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Genetic diversity and adaptations of desert plants to arid environments: a study of genetic and environmental factors

Ammar Hamad Nayel[1] and Arshad Naji Alhasnawi[2]

1&2Department of Biology, College of Education for Pure Sciences, Al-Muthanna University, Al-Samawah, 66001, Iraq

Abstract

Genetic diversity is the foundation of organisms' ability to adapt and survive in changing environments and represents an important element in preserving biodiversity. This research examines genetic diversity in desert plants, focusing on the genetic and environmental factors that influence it. The most important sources of genetic diversity, such as genetic mutations, genetic recombination, and genetic drift, are discussed, as well as their role in the evolution of species and their adaptation to harsh conditions. The characteristics of the Iraqi desert are highlighted as an environment characterized by high temperatures and scarce rainfall, leading to selective pressures that contribute to the emergence of physiological and morphological adaptations in desert plants, such as reduced transpiration, water storage, and the development of deep roots. The research also addresses the importance of these plants in maintaining ecological balance and the possibility of exploiting them in breeding programs and conserving genetic resources. Molecular markers, particularly the RAPD technique, are used as an effective tool for analyzing genetic diversity and revealing genetic relationships among desert plants. The research results confirm that studying the genetic diversity of plants in arid environments is an essential step toward understanding natural adaptation mechanisms and developing effective strategies for conserving and sustaining desert plant species in the face of rapid environmental and climatic changes.

Keywords: Plant, Genetic diversity, Desert plants, Drought adaptation, Molecular markers, RAPD technique.

Introduction

Genetic diversity is the average of the contrast in genes among individuals within a species or many species. It appears in the form of differences in phenotypic traits (plant height), functional traits (such as heat resistance), biochemical properties (such as protein synthesis), or variation in DNA sequences. Genetic diversity aims to categorize an individual or population in relation to other individuals or populations. It estimates the extent of genetic variety within a population, which is a primary source of biodiversity .

Genetic diversity is used to generate genetically modified plants to enhance crops and develop new varieties with desired features such as vegetative growth, increased seed production, or traits induced by humans. It is primarily driven by genetic variety within the population. Diversity may be defined as the degree of variation between and within species. Existing intra- and inter-specific differences provide the foundation of all crop improvement efforts. Deserts, with their severe temperatures and dry conditions, are the most problematic habitats for plant development. Despite this, they are home to a diverse range of plants that have evolved to live and flourish in dry circumstances, allowing them to withstand the severity of the desert environment (Shah Aadil Mir, et al ,2023).

Desert plants have evolved many adaptation mechanisms to escape water difficulties. They evolved succulent structures in their bodies, which allowed them to conserve water. Succulent plants can store water in living tissue, which may be used to sustain metabolic activity in the absence of a water source (Mohanta et al. 2024.(

Some plant species from the desert have therapeutic significance because they contain physiologically active chemicals, including teixitol, pyrene, and chametothecin, which are created by internal bacteria of medicinally essential plants and used in medicine and agriculture (Katz et al. 2021). Molecular markers are important instruments for genetic diversity research, which is the first step in breeding programs and genetic resource preservation. In taxonomy, ecology, biodiversity, plant breeding, protection, and genetic modification (Gopikrishna. 2022).

This article aims to highlight the concept of genetic diversity and its importance in the adaptation of desert plants to harsh environmental conditions. It also reviews the genetic and environmental factors and molecular techniques that contribute to understanding the mechanisms of this adaptation and supporting efforts to conserve plant resources in arid environments.

