 78–112.
[57] K. Yadav and S. Sarkar, "Biofertilizers, Impact on Soil Fertility and Crop Productivity under Sustainable Agriculture," Nov. 2018.
[58] N. Gruda, M. Bisbis, and J. Tanny, "Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production – A review," *J. Clean. Prod.*, vol. 225, pp. 324–339, Jul. 2019, doi: 10.1016/j.jclepro.2019.03.295.
[59] K. Mehta, "Socio-Economic Impact of Protected Cultivation on Tomato Growers of Himachal Pradesh," *Econ. Aff.*, vol. 65, Mar. 2020, doi: 10.30954/0424-2513.1.2020.1.
[60] P. Kumar, P. S. Khapte, A. Singh, and A. Saxena, "Optimization of Low-Tech Protected Structure and Irrigation Regime for Cucumber Production under Hot Arid Regions of India," *Plants*, vol. 13, no. 1, Art. no. 1, Jan. 2024, doi: 10.3390/plants13010146.
[61] P. S. Khapte, P. Kumar, A. Saxena, and A. Singh, "Performance evaluation and character association studies in arid region greenhouse tomato hybrids," *Indian J. Hortic.*, vol. 75, no. 03, Art. no. 03, Sep. 2018, doi: 10.5958/0974-0112.2018.00077.4.
[62] P. S. Khapte, P. Kumar, A. Singh, G. C. Wakchaure, A. Saxena, and L. Sabatino, "Integrative Effect of Protective Structures and Irrigation Levels on Tomato Performance in Indian Hot-Arid Region," *Plants*, vol. 11, no. 20, p. 2743, Oct. 2022, doi: 10.3390/plants11202743.
[63] P. Pachiyappan *et al.*, "Protected Cultivation of Horticultural Crops as a Livelihood Opportunity in Western India: An Economic Assessment," *Sustainability*, vol. 14, no. 12, Art. no. 12, Jan. 2022, doi: 10.3390/su14127430.

[64] C. Stanghellini and J. I. Montero, "Resource use efficiency in protected cultivation towards the greenhouse with zero emission," in *ISHS 28th Int. Horticultural Congress - Science and Horticulture for People - Abstracts Volume II (Symposia). Lisbon, Portugal, 22 - 27 August, 2010*, ISHS, 2010, pp. 186–187. Accessed: May 29, 2024. [Online]. Available: https://research.wur.nl/en/publications/resource-use-efficiency-in-protected-cultivation-towards-the-gree-2

[65] P. Dixit, A. Singh, C. Tripathi, R. Singh, and P. Kumar, "A Review on Protected Cultivation of Vegetables: Opportunities and Challenges," *Int. J. Environ. Clim. Change*, vol. 13, pp. 3371–3380, Nov. 2023, doi: 10.9734/ijecc/2023/v13i113511.

[66] R. Meena, P. Kalla, and B. Dhaka, "Constraints in adoption of protected cultivation technologies in semi-arid eastern plains zone of Rajasthan".

[67] I. Prabhakar *et al.*, "Constraints in adoption and strategies to promote polyhouse technology among farmers: A multi-stakeholder and multi-dimensional study," *Not Available*, Jan. 2017, Accessed: May 29, 2024. [Online]. Available: http://krishi.icar.gov.in/jspui/handle/123456789/14390

[68] M. Parmar *et al.*, *Desertification and Land Degradation Atlas of India (Assessment and analysis of changes over 15 years based on remote sensing)*. 2021.

[69] M. B. Abdullahi, A. A. Elnaggar, M. M. Omar, A. Murtala, M. Lawal, and A. A. Mosa, "Land degradation, causes, implications and sustainable management in arid and semi-arid regions: a case study of Egypt," *Egypt. J. Soil Sci.*, vol. 63, no. 4, pp. 659–676, Oct. 2023, doi: 10.21608/ejss.2023.230986.1647.

[70] A. Kumar, A. Panda, L. Srivastava, and V. Mishra, "Effect of conservation tillage on biological activity in soil and crop productivity under rainfed Vertisols of central India," *Int. J. Chem. Stud.*.

[71] S. Tambe *et al.*, "Compensatory afforestation policy in India: an analysis using an ecorestoration lens," *Int. For. Rev.*, vol. 24, no. 4, pp. 607–618, Dec. 2022, doi: 10.1505/146554822836282473.

[72] S. Murthy. R and J. Richard, "Windbreaks and Shelterbelts: Bio-Protectors for Soil and Wind Erosion," *SSRN Electron. J.*, Jan. 2022, doi: 10.2139/ssrn.4216977.

[73] N. Masebo and M. Menamo, "A Review Paper on: The Role of Agroforestry for Rehabilitation of Degraded Soil," *J. Biol.*, 2016.

[74] M. Ashraf, N. A. Akram, null Mehboob-Ur-Rahman, and M. R. Foolad, "Marker-assisted selection in plant breeding for salinity tolerance," *Methods Mol. Biol. Clifton NJ*, vol. 913, pp. 305–333, 2012, doi: 10.1007/978-1-61779-986-0_21.