Genetic diversity

Genetic diversity is the rate at which genes vary across individuals within a species or across many species. It emerges as changes in phenotypic qualities (plant height), functional traits (such as heat tolerance), biochemical properties (such as protein production), or variance in DNA sequences (Gopikrishna, 2022). Genetic variety is caused by genetic mutations, drift, migration, and gene combinations in DNA. Genetic diversity within plants is controlled by genes found in reproductive organs and is critical for plant populations to remain alive and develop. Plants can withstand extreme climatic circumstances including drought, pests, and diseases by retaining the genes that carry out these processes. Crop plants resist harsh climatic circumstances due to genetic diversity (Salgotra and Chauhan, 2023). The goal of genetic diversity is to create genetically modified plants in order to improve crops and create new types with desirable characteristics such as vegetative growth, higher seed number, and illness and drought tolerance (Henry, 2012). Genetic diversity enables breeders to retain crossbred varieties, resulting in the preservation of desirable features such as quality qualities and resistance to diverse pressures (Salgotra and Chauhan, 2023). Individual genetic variety demonstrates the occurrence of diverse alleles in the gene group, which results in varied genotypes within populations (Mukhopadhyay and Bhattacharjee, 2021). Genetic variety occurs on several levels. The maximum amount of variety is seen in ecosystems composed of various plant species. The second stage is species diversity, that occurs when various species coexist within a community. The third level is the genetic variation present among genotypes of individuals from the same species. The fourth level involves genomic diversity across many genetic locations in A solely individual (Bhanu, 2017).

Type of genetic diversity

Ecological and evolutionary factors impact the genetic structure and diversity of natural populations. These mechanisms have diverse effects on neutral and adaptive genetic diversity, and they also vary depending on the environment. Neutral genetic variability is influenced by historical associations, random processes like genetic drift, DNA recombination, mutations, and the flow of genes among populations. (Yıldırım, et al, 2018). Neutral genetic diversity may become positively associated with species diversity when societies persist as demographically separated regions of differing sizes. Population size and location affect neutral genetic diversity via genetic drift and immigration. Smaller, more isolated populations have higher rates of genetic diversity loss due to drift, and these groups often have lower genetic diversity (Whitlock, 2014).

Radiational markers are often limited in quantity, but AFLPs may produce up to a few thousand tags spread randomly over the genome. They are supposed to be classified as "neutral" (and, thus, they are known as "neutral genetic variability," NGV), but generation sequencing regularly provides many thousands to millions of SNPs (single-nucleotide poly) that cover all (whole genome DNA sequencing) or a significant part of the gene (they are thus called "genomic") and can be neutral or changing ("adaptive genetic variation," AGV) (Chung et al. 2023).

Adaptive genetic diversity may have intra-generational or 'instantaneous' impacts on the structure of the environment and functioning. Genomic composition can govern ecological responses through individual-level independent and additional effects of every component genotype ('additive replies'). In these circumstances, the component genotypes' responses and population frequencies are determined at the community or ecosystem level (Whitlock, 2014).

Factors affecting genetic diversity

Several factors affect genetic diversity. Evolutionary factors are constantly modifying the genetic frequencies of varieties of crops, thus affecting the genetic diversity of the population. The evolutionary factors that impact a population's gene pool include selection, mutation, transfer of genes, and genetic drift (Begna,2021).

Genetic mutation

Mutations are heritable alterations that emerge unexpectedly owing to errors in the nucleotide sequence of the DNA. A mutation is the cause of genetic variation that affects the appearance of crop species. Mutation-induced genetic variety may have positive, neutral, or negative effects on a plant species' traits. Natural or unforeseen mutations have played an important part in establishing the genetic variety that has resulted in food security; mutations are the final source of plant development when they confront environmental changes (Salgotra and Chauhan, 2023).

Evolution

Evolution is the slow process by which the current variety of plants evolved from the oldest and most rudimentary creatures. Evolution gradually transforms genetic diversity, resulting in the emergence of new crop species. The most suited individuals live and reproduce in higher numbers throughout time (Begna,2021.(

Genetic recombination

Meiotic recombination is a trait of all sexually reproducing organisms. During the process of meiosis, crossovers serve an important role in the correct segregation of chromosomes and rearrange alleles between chromosomes. The difference in recombination rates throughout the chromosome is not uniform across the genome and varies by species. Recombination also has an evolutionary function by breaking linking age disequilibrium among neighboring boring sites and establishing novel genetic combinations that are passed down to the next generation, allowing for more efficient selection of individual genetic variants (Mukhopadhyay and Bhattacharjee, 2021(.

Genetic drift

Genetic drift is the process by which a population's gene and allele counts vary across generations as a result of sampling mistakes. The sampling error modifies the allele frequency by chance, resulting in changes in genetic diversity across generations. Every pollen grain contains a unique mix of genes and may be transported by insects, wind, people, or other ways to hybridize with suitable flowers, which is mostly decided by chance. Thus, in every reproductive cycle, crop species' genetic diversity is lost at each generation due to random occurrences (Salgotra and Chauhan, 2023).

Environmental and human factors

The genetic diversity in wild populations is decreasing worldwide. Most species' genetically unique populations are also disappearing as their geographic ranges decrease, and there is a lack of adequate management and conservation techniques. The majority of genetic variety is lost as a result of infrastructural expansion, climate change, dispersion of habitat, overgrazing, and excessive harvesting (Salgotra and Chauhan, 2023b). Natural variability has decreased over time as a result of (i) lopsided breeding methods that focus on improving only a few features (such as yield and their associated traits), (ii) the frequent use of a few selected genotypes as parents in varietal development programs, and (iii) the introduction of a few desirable lines in several countries (Bhanu, 2017(.

Continual oscillations in a species' biotic and abiotic environments provide a backdrop of constantly shifting selection forces to which the species must adapt. Thus, temporal and geographical environmental variability, which continuously changes the selection value of characteristics or their combinations, is a major factor for sustaining genetic variety within natural populations. Selection on underlying existing genetic diversity within natural populations is therefore a major process that allows them to adjust to environmental variations (Jump, et al, 2009(.

Characteristics of the Iraqi desert

Iraq is a desert nation with access to abundant river resources and a big aquifer, but they have already been depleted for residential, industrial, and agricultural usage, resulting in reduced flow of the Euphrates and Tigris tributaries(Todd, 2023). Iraq's climate is usually dry continental, with extremely hot summers and frigid winters, with less rainfall in the south and center regions. Rainfall in desert places is often quite minimal, especially during the winter. The desert is situated in the west and south, stretching from Basra to the west of Anbar, and it is home to wild flora of scientific, medicinal, and commercial importance (Al-Dulaimi, 2022). Deserts, which occupy enormous areas of the Earth's surface, are among the most difficult settings for plant life. These locations are distinguished by their dry conditions and harsh temperatures; they get little precipitation and are often exposed to high amounts of solar radiation. Despite the extreme circumstances, desert habitats have a surprising variety of plant species that have developed specific adaptations to live and prosper (Shah Aadil Mir et al.2023).

Adaptations of desert plants

Desert plants are distinguished by their ability to thrive in difficult situations defined by high temperatures, strong sunshine, and little water. These adaptations include outward traits such as decreased leaf size, greater thickness of the topmost layer, and higher density in the root network. Functional adaptations include the utilization of water as a consequence of photosynthesis, as well as behavioral adaptations like the rate of germination after rainfall and seed production. These changes let the plant tolerate extreme temperatures and allowed the plant to keep its water content. Deserts, with their severe temperatures and dry conditions, are the most problematic habitats for plant development. Despite this, they are home to a diverse range of plants that have evolved to live and flourish in dry circumstances, allowing them to withstand the severity of the desert environment (Shah et al, 2023).

Resistance of desert plants to drought

Water distribution in desert soils is unstable and varies based on depth. Winter and spring rains replenish water in deep soils, while milder temperatures minimize evaporation and water loss. The water eventually penetrates deeper soil layers. Summer precipitation, on the other hand, only replenishes the top soil layers due to increased evaporation rates produced by high temperatures. Sahara plants' root network distribution and design determine whether they will take up water from surface reservoirs, deep-soil water, or both (Kirschner, et al, 2021).