[75] M. Kabi and S. K. Tripathy, "Smart Breeding," Oct. 2023.

[76] G. De Mori and G. Cipriani, "Marker-Assisted Selection in Breeding for Fruit Trait Improvement: A Review," *Int. J. Mol. Sci.*, vol. 24, no. 10, Art. no. 10, Jan. 2023, doi: 10.3390/ijms24108984.

[77] B. C. Y. Collard and D. J. Mackill, "Marker-assisted selection: an approach for precision plant breeding in the twenty-first century," *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 363, no. 1491, pp. 557–572, Feb. 2008, doi: 10.1098/rstb.2007.2170.

[78] F. Hospital, "Size of donor chromosome segments around introgressed loci and reduction of linkage drag in marker-assisted backcross programs.," *Genetics*, vol. 158, no. 3, pp. 1363–1379, Jul. 2001.

[79] F. Hospital and A. Charcosset, "Marker-Assisted Introgression of Quantitative Trait Loci," *Genetics*, vol. 147, no. 3, pp. 1469–1485, Nov. 1997.

[80] S. D. Tanksley, N. D. Young, A. H. Paterson, and M. W. Bonierbale, "RFLP Mapping in Plant Breeding: New Tools for an Old Science," *Bio/Technology*, vol. 7, no. 3, pp. 257–264, Mar. 1989, doi: 10.1038/nbt0389-257.

[81] M. A. Haque *et al.*, "Recent Advances in Rice Varietal Development for Durable Resistance to Biotic and Abiotic Stresses through Marker-Assisted Gene Pyramiding," *Sustainability*, vol. 13, no. 19, Art. no. 19, Jan. 2021, doi: 10.3390/su131910806.

[82] M. Jinek, K. Chylinski, I. Fonfara, M. Hauer, J. A. Doudna, and E. Charpentier, "A Programmable Dual-RNA–Guided DNA Endonuclease in Adaptive Bacterial Immunity," *Science*, vol. 337, no. 6096, pp. 816–821, Aug. 2012, doi: 10.1126/science.1225829.

[83] F. Hille and E. Charpentier, "CRISPR-Cas: biology, mechanisms and relevance," *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 371, no. 1707, p. 20150496, Nov. 2016, doi: 10.1098/rstb.2015.0496.

[84] M. Porteus, "Genome Editing: A New Approach to Human Therapeutics," *Annu. Rev. Pharmacol. Toxicol.*, vol. 56, no. 1, pp. 163–190, Jan. 2016, doi: 10.1146/annurev-pharmtox-010814-124454.

[85] Y. Mei, Y. Wang, H. Chen, Z. S. Sun, and X.-D. Ju, "Recent Progress in CRISPR/Cas9 Technology," *J. Genet. Genomics*, vol. 43, no. 2, pp. 63–75, Feb. 2016, doi: 10.1016/j.jgg.2016.01.001.

[86] H. Nishimasu *et al.*, "Crystal structure of Cas9 in complex with guide RNA and target DNA," *Cell*, vol. 156, no. 5, pp. 935–949, Feb. 2014, doi: 10.1016/j.cell.2014.02.001.

[87] M. Shao, T.-R. Xu, and C.-S. Chen, "The big bang of genome editing technology: development and application of the CRISPR/Cas9 system in disease animal models," *Dong Wu Xue Yan Jiu Zool. Res.*, vol. 37, no. 4, pp. 191–204, Jul. 2016, doi: 10.13918/j.issn.2095-8137.2016.4.191.

[88] S. A. Ceasar, V. Rajan, S. V. Prykhozhij, J. N. Berman, and S. Ignacimuthu, "Insert, remove or replace: A highly advanced genome editing system using CRISPR/Cas9," *Biochim. Biophys. Acta BBA - Mol. Cell Res.*, vol. 1863, no. 9, pp. 2333–2344, Sep. 2016, doi: 10.1016/j.bbamcr.2016.06.009.

[89] F. Jiang and J. A. Doudna, "CRISPR–Cas9 Structures and Mechanisms," *Annu. Rev. Biophys.*, vol. 46, no. 1, pp. 505–529, May 2017, doi: 10.1146/annurev-biophys-062215-010822.

[90] M. Liu *et al.*, "Methodologies for Improving HDR Efficiency," *Front. Genet.*, vol. 9, p. 691, Jan. 2019, doi: 10.3389/fgene.2018.00691.

[91] H. Yang *et al.*, "Methods Favoring Homology-Directed Repair Choice in Response to CRISPR/Cas9 Induced-Double Strand Breaks," *Int. J. Mol. Sci.*, vol. 21, no. 18, p. 6461, Sep. 2020, doi: 10.3390/ijms21186461.

[92] M. Kumar *et al.*, "Application of CRISPR/Cas9-mediated gene editing for abiotic stress management in crop plants," *Front. Plant Sci.*, vol. 14, p. 1157678, Apr. 2023, doi: 10.3389/fpls.2023.1157678.