Drought stress induces a range of morphological, physiological, and biochemical changes in plants, activating adaptive mechanisms to mitigate the deleterious effects of drought. The three most common climatic factors linked with dry desert habitats are severe water shortages, significant temperature changes, and salt. Drought is the primary abiotic stressor affecting plant survival, development, and reproduction in desert ecosystems. Despite severe environmental difficulties, most native plants of the desert can tolerate and adapt to drought stress by improving water use efficiency through a variety of functional and biological adaptations, including regulating stomatal activity, separating aboveground and belowground reactions, and controlling nutrient reabsorption (Madouh and Quoreshi, 2023).

Physiological and phenotypic adaptations

Desert plants have evolved many adaptation mechanisms to escape water difficulties. They evolved succulent structures in their bodies, which allowed them to conserve water. Succulents are characterized by a mechanical method with the presence of water, keeping live tissue in one or more organs. Succulent plants can keep water in living tissue, which may be used to sustain metabolic activity in the absence of a water source(Mohanta et al. 2024). Desert plants are classified into multiple groups based on the adaptability of their roots to the arid environment. Trees and plants, for example, have long, vertical roots that may extend more than five meters. Cactus is an example of a perennial plant with shallow roots that grow near the surface. Some are seasonal herbs with surface roots that sprout with rainfall, such as bulbs(Tariq et al. 2024). Drought stress reduces plant volume and weight, including cell proliferation, elongation, and differentiation. Drought impairs enzyme activity, causes turgor loss, and reduces energy availability, which affects both cell division and cell growth (Alkhedir and Taniguchi, 2024(.

The importance of desert plants

Desert vegetation is an essential aspect of arid and semi-arid landscapes, helping to reduce wind and sand erosion, save water and soil, and maintain an ecological balance (Zhou et al., 2021). play an important role in providing food security, conserving traditional agricultural practices, conserving terrestrial ecosystems, promoting sustainable land management, and strengthening community resilience(Bahnasy, 2025).

Some desert plants have therapeutic significance because they contain physiologically active chemicals, including pyrene, teixitol, and chametothecin, which are created by internal bacteria of medicinally essential plants and used in medicine and agriculture. Plants cannot move; therefore, they have developed chemical protections to help them adapt to changes in their environment. Plants may create poisons to deter predators. This theory explains why plants contain so many medications, toxins, colors, and other valuable chemicals. Plants create compounds known as specific metabolites, which may vary greatly across and even within species. Over millions of years, genetic variations and evolution have produced a diverse range of specialized metabolites (Katz et al, 2021).

Molecular markers

A molecular marker is a DNA sequence with a known location on a chromosome, or a gene whose characteristic expression can be clearly recognized and used to identify an individual, or as a tool to designate chromosomes, nuclei, or loci (Idrees and Irshad, 2014). Molecular markers are important instruments for genetic diversity research, which is the first step in breeding programs and genetic resource preservation. In taxonomy, ecology, biodiversity, conservation, breeding plants, and the application of genetic engineering (Gopikrishna, 2022). Various types of DNA markers have recently gained popularity in plant research because they have the ability to give a considerably larger number of markers.

Within the several DNA-based approaches, PCR-derived markers produced using unspecific primers have proven quite popular for estimating intra-species diversity. Because no sequence data related to the target species is required, these approaches are particularly well suited to circumstances in which little or no molecular genetic study has been undertaken before. (Nybom and Bartish, 2000).

Molecular markers are being extensively utilized for plant genome diversity and population genetic investigations, vital for breeding and crop development, conservation, preservation, introduction, and restoration of endangered and important plants. They may also identify novel plant types and detect genetic alterations in recognized ones, offering significant insights into current genetic differences within and across plant populations (Bidyananda et al., 2024).

Molecular marker techniques have also helped to assemble genetic maps and accelerate plant breeding via marker-assisted selection. Molecular or DNA markers can help to introduce desired features from wild relatives into farmed plants by giving important phylogenetic information. Furthermore, the use of molecular marker technology allows changes in gene sequence to be explicitly detected and documented (Amiteye, 2021). Ideal DNA markers have properties such as high polymorphism, codominant inheritance, frequent occurrence in the DNA sequence, selective neutral expression, ease of access, fast assay, excellent reproducibility, and easy data exchange between labs (Arif et al., 2010).

Molecular markers are significantly more appropriate for analyzing genetic diversity than physical and biochemical features since they segregate as just one gene and are unaffected by environmental factors. A wide range of molecular markers, including randomly amplified polymorphic DNA (RAPD), amplified fragment length polymorphism (AFLP), restriction fragment length polymorphism (RFLP), microsatellites or simple sequence repeats (SSR), and inter simple sequence repeats (ISSR) have been utilized to assess genetic variation in plant species from around the world (Mint Abdelaziz et al., 2020).

Random amplified polymorphic DNA (RAPD)

Randomly amplified polymorphic DNA is typically composed of 8-15 base pair lengths oligonucleotide primers of variable sequence that bind to nonspecific locations on the DNA and generate band patterns. Primers randomly attach to the DNA at low annealing temperatures. RAPD markers may identify polymorphisms even when only modest quantities of genomic DNA are available. Because the primers may bind anywhere in the genomic DNA, sequencing RAPD is a straightforward and efficient approach (Gopikrishna, 2022).

RAPD markers are examples of randomly amplified dominant markers. They are commonly employed in studies of plant population genetics, qualitative trait loci mapping, and DNA fingerprinting. The use of a random primer allows us to perform a polymorphism study without knowing the organism's DNA sequence. This is just one of the primary benefits of the RAPD approach (Hromadová et al., 2023).

A primer sequence used for RAPD needs to contain at least 40% GC (Guanine and Cytosine) content, while 50%-80% GC is commonly preferable. At this GC concentration, the primer will be able to work effectively at the annealing temperature, allowing DNA polymerase to perform DNA elongation. RAPD primers may often generate PCR products from one to 10 genomic DNA locations simultaneously. RAPD PCR fragment lengths typically vary from 0.5 to 5 kb (Amiteye, 2021a). This marker exhibits dominant behavior due to varying repeatability outcomes but limited genetic information per locus, inability to discriminate between heterozygotes and identical individuals, and response circumstances that differ across labs (Al-Hadeithi and Jasim, 2021).

Inter simple sequence repeat (ISSR)

(ISSR) is the area located between two microsatellites (SSR). It is a several-locus marker, with the area between two small satellites (SSR) amplified using a method called polymerase chain reaction. Inter Simple Sequence repetitions (ISSRs) are ubiquitous in nature (they do not differentiate between heterozygotes and homozygotes) and are utilized in genetic diversity, varietal identification, biological evolution, gene labeling phylogeny, and genetic mapping research (Gopikrishna, 2022). ISSR markers have been shown to be the most effective technique for genetic diversity analysis since they are low-cost, simple, reproducible, and need no previous information. Because of their high polymorphism, ISSR markers are often employed(Venkatesan et al. 2021).ISSRs are DNA segments bordered on both sides by small DNA motifs of 2-5 nucleotides in length, which are repeated numerous times (Mint Abdelaziz et. al., 2020).

Conclusions

The review demonstrated that genetic diversity plays a crucial role in the adaptation of desert plants to harsh conditions of heat and drought through advanced physiological and molecular mechanisms. The study recommends the need to enhance molecular research using techniques such as RAPD and ISSR to accurately determine genetic diversity, and to adopt national programs to conserve desert plant genetic resources and support environmental sustainability strategies in arid regions.

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